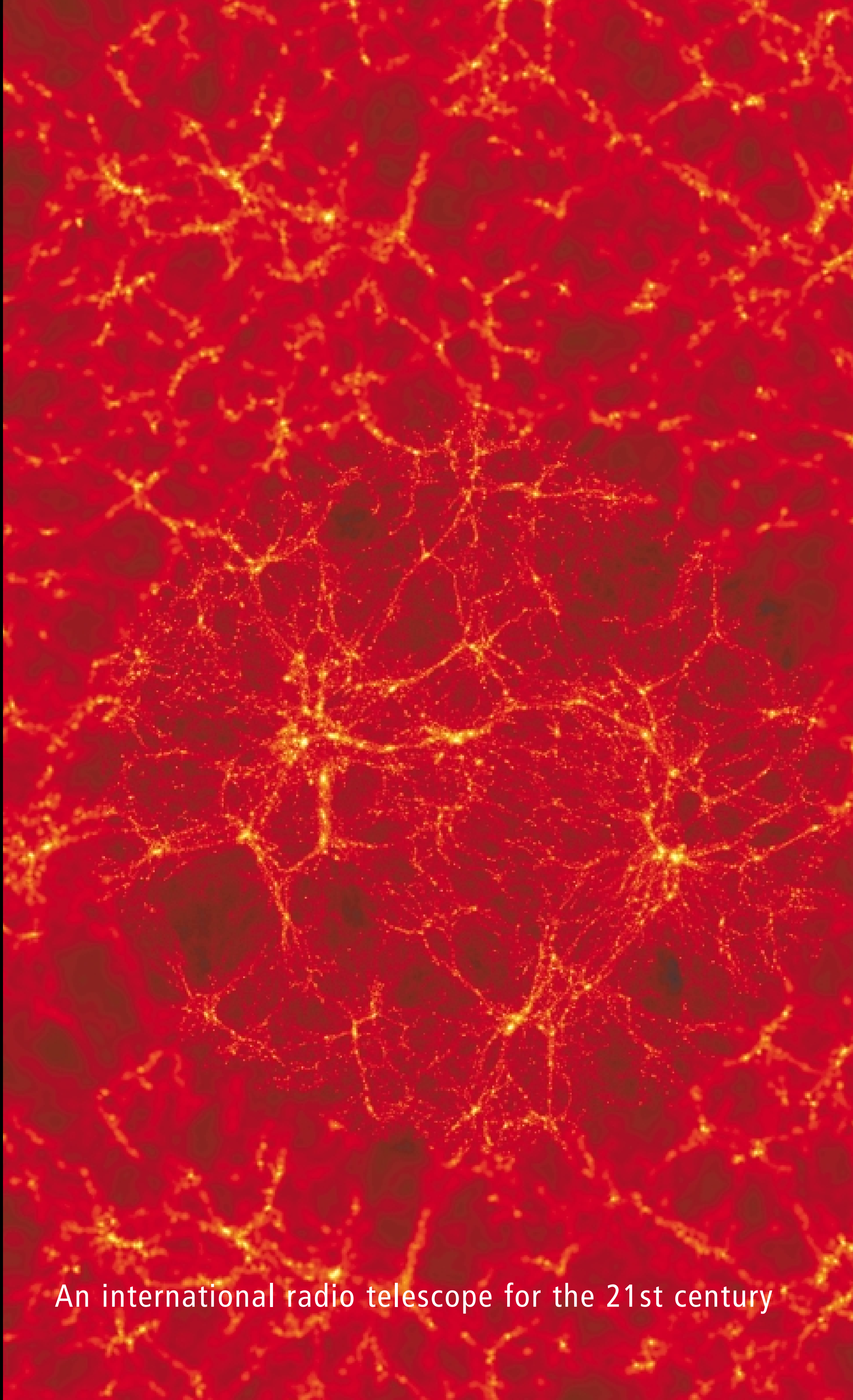
# The Square Kilometre Array



An international radio telescope for the 21st century

# A Revolutionary View of the Universe

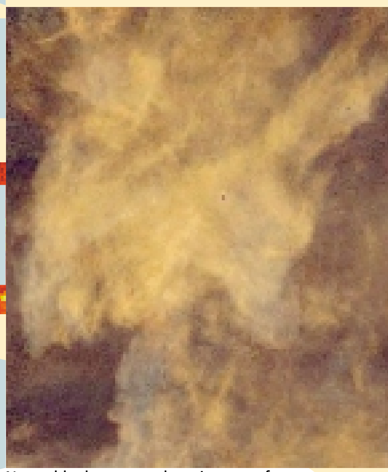
**The Square Kilometre Array (SKA)** is a unique radio telescope being planned by an international consortium. Covering frequencies of 0.15–20 GHz, it will make a revolutionary break with today's radio telescopes. It will:

- have a collecting area of one square kilometre, giving it 100 times the sensitivity of today's best radio telescopes;
- be the first aperture synthesis telescope with multiple independent fields of view (up to 100 at one time); and
- integrate computing hardware and software on a massive scale, in a way that best captures the benefits of these exponentially developing technologies.

**Why one square kilometre?** The idea of the SKA sprang from the desire to see and map structures forming in the early Universe and the interstellar media of the first galaxies. For $5 < z < 20$, the first structures will appear as inhomogeneities in the primordial hydrogen, heated by infalling gas or the first generation of stars (and/or quasars). For $z < 5$ we expect to see a growing "cosmic web" of neutral hydrogen and galaxy halos forming and evolving. To study such processes the SKA needs a collecting area of one square kilometre.

The same sensitivity is needed to image the interstellar medium in high-redshift and primordial galaxies. By measuring radio synchrotron and free-free continua we will be able to detect stellar activity and magnetic fields and see them evolve.

