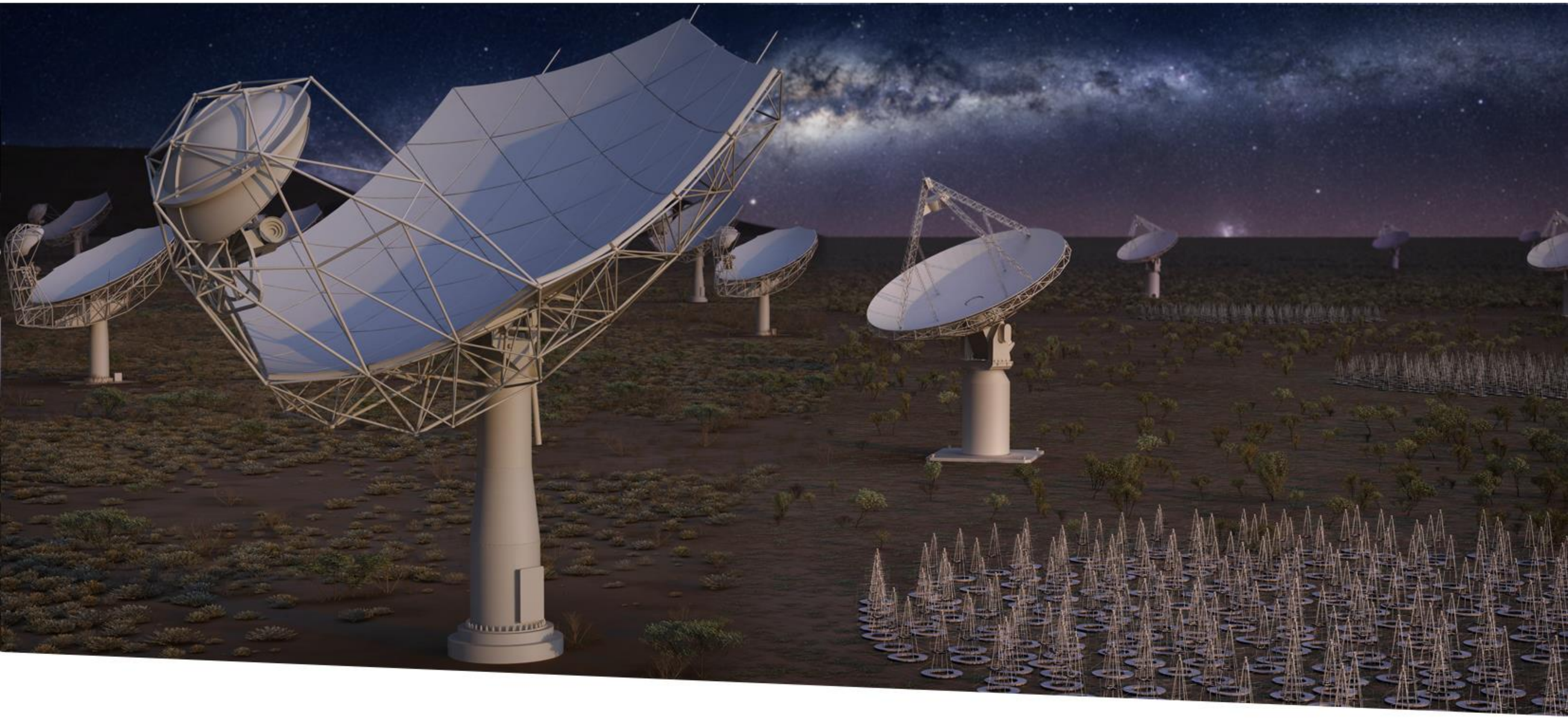
# Current and Future Arrays



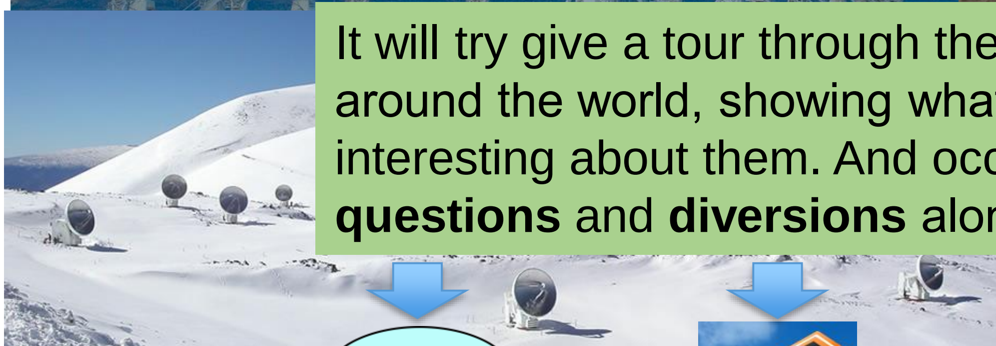
SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

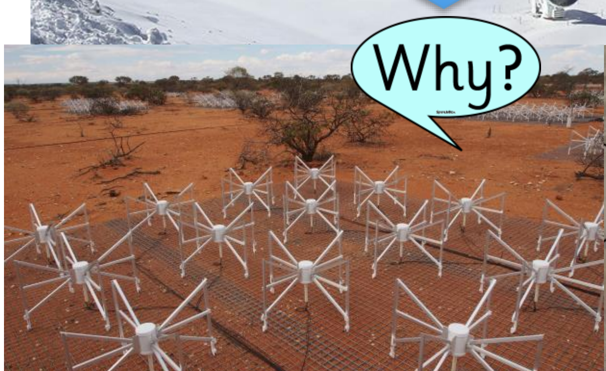
**Daniel Hayden**

20 March 2018

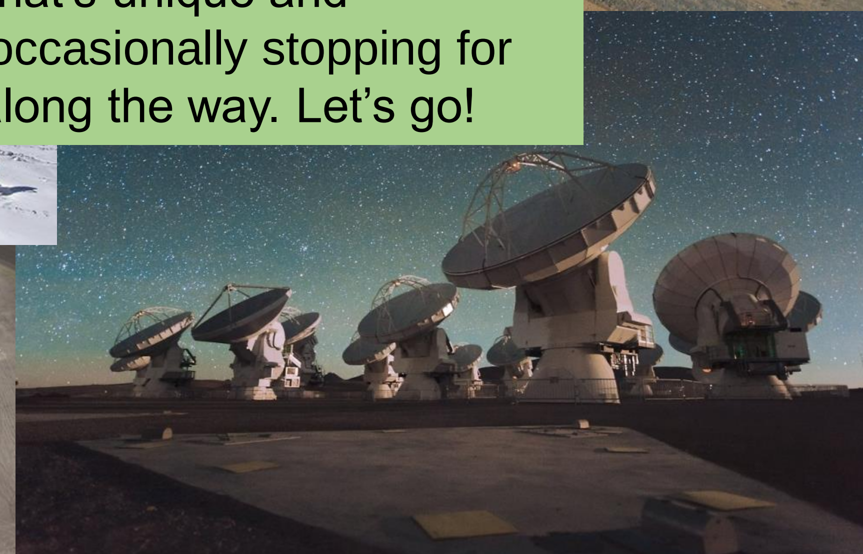
# What is this talk about ?



It will try give a tour through the diversity of arrays around the world, showing what’s unique and interesting about them. And occasionally stopping for **questions** and **diversions** along the way. Let’s go!







# Very Large Array (it's in the name)

The VLA discovered aliens! (in a movie, unfortunately not yet in real life)

# Very Large Array

- Consists of 28 x 25m dishes.
- From 1 GHz to 50 GHz.
- Built in a remote desert in New Mexico, U.S.A. 

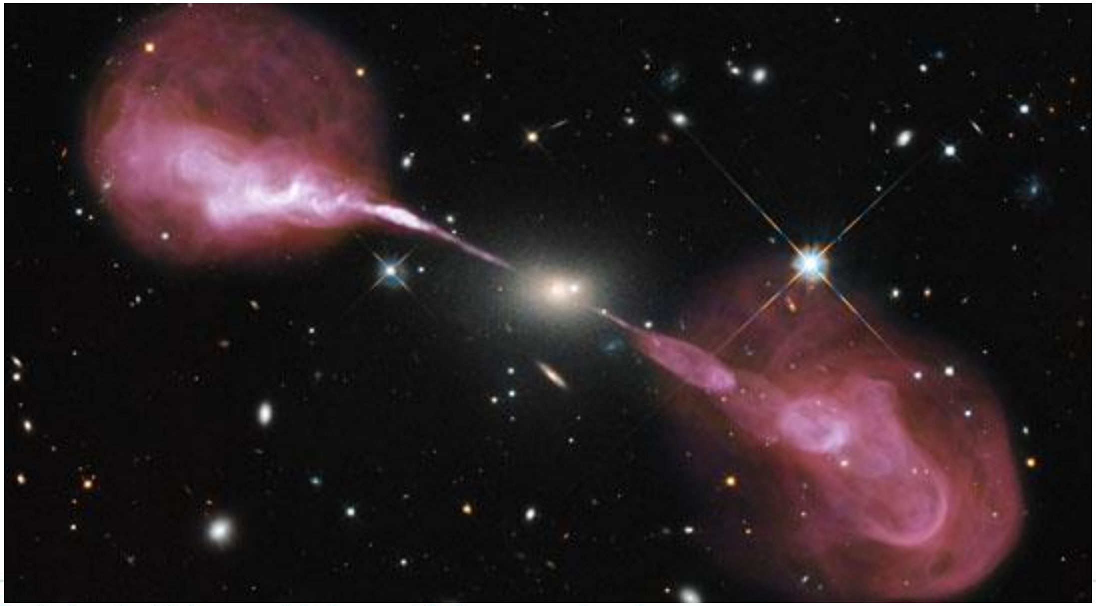
- Currently the most widely used radio telescope in the world.
- The dishes are on rails! Four times a year, a custom designed truck picks up the dishes (200 tons each!) and moves them along their tracks. So the VLA lengthens each of its legs from 0.6 miles to 23 miles long.

**There are 2 questions here:**

- Why are the dishes allowed to move?
- Why is it in a ‘Y’ shape?

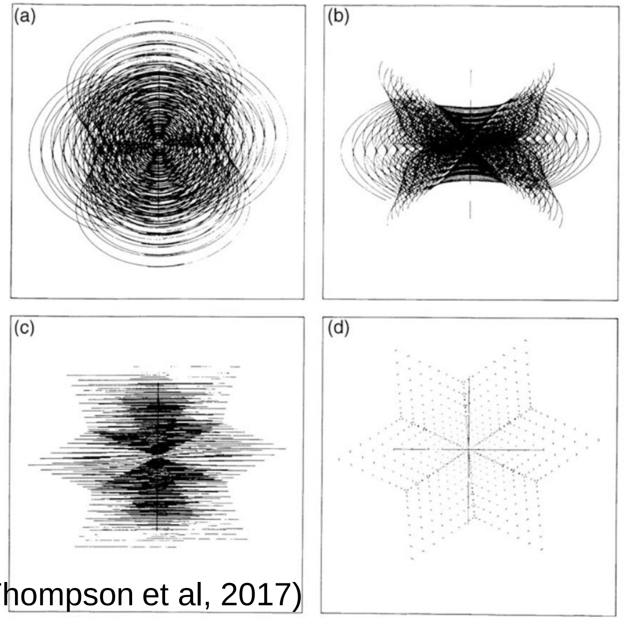

# Why are the dishes allowed to move?

- Longer baselines let you study small spatial scales. But they resolve out large scale structures.
- Moveable dishes let you study both: they can map large-scale structure of gas and molecular clouds and also, for example, pinpoint ejections of plasma from supermassive black holes.