The SKA will detect both neutral hydrogen line emission (at long wavelengths) and ionised hydrogen continuum emission (at short wavelengths). The latter will be a direct measure of ionising flux and hence of current massive star formation.

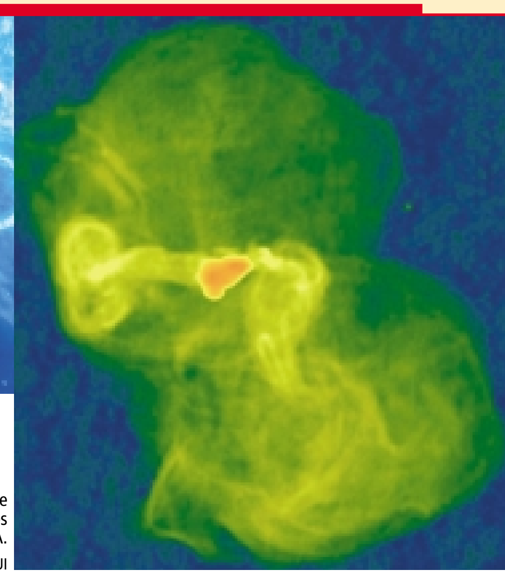


Neutral hydrogen gas bursting out of the Galaxy's disk. The SKA should find similar structures in the early Universe.

Credit: Canadian Galactic Plane Survey

Ionised hydrogen in a Galactic star-forming region, Cygnus X. The SKA may see similar regions in the early Universe, ionised by the first stars.

Credit: Canadian Galactic Plane Survey



High-energy particles interact with magnetic fields to make huge radio-emitting "bubbles" around M87. The first such structures in the early Universe will be easily imaged by the SKA.

Credit: VLA image (λ 90 cm), NRAO/AUI

## New instruments drive discovery

Radio astronomy has been crucial in uncovering phenomena such as quasars, pulsars, superluminal motion and the cosmic microwave background, and has led to three of the five Nobel prizes awarded for work in astrophysics. Major advances in knowledge can be expected from a new radio telescope with the sensitivity of the SKA.

Being sensitive to neutral and ionised hydrogen gas, high-energy particles and magnetic fields, **the Square Kilometre Array will complement other planned instruments in the optical, infrared and millimetre wavebands.** It will study the hydrogen gas content and magnetic fields of the same galaxies observed in dust and molecules by ALMA (the Atacama Large Millimeter Array) and in stars by the NGST (Next Generation Space Telescope). Combining centimetre-wave observations from the SKA with those at millimetre-wavelengths from ALMA (will give distances to starburst galaxies—even those optically obscured—at any redshift.

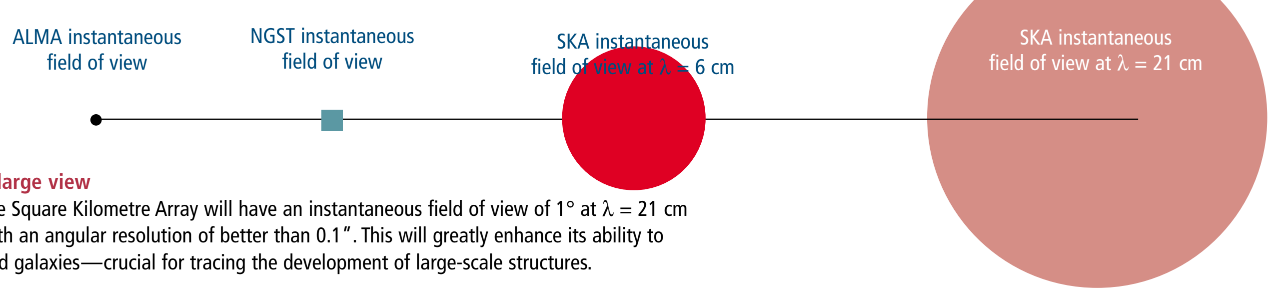
## The Square Kilometre Array will be the world's premier instrument for astronomical imaging

No other instrument, existing or currently planned, on the ground or in space, at any wavelength, will provide simultaneously:

- a wide instantaneous field of view (≈ 1 square degree) and exquisite angular resolution (0.1″– 0.001″)
- wide instantaneous bandwidth ($\Delta\nu/\nu > 50\%$), coupled with high spectral resolution ($\nu/d\nu > 10^4$) for detecting small variations in velocity

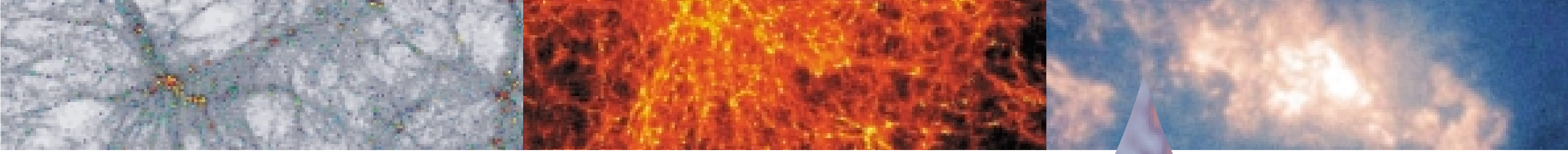
**. . . and with enough sensitivity to see even normal galaxies in the early Universe.**

The SKA's superior resolving power and image quality will be crucial to studying the formation and early history of stars, galaxies and quasars, untroubled by dust. It will let astronomers see, for the first time, even normal galaxies at distances where cosmological effects dominate.




## A large view

The Square Kilometre Array will have an instantaneous field of view of 1° at λ = 21 cm with an angular resolution of better than 0.1″. This will greatly enhance its ability to find galaxies—crucial for tracing the development of large-scale structures.



# The First Galaxies and Stars

- **The Dark Ages and the dawn of galaxies**

The first objects to form after the Big Bang re-ionised the intergalactic medium. The SKA will observe this process directly, through redshifted 21-cm emission from the primordial hydrogen, and define the epoch and nature of those very first objects.