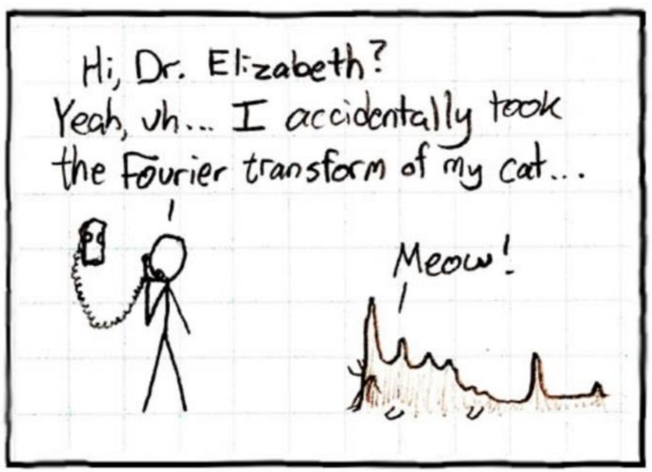


A combined Hubble and VLA image of spectacular jets powered by the gravitational energy of a super massive black hole in the core of the elliptical galaxy Cygnus A

# But why a ‘Y’ configuration?




(Thompson et al, 2017)

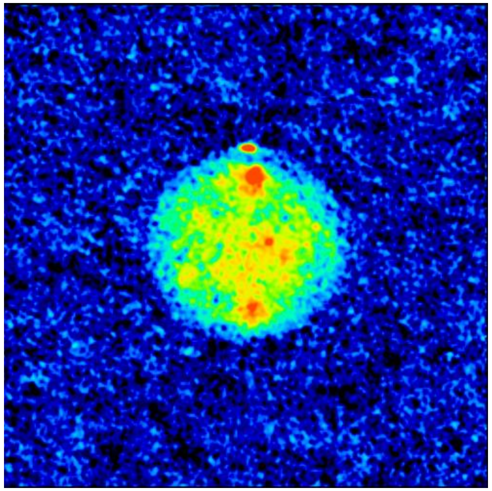



- One wants a configuration that <u>minimises ‘holes’</u> in the U-V plane.


- Because these holes create sidelobes in the synthesized beam which ‘dirty’ the image. (Remember that the inverse Fourier transform of the sampled visibilities in the U-V plane yields the dirty sky image.)

- For a given number of antennas, the equiangular Y shape is superior to the cross and T-shaped array.

# Some VLA achievements

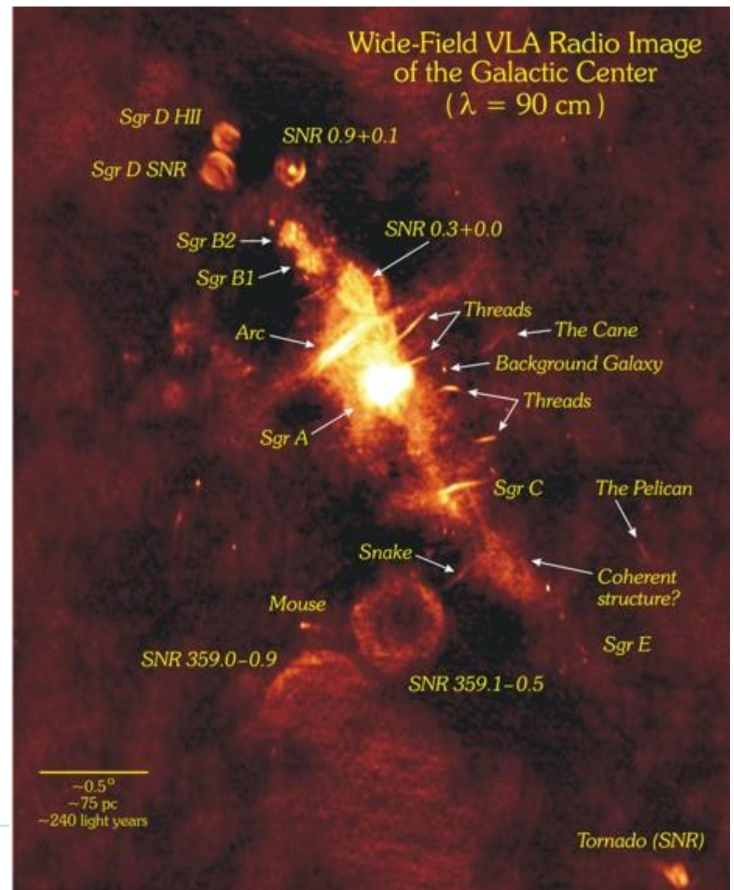


**Ice on Mercury**

Red regions in image, believed to be ice that collects on floors of deep craters where it can reach temperatures as low as -150 degrees Celsius (remember Mercury can reach >400 degrees).

**Revealing the Shrouded Centre of the Milky Way**

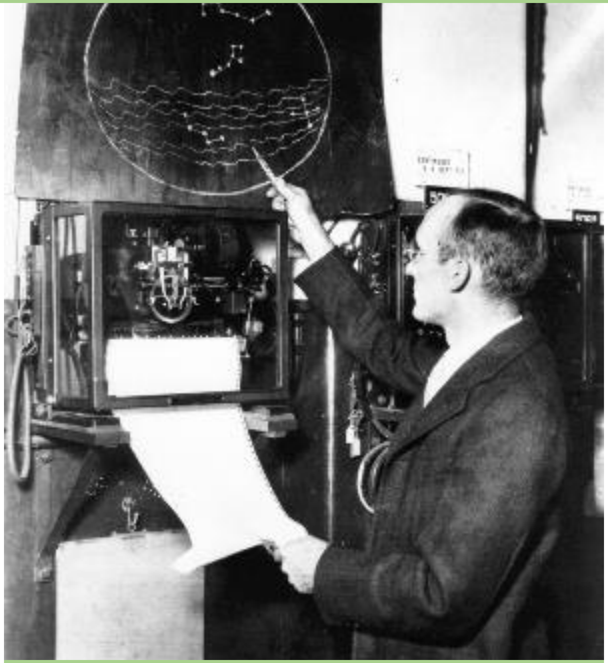
This image is the largest and most sensitive radio image ever made of the Milky Way's centre at a uniform and high resolution. This cannot be seen in visible light because it lies behind a thick veil of gas and dust.



# More than just a name change

- Originally dedicated in 1980
- In 2012 was re-named ‘Karl G. Jansky Very Large Array. Why? It was seriously upgraded.
- **OUT:** 1970s-vintage electronic equipment, analog data-transmission system, and the computing "heart" of the system.
- **IN:** State-of-the-art receivers and electronics, an all-digital, high-bandwidth fibre-optic data-transmission system, and a new, central supercomputer.
- The Jansky VLA is more than <u>ten times</u> more sensitive than the original VLA, and covers more than <u>three times</u> more radio frequency range.
- **Moral of the story?** An array is MUCH more than its antennas.

The new name was selected from among 23,331 suggestions submitted by 17,023 people from more than 65 countries!

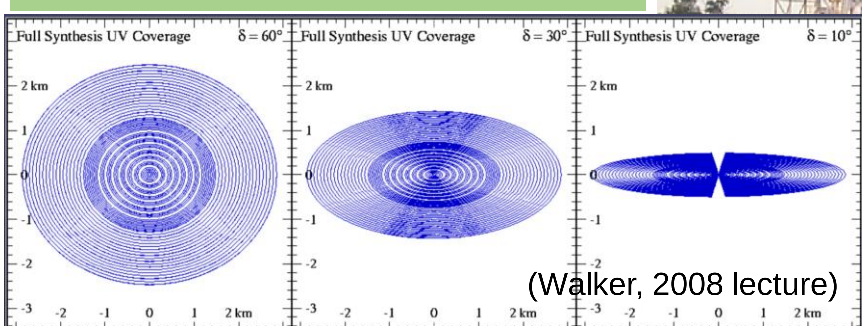


Karl Jansky didn’t know at the time he’d have a giant array named after him

# What about the Southern Hemisphere?

- The Australia Telescope Compact Array (ATCA), located in.. Australia.. consists of 6 x 22m antennas. It is an East-West array that also moves on a track.
- But Why? can an East-West array give you good U-V coverage?
- Tracking a source for 12 hours traces out concentric ellipses in the U-V plane, one for each baseline.
- But U-V coverage becomes seriously <u>limited near the celestial equator</u>.

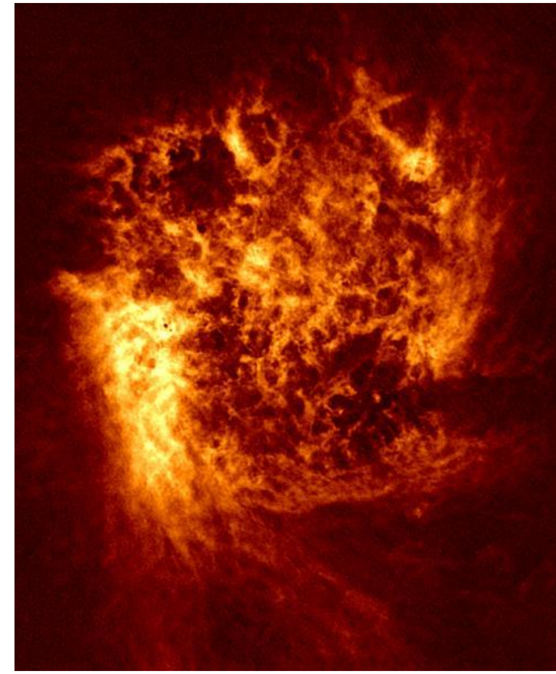
This shows UV coverage for another E-W array, but the shapes are the same




(Walker, 2008 lecture)

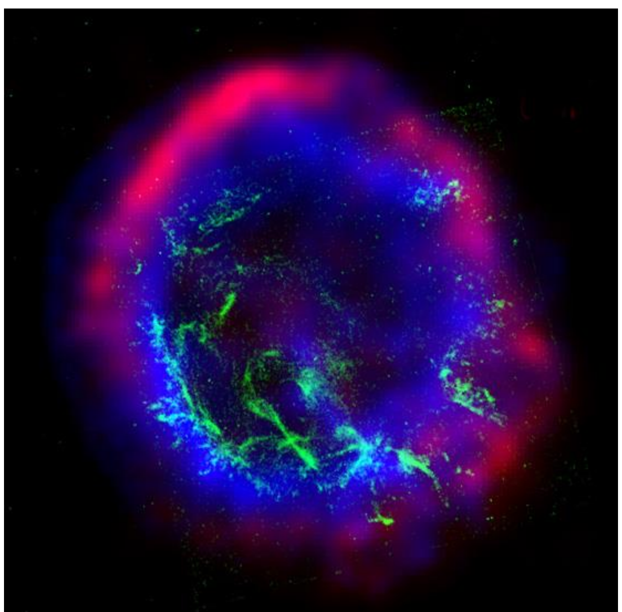
# ATCA can see clouds

- Because ATCA is in the southern hemisphere, it can see the Large and Small Magellanic clouds.
- The right image shows the LMC in neutral hydrogen.



Why does neutral hydrogen emit radio waves?



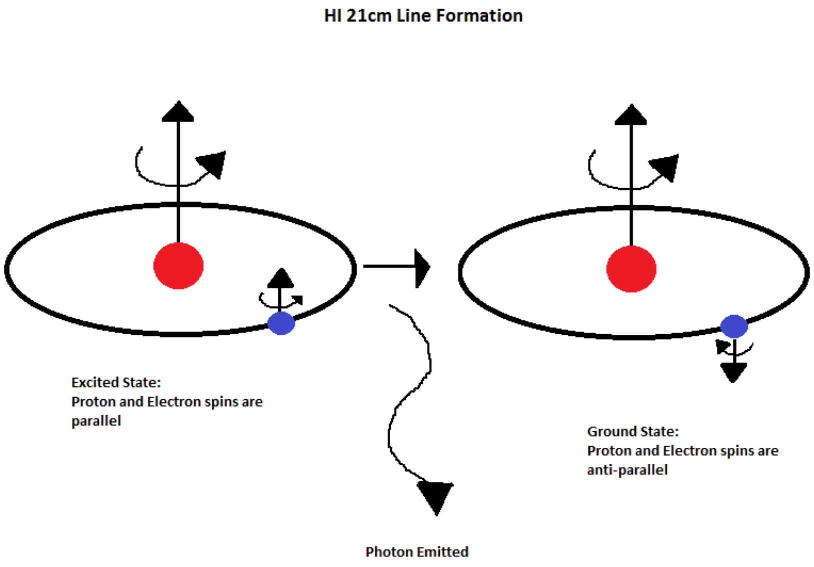


The left image shows a supernova remnant in the SMC (x-rays in blue, optical in green, radio in red).

**Note:** ATCA also has a short N-S spur, to allow for better u v coverage in shorter tracks at higher frequencies (24-110 GHz).

# How neutral hydrogen (HI) emits

- A 'spin-flip' transition in neutral hydrogen atoms releases a photon with a frequency of 1420 MHz.
- This transition is highly forbidden with a mean lifetime of the excited state of around 10 million years!
- But because of the sheer number of H atoms in galaxies along our line of sight, they're always 'glowing' at this frequency.



# Moving up now – in frequency

- Some history first. 