- **Large-scale structure of Universe**

The SKA will reveal the earliest pre-galactic structures and trace the evolution of large-scale structure of the Universe. Through wide-field spectroscopic imaging, the SKA will show how atomic hydrogen was distributed during the epoch of peak galaxy and star formation ($z = 1$ to 3).

- **Galaxy evolution and star formation**

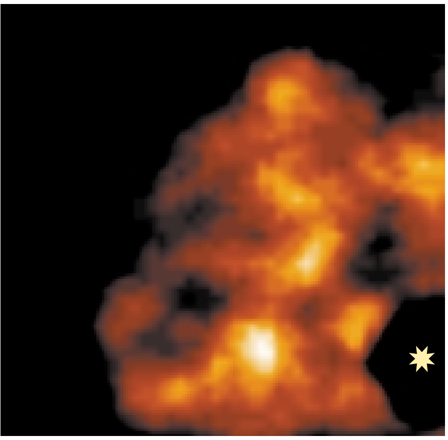
The SKA will observe the evolving galaxies and the stars forming within them, exploring the roles of mergers, Dark Matter and magnetic fields in these processes. Star formation has become more complex as each succeeding generation has modified its environment and the SKA will help us understand the formation of stars from matter in its pristine state. In our own Galaxy, the SKA will probe protostellar and protoplanetary disks.

- **Evolution of the heavy elements**

Using its highest frequencies the SKA will be able to measure redshifted molecular lines in the interstellar medium of early galaxies. CO, for instance, can be studied easily at any $z > 4$.

More than just a tool for astronomy, the Square Kilometre Array is a radio science instrument that could:

- track simultaneously many satellites and deep space probes (with low transmitter power needed on the spacecraft)
- study space weather
- image the planets with bistatic radar



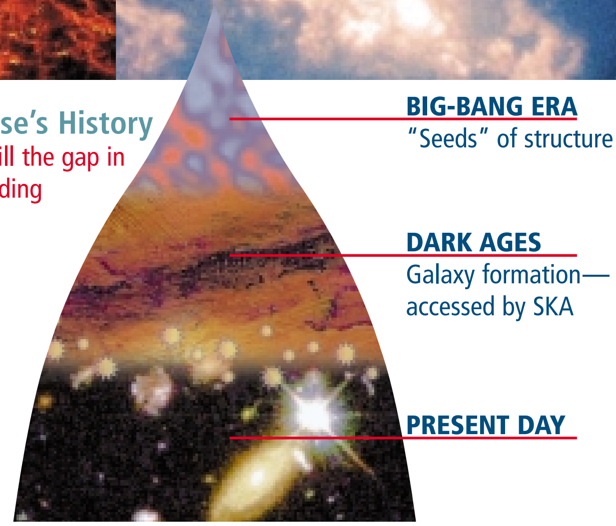
**What the SKA might see**
One quadrant of a simulation of 21-cm emission from the region surrounding a newly formed quasar (bottom right). This emission appears when the quasar's soft X-rays heat the protogalactic medium above CMB temperature for the first time.

Image: A. Meiksen

WHY

## The Universe's History

The SKA will fill the gap in our understanding




# Other Areas the SKA will Probe

- **Dark Matter**

The SKA will be able to measure galaxy rotation curves to $z = 0.5$, giving unique information about the total Dark Matter present in those galaxies. With its large field of view and compact, well-defined point spread function ($< 0.1''$), the SKA will be superb for using weak gravitational lensing to map the distribution of Dark Matter on large scales.

- **The micro-arcsecond Universe**

Radio sources with very small angular sizes scintillate, because of turbulence in the interstellar medium. This scintillation reveals information about the source structure on the micro-arcsecond scale—resolution 1,000 times better than any other astrophysical technique can achieve. With current telescopes, this new tool is extremely difficult to use. But the SKA's great instantaneous sensitivity will make the process routine, even for faint sources, opening a new window on the micro-arcsecond Universe.