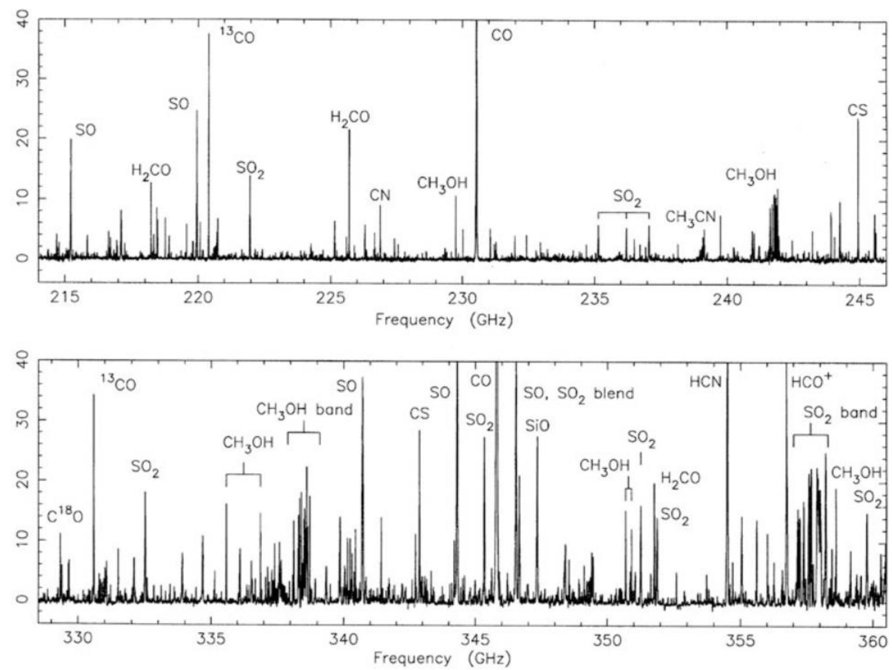

- The first large arrays, like VLA and ATCA, were in the range of roughly 500 MHz to 30 GHz.

- But what about higher frequencies, where spectral lines are particularly numerous?

- Only a few decades later were arrays developed for these frequencies. 

the wait?

(Thompson et al, 2017)




Note the higher density of lines at higher frequencies

# Higher frequencies - higher surface accuracy

Ruze’s equation

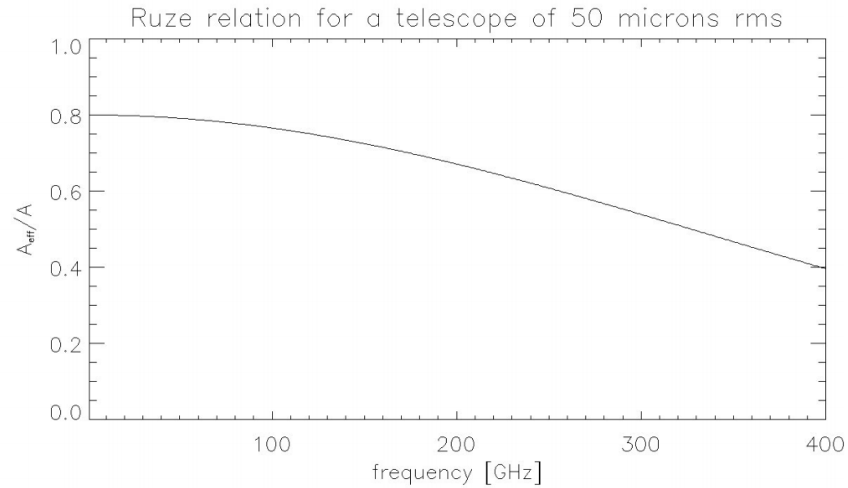
$$A = A_0 e^{-(4\pi\sigma/\lambda)^2}$$

- Technology for more accurate reflector surfaces needed to develop first. 


- Surface deviations produce deviations in the path length of a reflected ray.

- For higher frequencies this causes a <u>higher phase shift</u>.

- Therefore surface deviations are more problematic at higher frequencies.

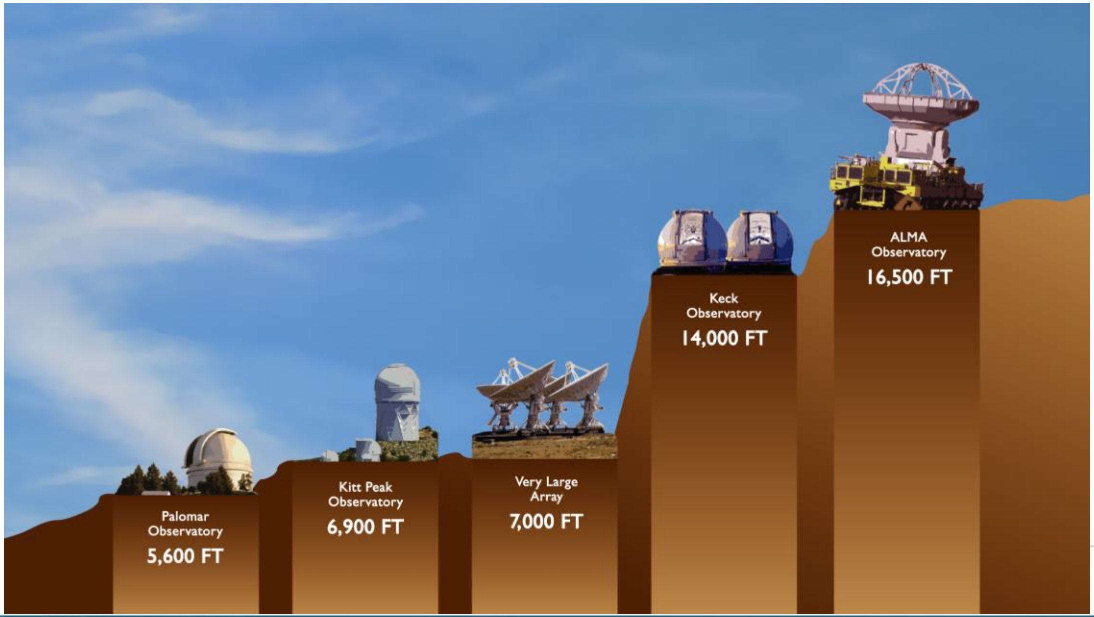



(Lecture by Bremer, 2016)

The surface of an ALMA antenna is smooth to less than the thickness of a human hair!

# Higher frequencies – higher altitude

- Because wavelengths are much shorter, any irregularity in atmospheric path length → large affect on signal phase.
- Atmospheric water vapor and clouds are more absorbent, therefore:
  - observations are more dependent on weather.
  - Tsys of low elevation observations becomes worse.
- The antennas may need de-icing at these altitudes (av. temperature at ALMA is 1 degree Celsius).




During ALMA construction, vehicle operators needed to wear portable oxygen canisters while driving. The backrests of the driver seats were shaped to allow this.

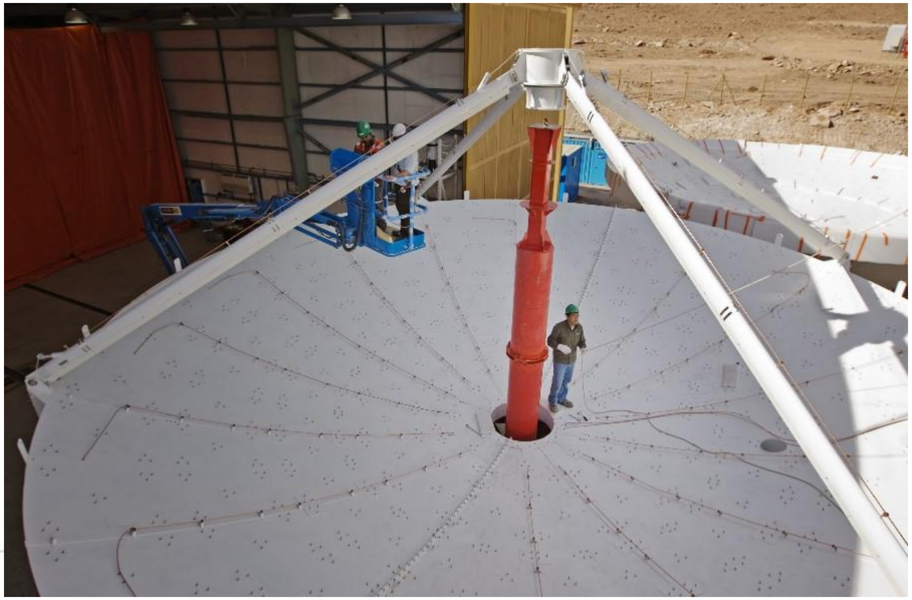
# Why smaller antennas?

- VLA antennas are 25m, ALMA are 12m. 

- Antenna beams become narrower at shorter wavelengths, therefore need smaller diameter to maintain wider field of view.
- But then to get enough sensitivity, a larger number of antennas is needed.
- So, while VLA has 27 dishes, ALMA has… **66**!

But they're still pretty big. Spot the human.

**Let's now look more at ALMA…**



# Atacama Large Millimeter/Submillimeter Array

Is that a fireball in the sky?

- Frequency range: 31 – 950 GHz.
- 54 x 12 m dishes, moved around by antenna transporters (each dish is **100 tons**)
- Configuration can be from 150m to 16km across.
- Also a compact array of smaller antennas (mostly 7m) Why?

# Stellar example of international collaboration

U.S.A

Berkely-llinois Maryland Array

Owens Valley Array

Northern Extended Millimeter Array

Europe

Nobeyama Millimeter Array

Japan

Taiwan

Chile

Canada

South Korea

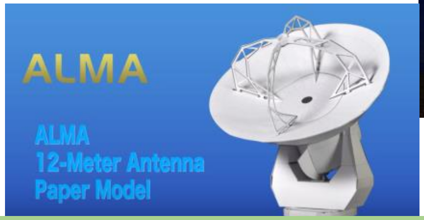
Extent of countries' involvement not shown to scale.

# And compromise

- Dish size was a compromise . 

  - 15 m proposed by Europeans
  - 6-8 m proposed by U.S.
- A debate about FoV vs sensitivity

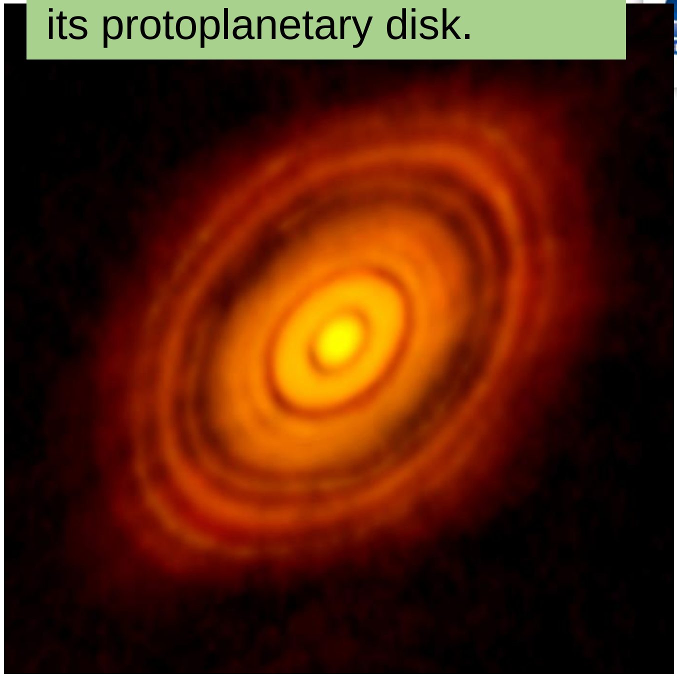
- Also, ALMA consists of different types of dishes:
  - Europe built 25 12-metre dishes.
  - U.S.A built 25 more.
  - Japan built 4 more and twelve 7-metre dishes.




And here's a  less expensive model

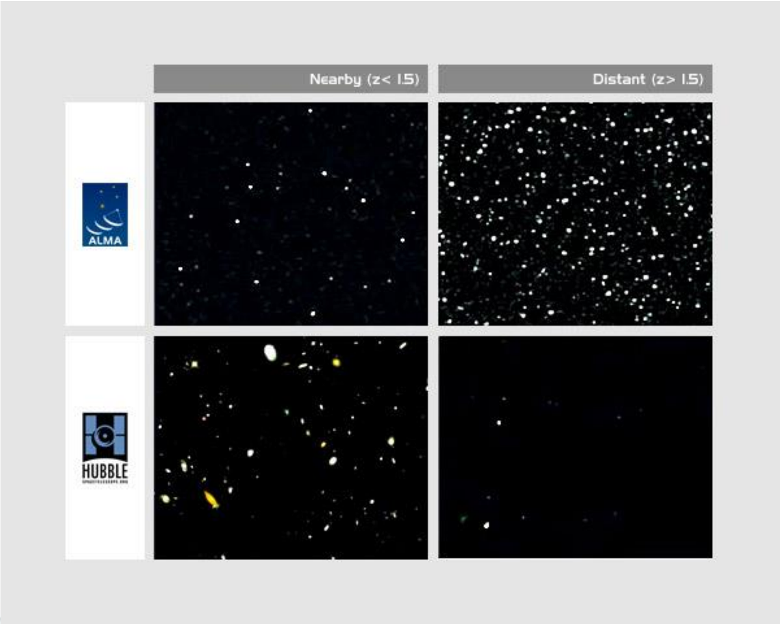
# Some ALMA Science

The young star HL Tau and its protoplanetary disk.