- **Gamma-ray burst sources**

The SKA will be able to track the full evolution of the fireball of these explosions and detect them even in obscured galaxies. It will be the only instrument able to capture information at the sub micro-arcsecond scale, again using interstellar scintillation.

- **Gravitational waves**

By timing a suite of millisecond pulsars to sub-microsecond accuracy, the SKA will be able to detect the long-period gravitational radiation emitted by ultra-massive black hole binaries throughout the Universe.

- **Extrasolar planets**

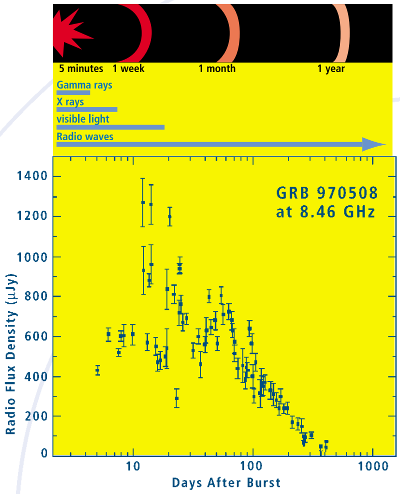
Through astrometric observations of parent stars the SKA will compile a census of Jovian planets in the solar neighbourhood and put statistical constraints on orbital separations and masses.

- **Search for Extraterrestrial Intelligence (SETI)**

The SKA could conduct SETI searches with a sensitivity up to 100 times greater than is now possible, targeting many stars simultaneously.

The long-lived radio emission from gamma-ray burst sources is crucial to understanding the evolution of these events. Scintillation caused by the interstellar medium can be used to track the expansion of these sources. This example—a strong, slowly decaying source—is the only one measured to date, but the SKA would make the process routine.

Credit: D. Frail, S. Kulkarni




Scintillation of the radio emission from gamma-ray burst GRB 970508

# HOW

## Design Goals

The collecting area of the SKA is derived from the sensitivity the instrument needs to detect neutral hydrogen in the early Universe. Other design goals have been arrived at by considering the full range of SKA science drivers. The science case for the SKA can be found at www.ras.ucalgary.ca/SKA/science/science.html; the design goals are shown overleaf.

### Technologies

To provide a square kilometre of aperture at an acceptable cost the Square Kilometre Array must make a revolutionary break with current radio telescopes. Some aspects of the technology it will need are still in the development stage. Institutions participating in the SKA are now designing and building prototype systems, and the key technologies will be determined from these. Many different technological solutions will be selected and integrated into the final instrument.

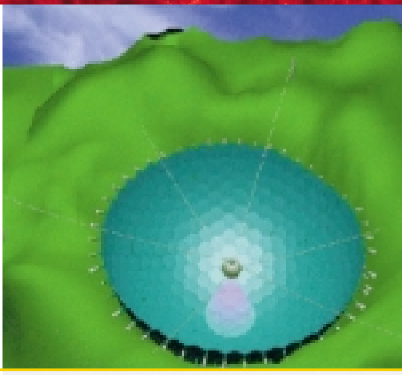
Both planar phased arrays and reflectors/refractors are being considered for the antennas. Whichever is used, the technology must allow for multibeaming over large areas of sky, preferably with fields of view that can be targeted independently. It must also provide for adaptive nulling, to mitigate interference.