## Star and planet formation

Peering through the dust, can observe young, still forming stars, and newly developing planets. Can study the complex molecules (such as CO) in the gas and dust clouds that lead to star and planet creation.




## High redshift galaxies

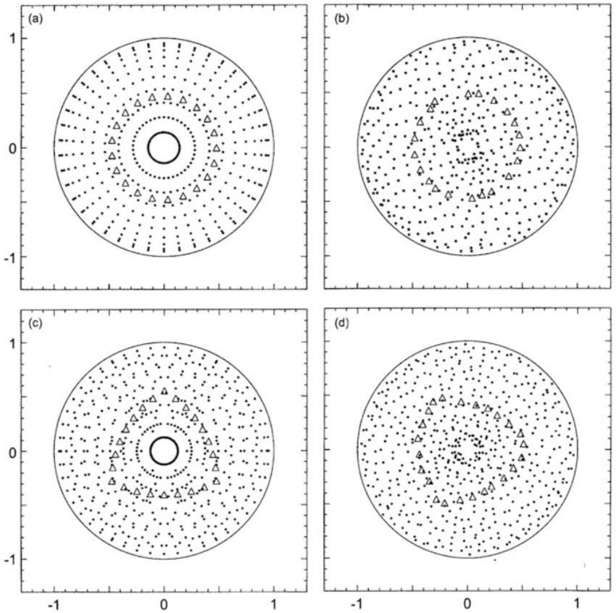
Can see the emission from the warm dust from high redshift galaxies (see simulation on left).

## Extrasolar planets

At higher frequencies, the parent star is not as bright and outshining the view of its planets.

# Back to U-V coverage – an example

- Recall the U-V coverage given by a Y configuration (VLA).
- There are other configurations that give more uniform U-V coverage, such as a circle and Reuleaux triangle. With uniformly spaced antennas, the latter is superior.
- But if higher resolutions are needed, these configurations are not easily extended.
- The Submillimeter Array (SMA) in Hawaii uses the Reuleaux configuration.



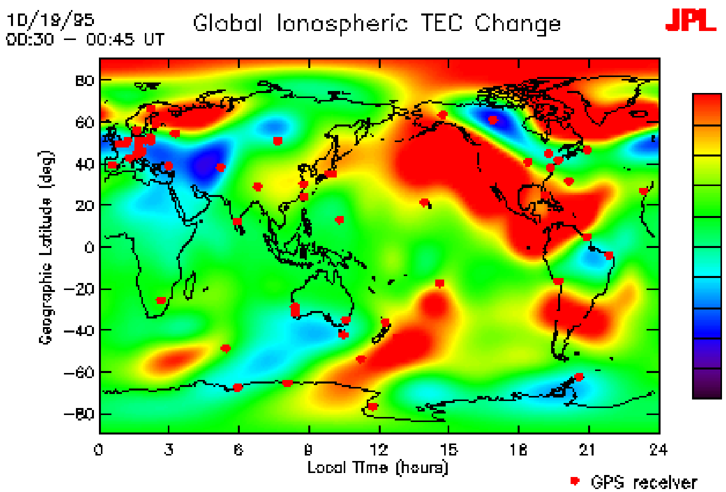

(Thompson et al, 2017)

# Let’s move down to low frequencies. Different antennas?

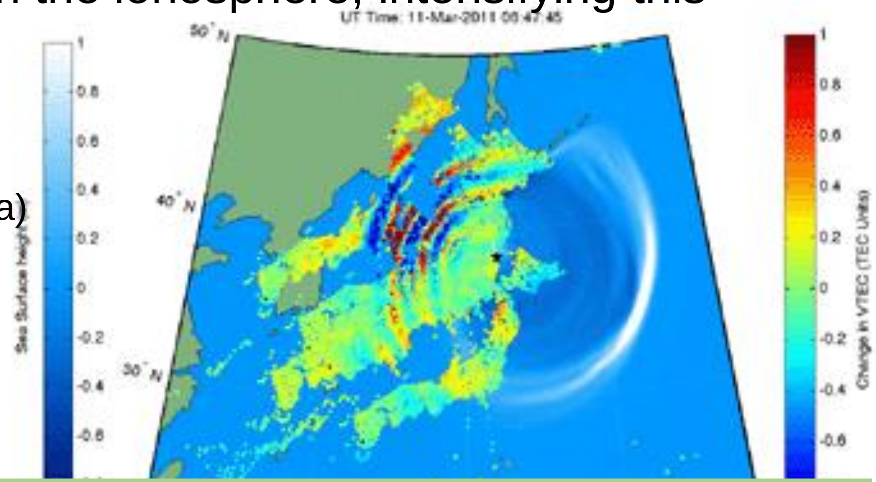
- For <u>mid and high frequencies</u>, reflecting dishes are used because wire antennas give too small a collecting area.
- But for <u>low frequencies</u> a reflecting dish is often less competitive than the same size dipole.

# The problematic ionosphere


- For the first few decades, low frequency radio astronomy was limited to measurements of a few strong sources. (Why?)
- The ionosphere (upper atmosphere) presents a major problem.
- What is it? It is a shell of electrons and charged particles, which is ionized by the sun's radiation.
- It has a high space and time variability.
- The electrons in the path of the radiation cause phase delays. Which also therefore have a high space and time variability.
- Large wavelike structures can propagate in the ionosphere, intensifying this variability.




(Nasa)




Ionospheric waves caused by earthquake and tsunami of March 2011

# Two challenges with using simple dipole antennas

Challenge 1

- To calibrate the effects of the ionosphere, one needs to create beams that are no wider than the aplanatic structure of the ionosphere.
- **How to do this with dipole antennas that have a large beam?**

Challenge 2

- **How do you steer the beam to where you want to look?** Especially if you are using a very large number of dipoles to achieve a high sensitivity.

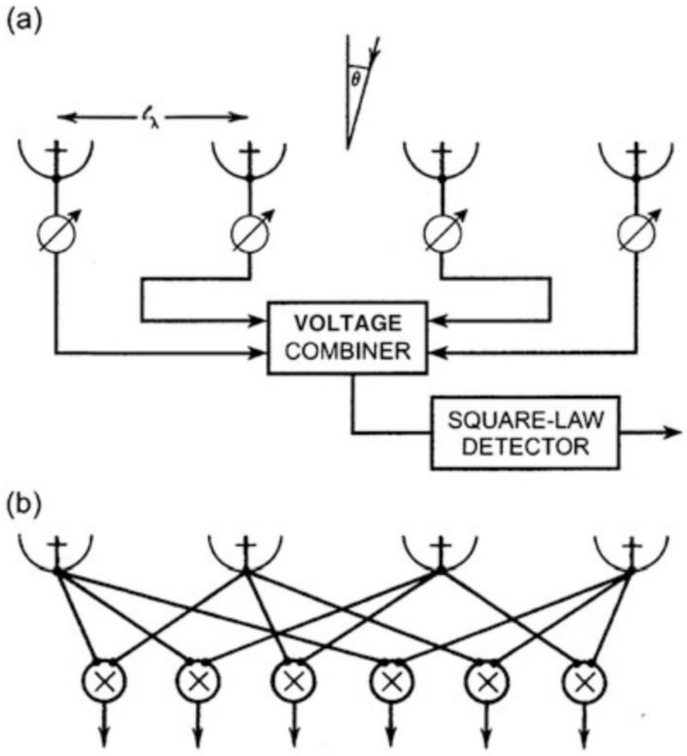

(Reeve.com)

# Beamforming!

- Combining signals from multiple antennas so that signals only at particular angles experience constructive interface.
- Complex weights can be applied to the antenna outputs:
  - **Amplitude weights**: control the sidelobe level and main beam width
  - **Phase weights**: control the angle of the main beam and nulls.
- Phase weights are applied by a phase shifter. This is the electronic equivalent to adding an adjustable length of cable to each output.
- This lets you form narrower beams with higher sensitivity, and steer them in a desired direction.
- The difference between interferometry and beamforming?

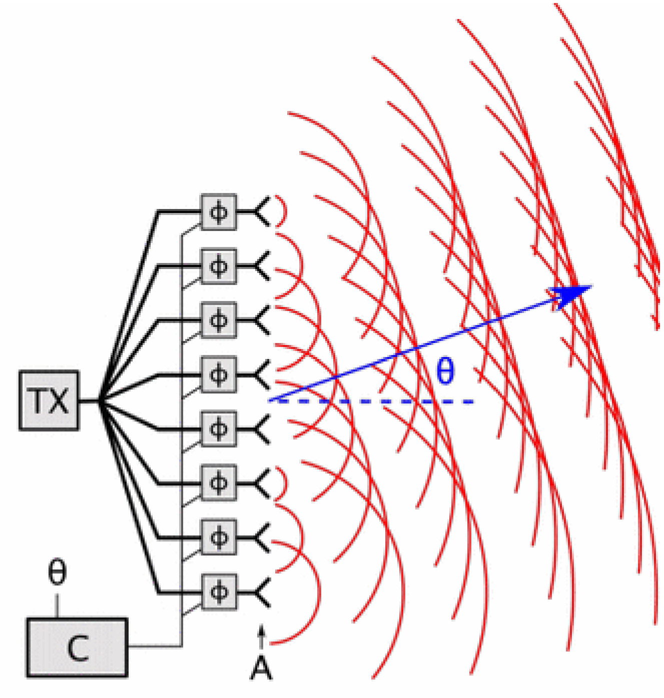
  a) **Beamformed array**: signals from all antennas are combined.

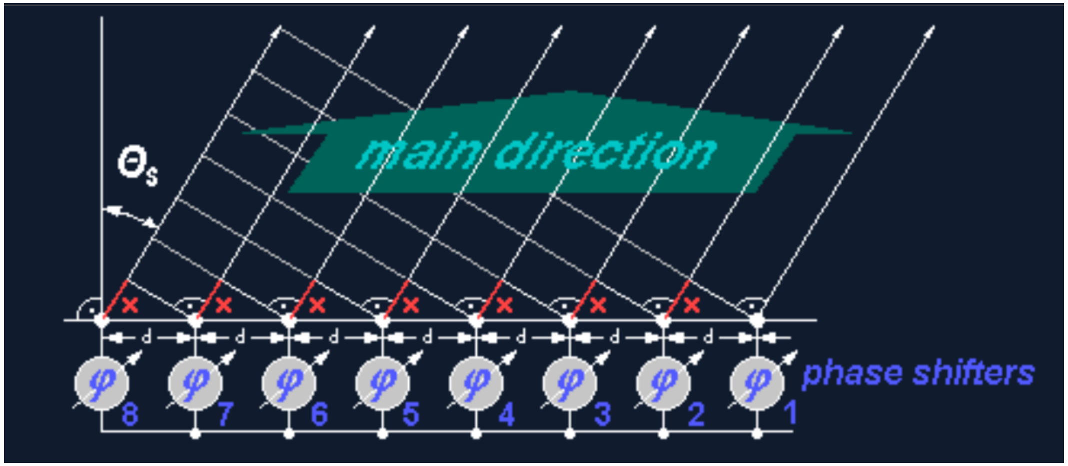
  b) **Correlator array**: signals from every pair of antennas are correlated.




(Thompson et al, 2017)

# Beamforming




radartutorial.eu

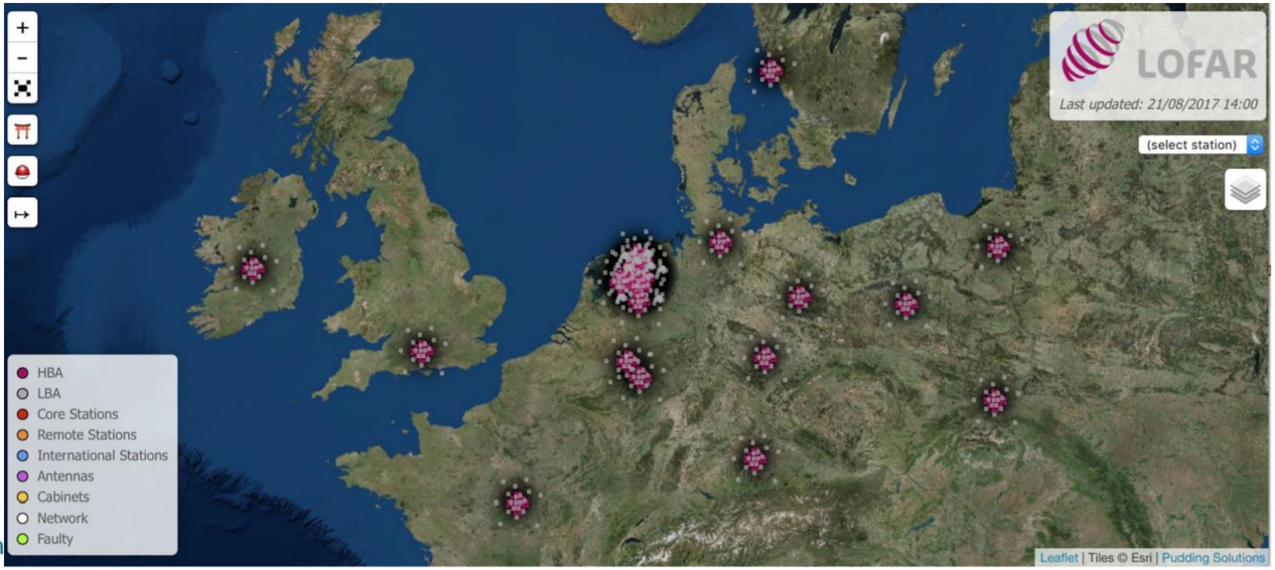
For low frequency interferometric arrays, this therefore introduces a new 'layer' in the way that signals are combined.

- **First**, signals from many antennas are combined in a single beam.
- **Second**, these beams can be correlated with each other to produce an image.

**So how many antennas are we talking?**

# LOFAR (an IT array)

- LOFAR (LOw Frequency ARray) spans several countries, including the Netherlands, France, Germany, Ireland, Poland, Sweden and UK.
- It consists of about **8000** antennas distributed among **51** stations.
- The antennas themselves can be simple. The cost is instead dominated by the electronics used to condition, combine and calibrate these signals (following Moore's law, this should become cheaper with time).



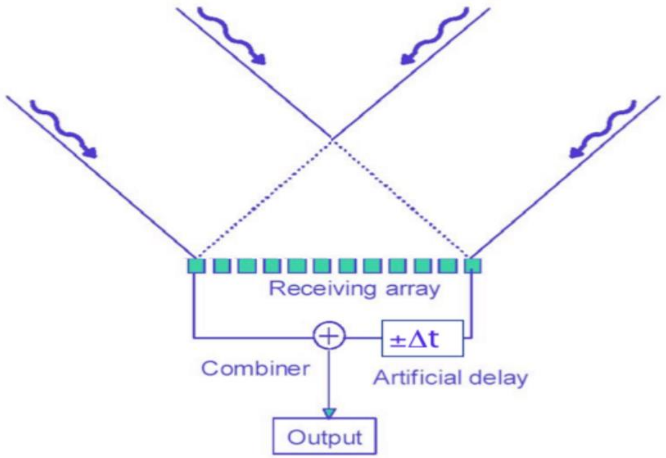
# Many eyes on the sky at once

- Unlike parabolic dishes, which look in only one direction, an array of antennas can form multiple beams on the sky simultaneously.

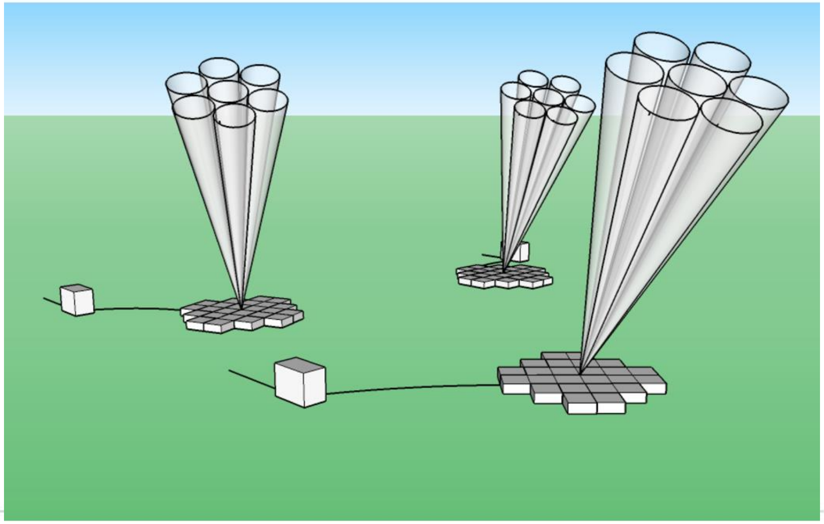
- This is possible by buffering the signal data at the individual antennas, and later recombining these with the appropriate electronic delays (which are different for each pointing direction).

- Why? is this useful?

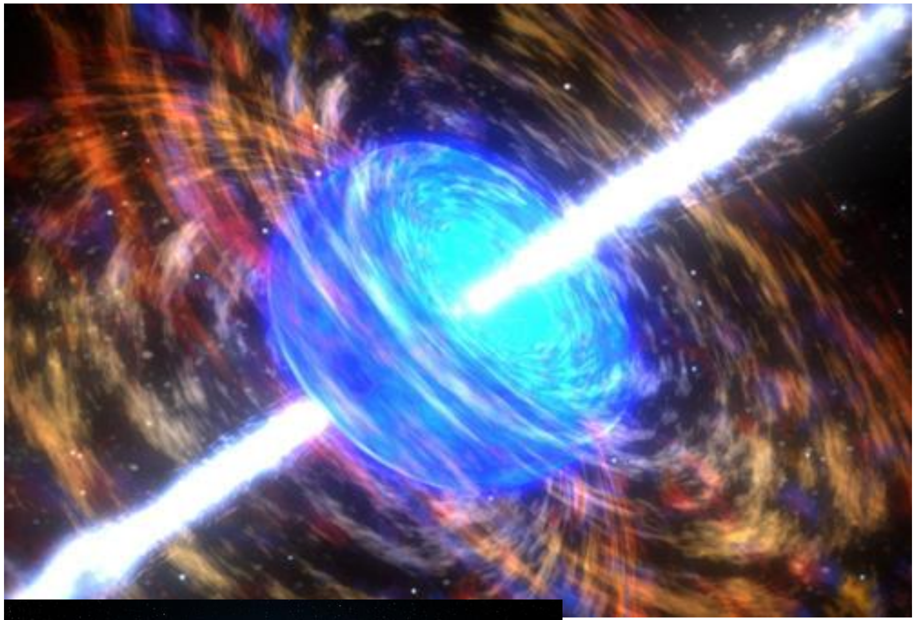
Note that if different beams are correlated, they must point in the same direction.

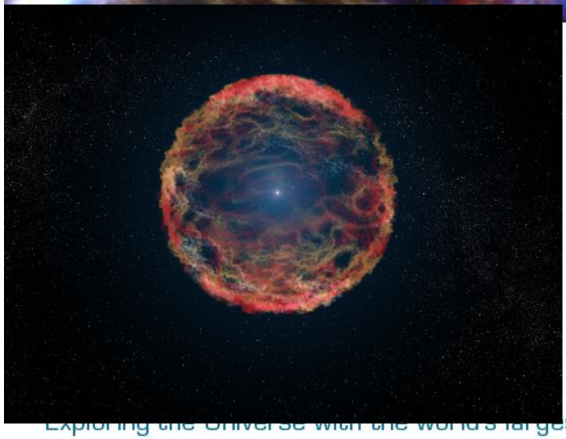


(Garrett, 2012)


(inspirehep.net)

# Why are many eyes useful?



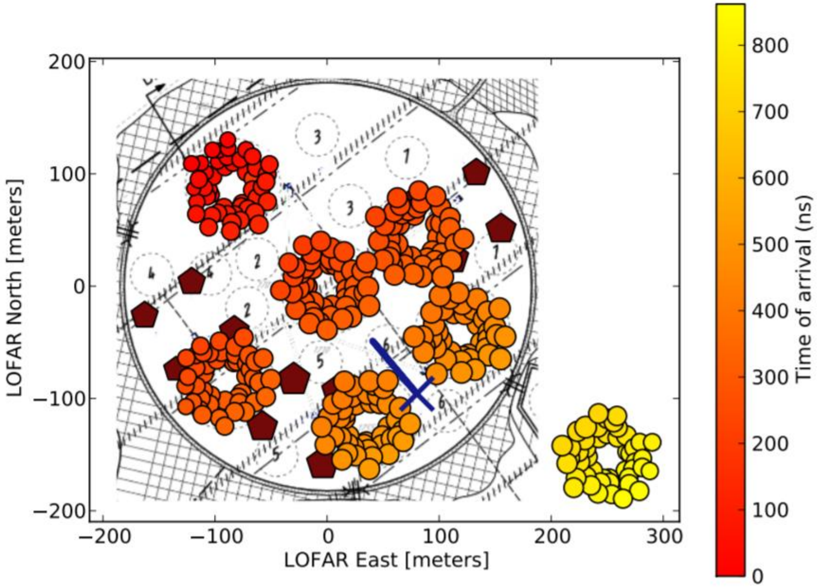



- To catch events which change very rapidly.
- Such as: gamma-ray bursts, radio supernovae, and flare stars. **Or, bursts of unknown origin.**
- Using multiple beams LOFAR continuously monitors a large area of sky. Detections can provide alerts to other telescopes for follow-up observations at other wavelengths.

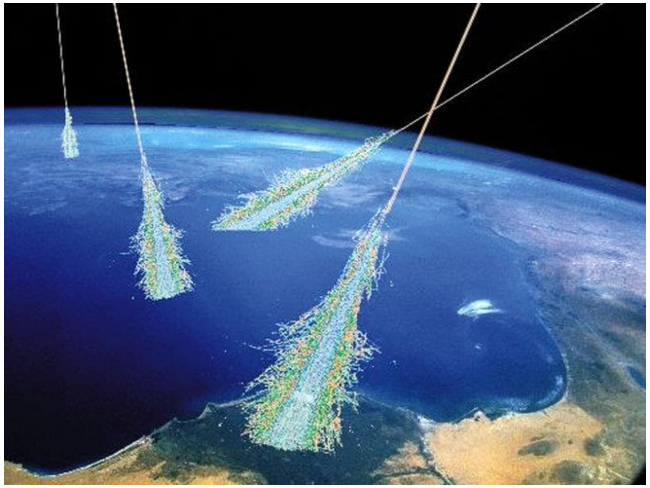
Did you know: There's a study that says Fast Radio Bursts could be extra-terrestrial radio beams used to power alien light sails?

# Detecting cosmic rays

- In addition to detecting transients using beamformed antennas, LOFAR can also detect cosmic rays using individual antennas.
- When a cosmic ray particle enters the Earth's atmosphere, it initiates a cascade of secondary particles called an air shower. These lead to bright, low-frequency radio emission.
- This can be detected by an individual antenna. And the signal at multiple antennas can be used to reconstruct directional and other properties.