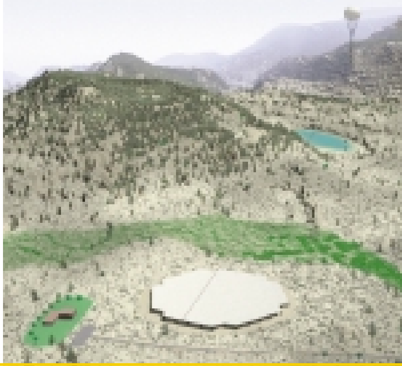
### Station design

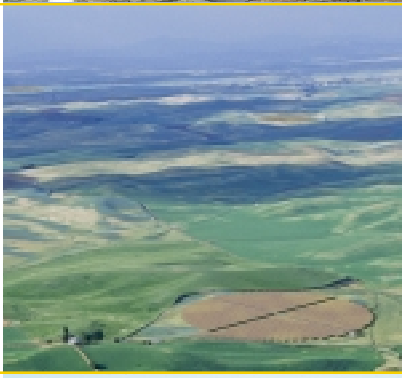
The SKA's collecting area of one million square metres will be distributed over a number of "stations"—perhaps as many as 1,000. Each station will have a diameter of 30–300 m.

Options that have been suggested for the stations are (shown top to bottom):

- a set of large (Arecibo-like) spherical reflectors, each of which can be dynamically shaped to form local parabolic patches
- a large, low-profile parabolic reflector of very long focal length, with the receiver supported by an aerostat at prime focus
- an array of steerable parabolic dishes
- a fixed planar array
- an array of spherical Luneburg lenses.



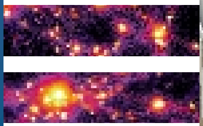


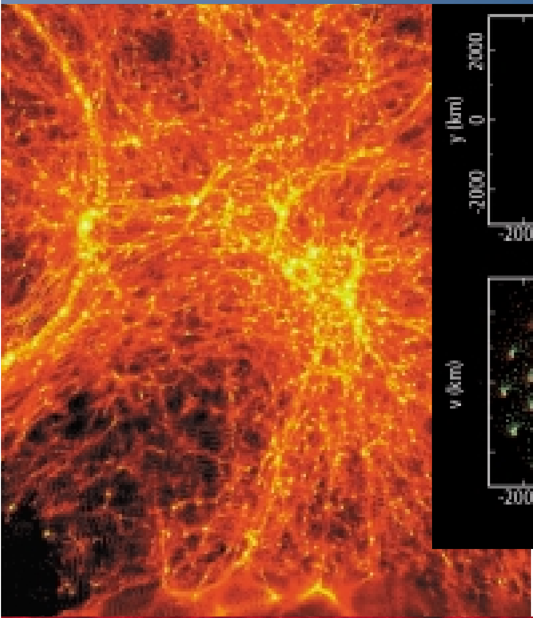


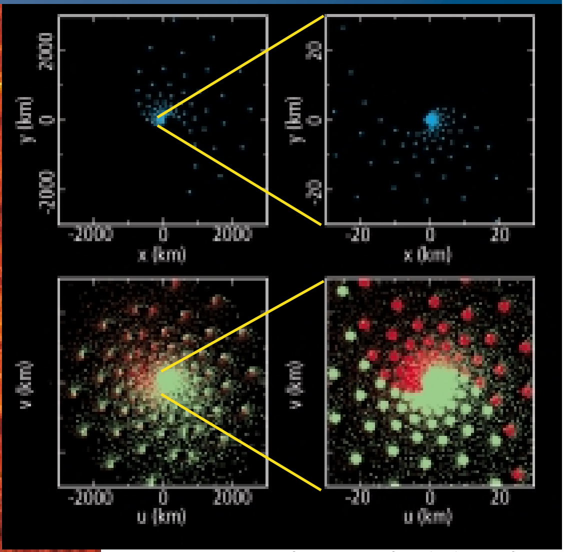
## "Virtual" Astronomy

Entirely new ways of doing astronomy may be possible with the SKA. With an array that is pointed electronically, the raw, "undetected" signals can be recorded in memory. These stored signals could be used to construct "virtual" beams, pointing anywhere in the sky. Using such beams astronomers could literally go back in time to study pulsar glitches, supernovae and gamma-ray bursts with full sensitivity.

Candidate SETI signals could be investigated with the full power of the SKA following a detection by an omnidirectional telescope of modest aperture.