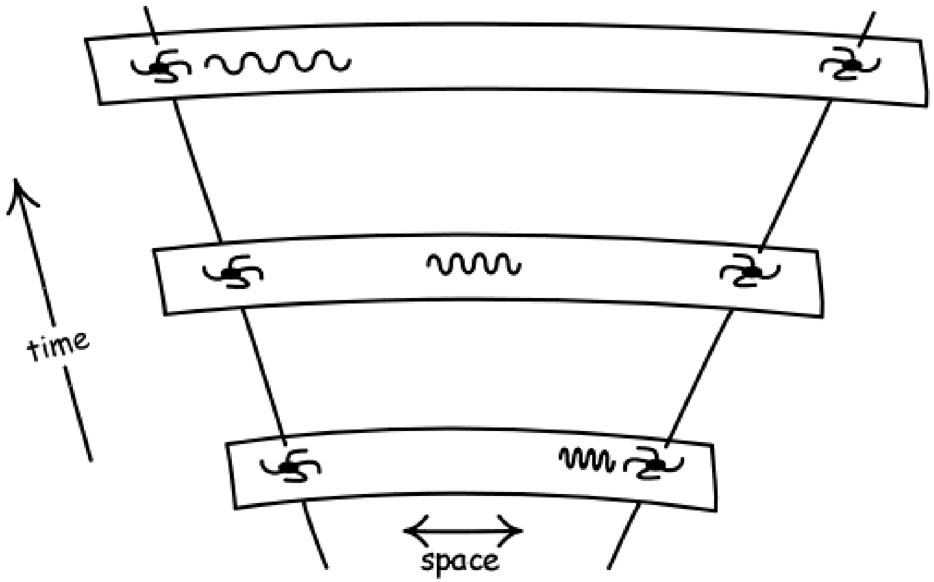

(Schellart et. al 2013)



(Space.com)

# One of LOFAR's main aims

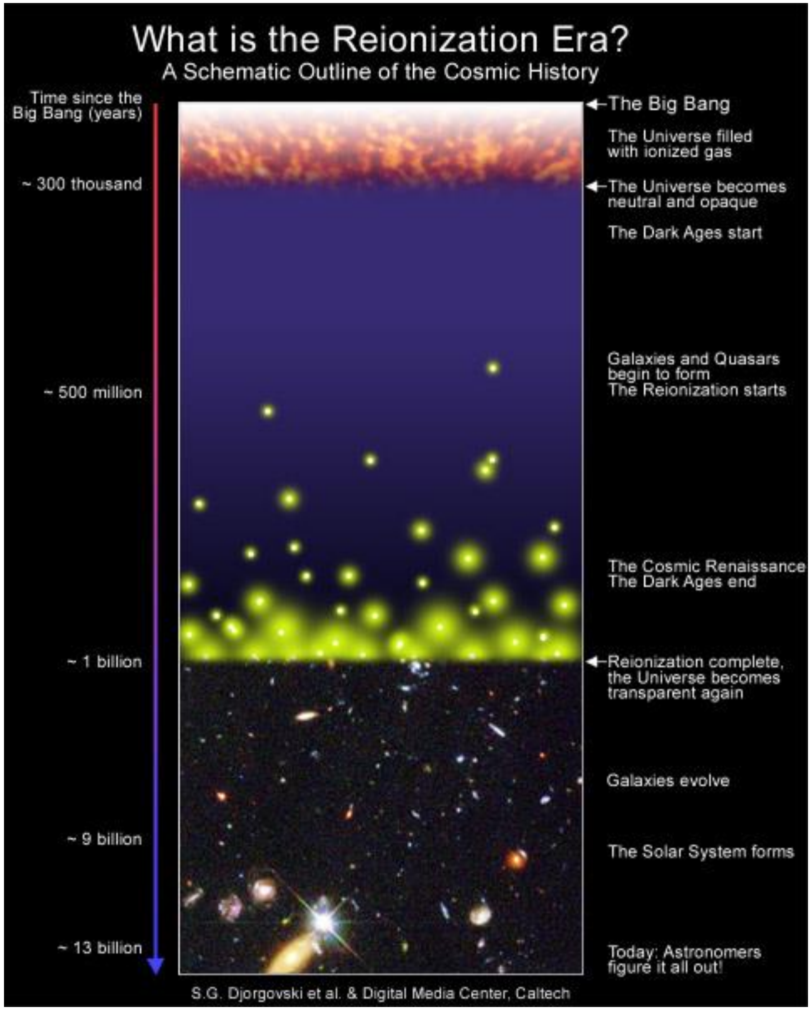
- Remember that neutral hydrogen emits at 1420 MHz?
- Waves that were emitted by hydrogen a few 100 million years after the big bang will have been 'stretched' or redshifted by the expansion of the universe.
- If we detect this emission now, it will be at much lower frequencies, and very faint (hence LOFAR)
- **But Why? do we want to know what happened a few 100 million years after the big bang?**




(J.Norton, Pittsburg university)

# Epoch of Reionisation 







- This means the period in the history of the universe when the neutral intergalactic medium was ionized by the emergence of the first luminous sources.

- By studying the emission from this period, we could answer:
  - When exactly did the first stars form?
  - What was the most important source of heating in the Universe? Was it stars, clusters, or black holes?
  - How exactly did the process unfold?

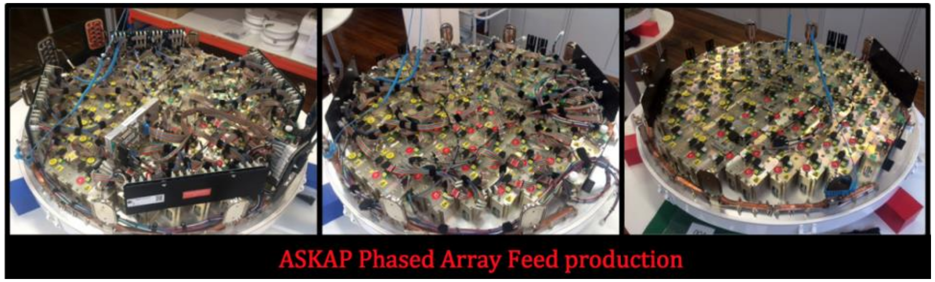
# Other challenges for LOFAR - local residents

"However, around this time a new problem began to emerge, specifically the breeding season for birds threatened to halt all activities in and around Exloo. Fortunately, excellent communications with the regional government, the local population and the relevant bird protection organisations averted this nightmare scenario, and strict safeguards were introduced to ensure the well-being of <u>nesting birds and their chicks </u>while the station rollout continued." (Garrett, 2009)


(ASTRON)

There's a moral here. For large arrays, the local environment and its residents need to be taken into account!

# PAFs (Phased Array Feeds)


- Earlier I said reflector dishes can usually observe in one direction at a time. There are exceptions to this.

- A phased array feed can be used. The feed used in ASKAP is made up of 188 individual receivers in a chequerboard-like arrangement, to create 36 simultaneous beams.

- This is like an ‘upside down’ phased array that employs beamforming in the way previously described.

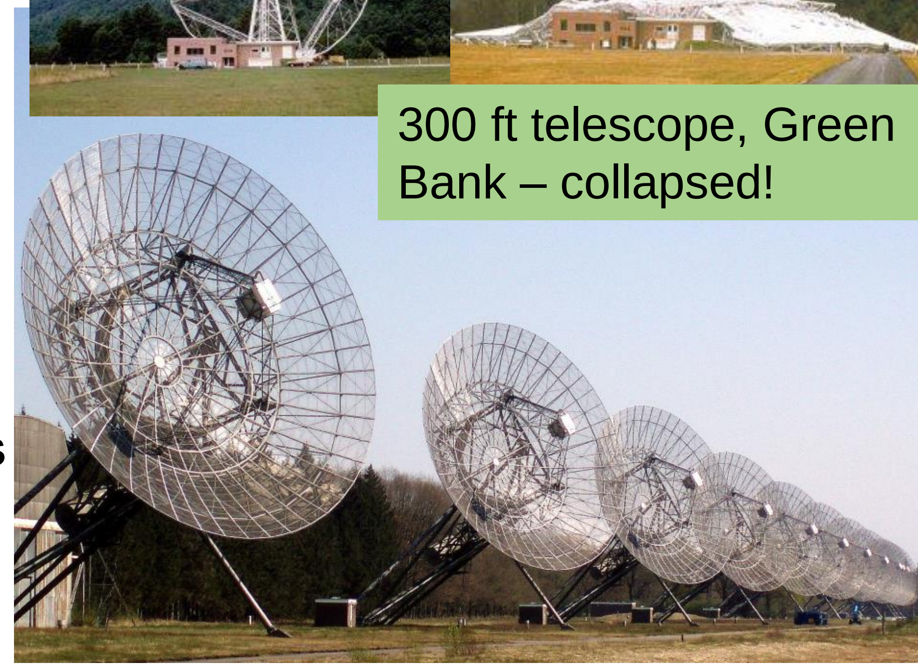
(CSIRO)

# Making large dishes out of mesh


- If reflecting dishes are used for low frequencies they need to be larger than for high frequencies.
- But for lower frequencies the dish surface doesn't have to be continuous.


- It could be made from mesh, because the longer waves won't 'see' the holes and will still be reflected.
- This explains why some low frequency arrays have used <u>large, light-weight dishes</u> made with a mesh surface.

300 ft telescope, Green Bank – collapsed!



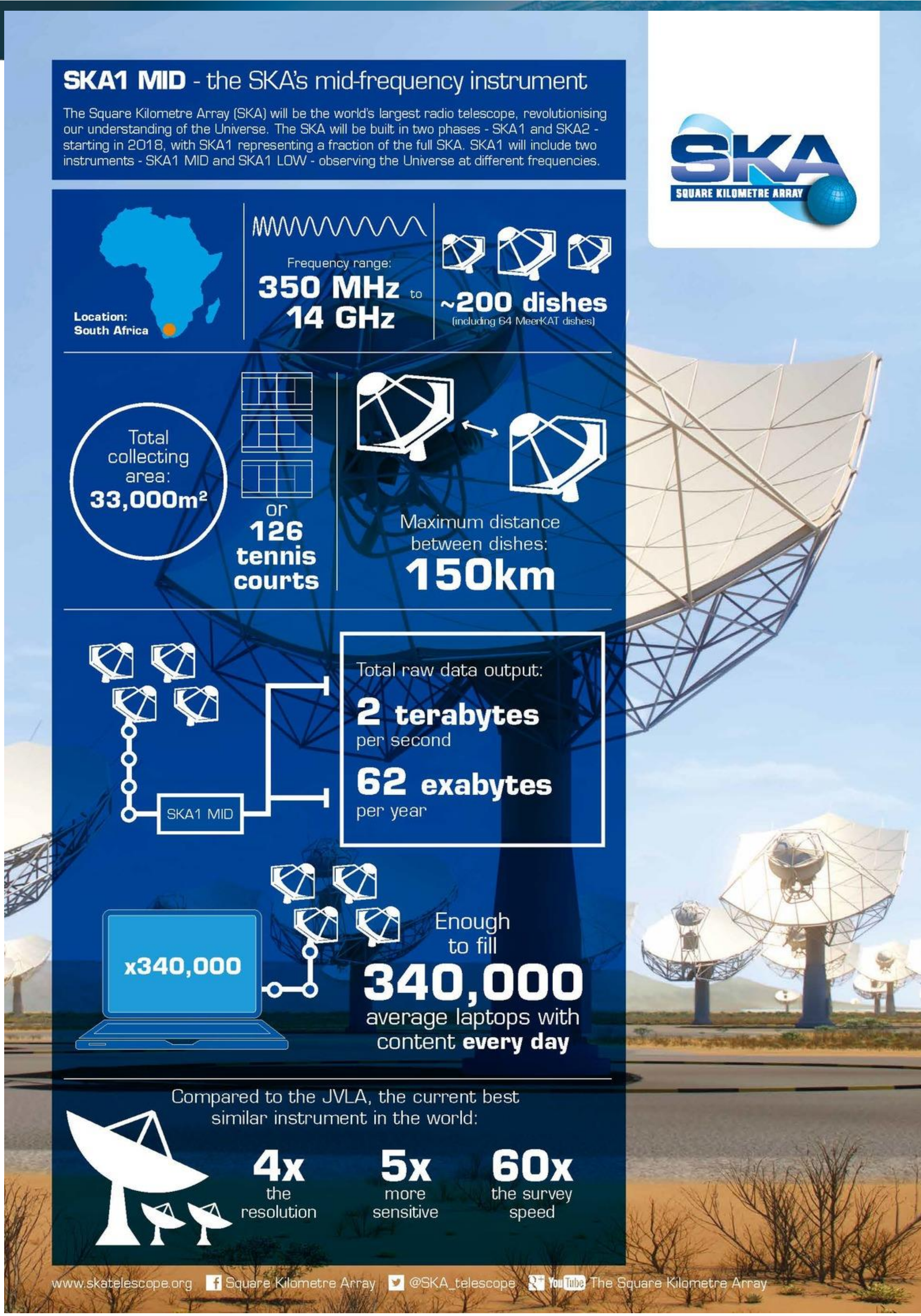
Westerbork Syntheis Radio Telescope (WSRT)

# The future is now!

It really is! Prototyping for the next generation of radio telescopes has already begun.

[redacted]

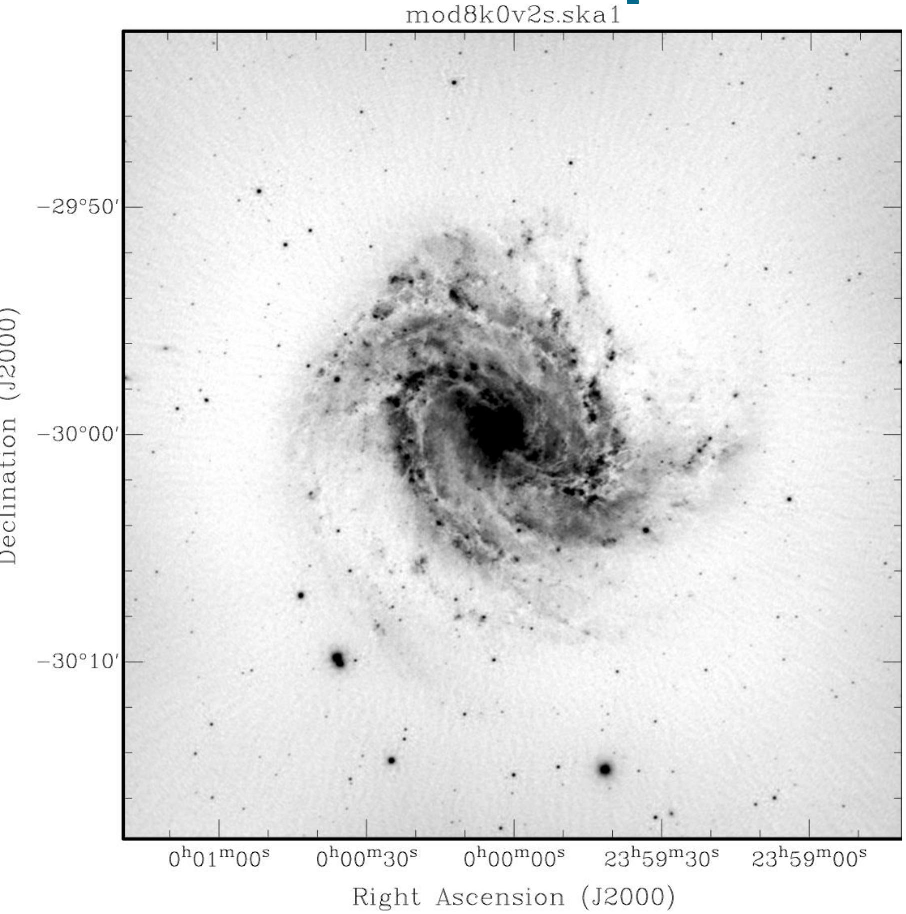
**If this is the start, where is it going?**

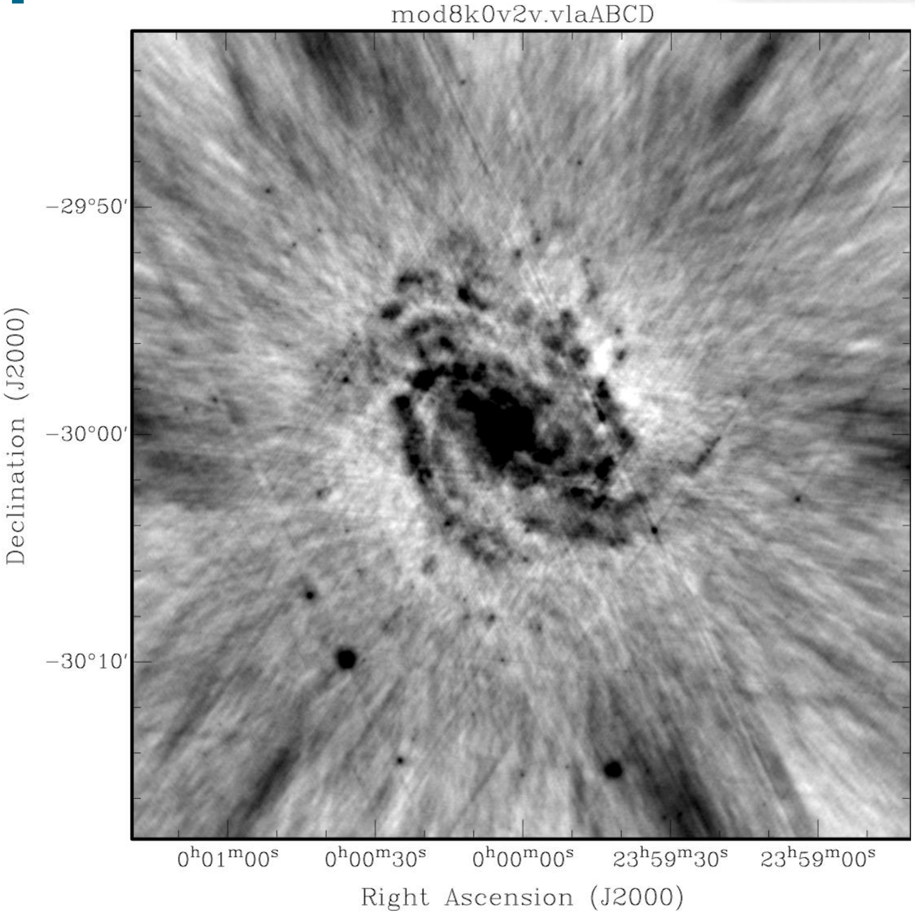



# SKA1 MID

- **~200 dishes (~15m diameter)**
- Maximum distance **150 km apart**
- 350MHz to 14 GHz

# SKA1 MID expected performance




Single SKA1-Mid dirty snap-shot compared to combination of snap-shots in each of VLA A+B+C+D

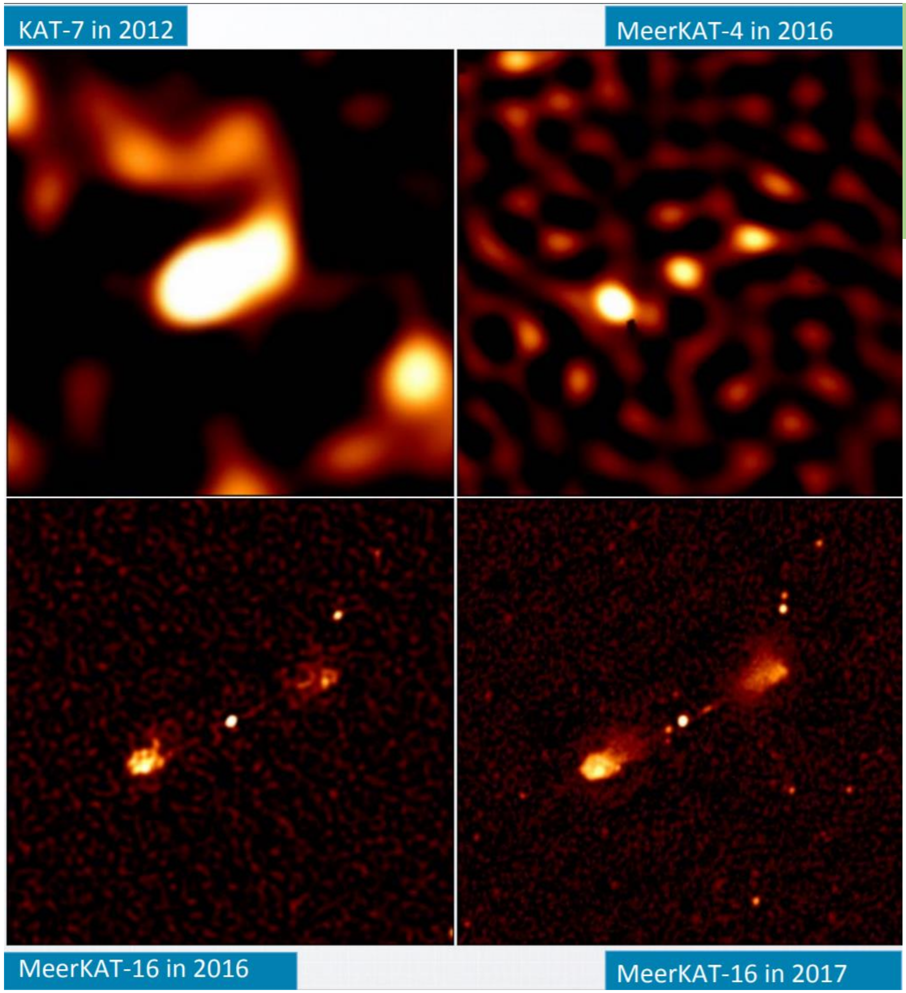
# MeerKAT: precursor to SKA1-MID

- A world-class telescope in its own right. 64 dishes, each 13.5 m in diameter, spread over 8km.
- Most sensitive radio telescope in L-band (0.9 -1.67 GHz).
- 32 dish array completed March 2017.
- 64 dish array scheduled for completion March 2018.

MeerKAT antennas contracted to local company with external support.

(SKA SA presentation, R. Adam, 2017)

# MeerKAT



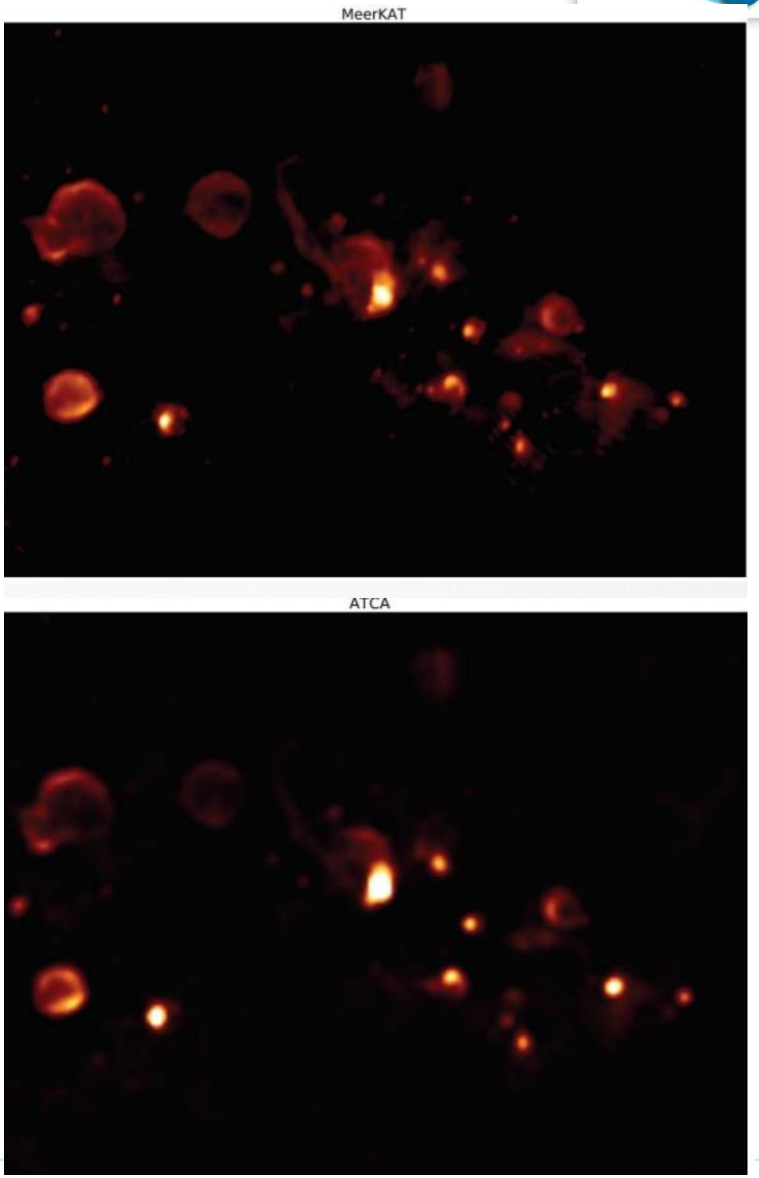

(SKA SA presentation, R. Adam, 2017)

Galaxy in distance universe observed at different stages in MeerKAT's development