Coverage of Fourier transform (u-v) plane for one possible SKA configuration—a close-packed central hexagon of antennas with a 7-arm spiral extension Image: M. Wieringa

# WHO

The international consortium planning the Square Kilometre Array at present includes:

- **Australia**
  Australia Telescope National Facility, CSIRO — www.atnf.csiro.au/SKA
  University of Sydney
- **Canada**
  Herzberg Institute of Astrophysics — www.drao.nrc.ca/science/ska
  University of Calgary
- **China**
  Beijing Astronomical Observatory — www.bao.ac.cn/bao/LT
- **Europe**
  The European SKA consortium: — www.astron.nl/ska
  - Istituto di Radioastronomía, Bologna
  - Joint Institute for VLBI in Europe
  - Max-Planck-Institut für Radioastronomie
  - Netherlands Foundation for Research in Astronomy
  - Onsala Space Observatory
  - Torun Centre for Astronomy
  - University of Manchester, Jodrell Bank Observatory
- **India**
  The Indian SKA consortium:
  - National Centre for Radio Astrophysics, TIFR — www.ncra.tifr.res.in/ska
  - Raman Research Institute
- **USA**
  The US SKA consortium: — www.usska.org
  - California Institute of Technology, including the Jet Propulsion Laboratory
  - Cornell University, including the National Astronomy and Ionosphere Center
  - Georgia Institute of Technology
  - Harvard-Smithsonian Center for Astrophysics
  - Massachusetts Institute of Technology, including Haystack Observatory
  - National Radio Astronomy Observatory
  - Ohio State University
  - SETI Institute
  - University of California, Berkeley
  - University of Minnesota

The SKA is the first project in the field of radio astronomy that has been “born global”, growing out of discussions within URSI (the International Union of Radio Science) and the IAU (International Astronomical Union). The scientific case for the SKA project has been developed by the URSI Large Telescope Working Group. Organisations in ten countries have committed themselves to sharing research and development for the instrument.

# WHEN

## Timeline

- **2000** International Square Kilometre Array Steering Committee formed
- **2002** International SKA Management Plan established
- **2005** International agreement reached on technical implementation and site
- **2008** SKA scientific and technical proposal completed
- **2010** SKA construction begun

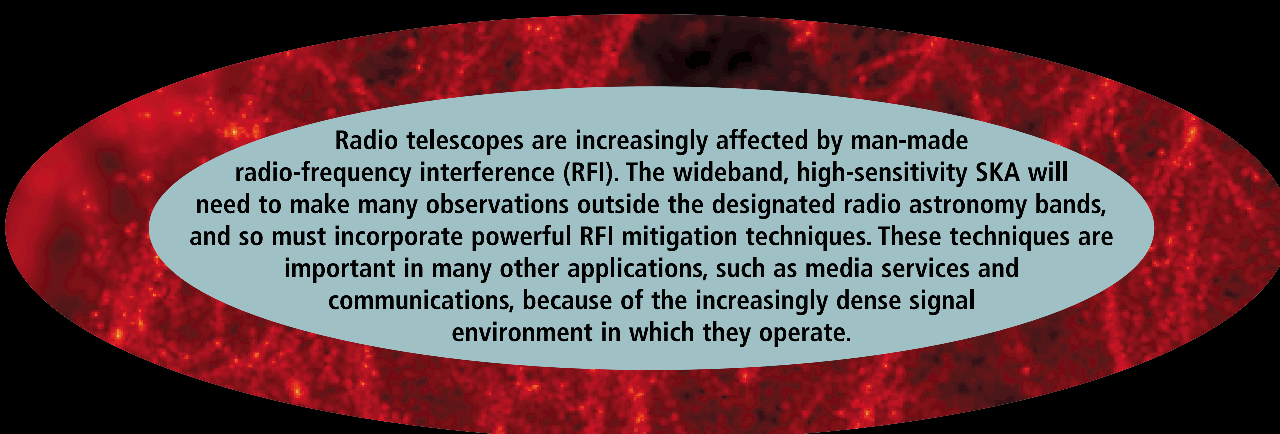
# WHERE

The site for the Square Kilometre Array will be chosen to optimise the scientific returns from this ambitious project. Important factors will be:

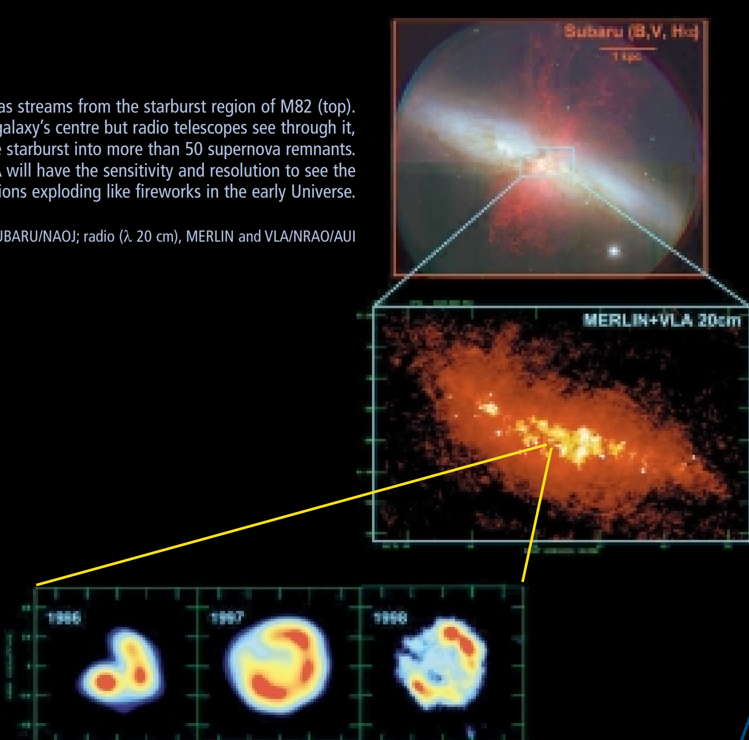
- a configuration that allows SKA stations to be distributed over thousands of kilometres
- low levels of radio-frequency interference
- access to communication links.

## Current design goals for the Square Kilometre Array

| | |
|---|---|
| Frequency range | 0.15–20 GHz |
| Imaging field of view | 1 square degree at 1.4 GHz |
| Number of instantaneous beams | at least 100 |
| Angular resolution | < 0.1 arcsec at 1.4 GHz |
| Number of spatial pixels | $10^8$ |
| Surface brightness sensitivity | 1K at 0.1 arcsec (continuum) |
| Instantaneous bandwidth | (0.5 + 0.2 x frequency) GHz |
| Number of spectral channels | $10^4$ |
| Sensitivity | $A_{eff}/T_{sys} = 2 \times 10^4\ m^2\ K^{-1}$ |
| Image dynamic range | $10^6$ at 1.4 GHz |
| Polarisation purity | -40 dB |



**Radio telescopes are increasingly affected by man-made radio-frequency interference (RFI). The wideband, high-sensitivity SKA will need to make many observations outside the designated radio astronomy bands, and so must incorporate powerful RFI mitigation techniques. These techniques are important in many other applications, such as media services and communications, because of the increasingly dense signal environment in which they operate.**




Ionised gas streams from the starburst region of M82 (top). Dust veils the galaxy's centre but radio telescopes see through it, resolving the starburst into more than 50 supernova remnants. The SKA will have the sensitivity and resolution to see the first star-forming regions exploding like fireworks in the early Universe.

Credits: Optical image, SUBARU/NAOJ; radio (λ 20 cm), MERLIN and VLA/NRAO/AUI

Cover: A high-resolution N-body simulation of the ΛCDM universe, constrained to reproduce the observed large-scale structure of the local universe, at $z = 0.84$

Credit: V. Springel, S. White, G. Lemson, G. Kauffmann, A. Dekel and the GIF Consortium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