Hydrogen gas (red) in M83, a galaxy discovered in Cape Town in 1752

# MeerKAT

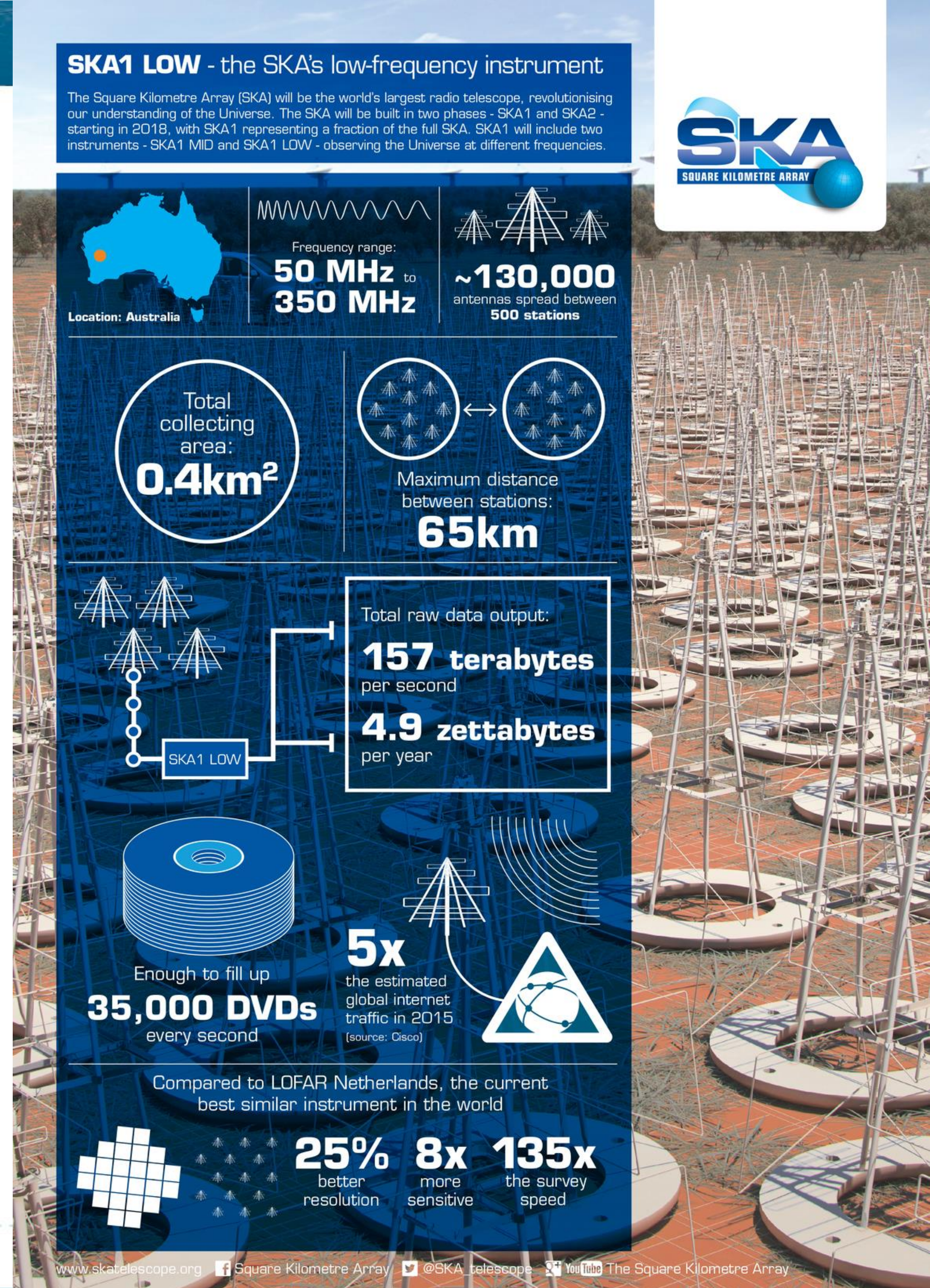
- These bubbles and arcs show stellar nurseries in the Milky Way.
- The top image was obtained with MeerKAT; the bottom image with ATCA.
- The MeerKAT image is sharper and more sensitive



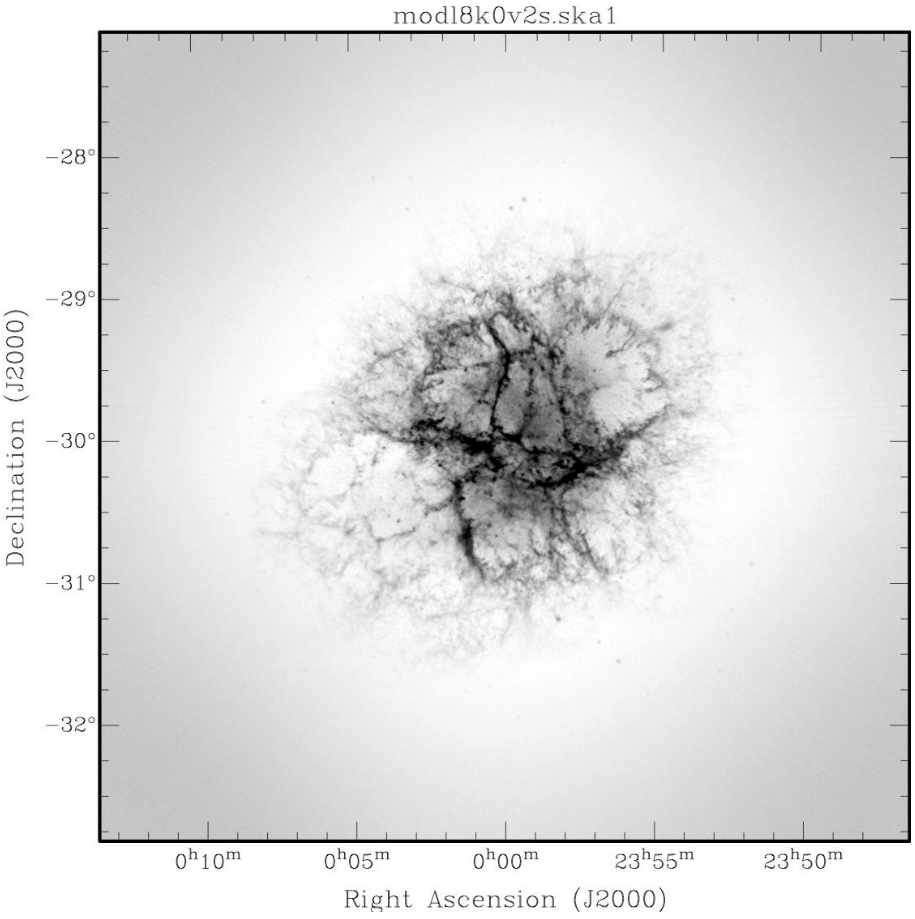

(SKA SA presentation, R. Adam, 2017)

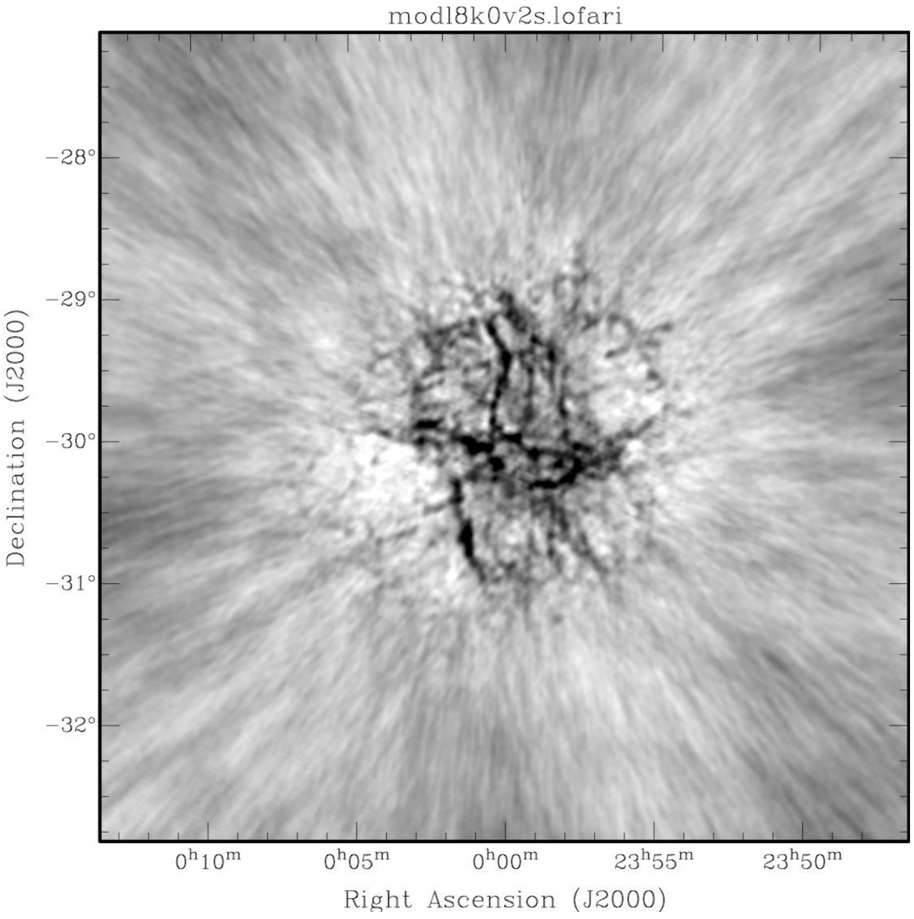
# SKA1 LOW

- **130000 antennas** spread between 500 stations
- Maximum distance **65 km apart**
- 50MHz to 350 MHz



# SKA1 LOW expected performance




Single SKA1-Low snap-shot compared to LOFAR snap-shot

# What will they look like?

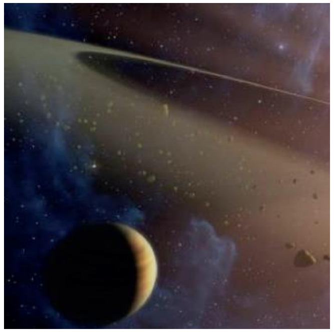
SKA1 MID

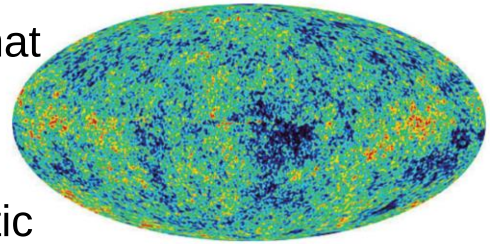
SKA1 LOW

# A massive international collaboration

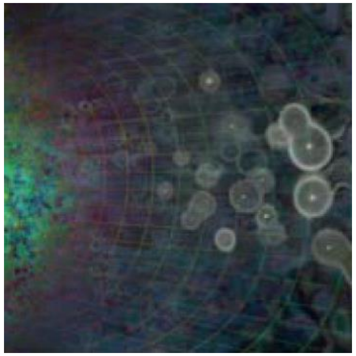
- Design phase now in final year
- Construction 2019-2025
- Cost cap 674M Euro
- 10 full member countries

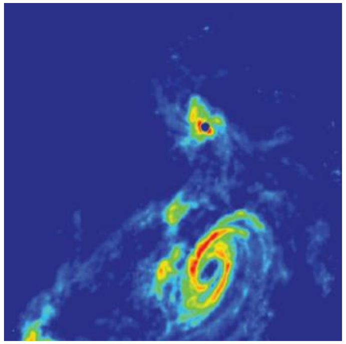
# SKA1 – what does it hope to do?

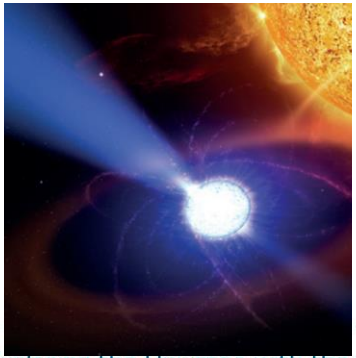




- Direct imaging of EoR structures (this is what lead to the concept of the SKA)
- Produce the first three dimensional magnetic map of the universe, to explain how and where magnetic fields arose.
- Map 10 million galaxies spanning 8 billion years of evolution – to study dark matter and dark energy.
- Understand how the small pebbles in the disk surrounding a young star stick together to form the boulders that turn into planets.
- Do gravitational wave astronomy with pulsars
- Find aliens.

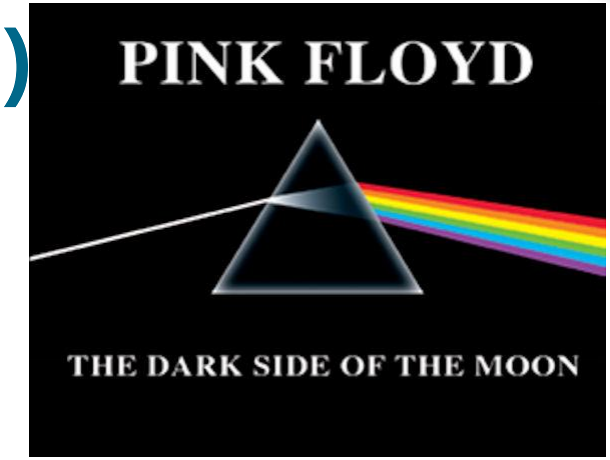






# The sky is the limit (let's allow our imaginations to run)

- Building a radio telescope on the moon? But Why?
- - large stable ground
- - shielding from earth and sun interference
- **But most importantly, no ionosphere!**




It would open up a previously unexplored radio window – below ~30 MHz.

**ARTICLE 22**
**(ITU Radio Regulations)**
**Space services**

**Section V – Radio astronomy in the shielded zone of the Moon**

**22.22 § 8 1) In the shielded zone of the Moon31 emissions causing harmful inter-ference to radio astronomy observations32 and to other users of passive services shall be prohibited in the entire frequency spectrum except in the following bands:**

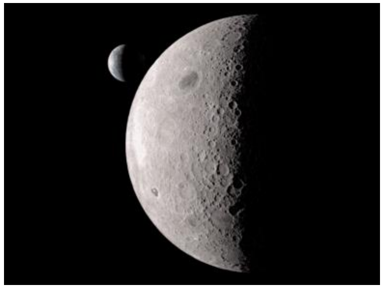
The back side of the moon is a radio protected site within the ITU Radio Regulations (an international treaty within the UN)

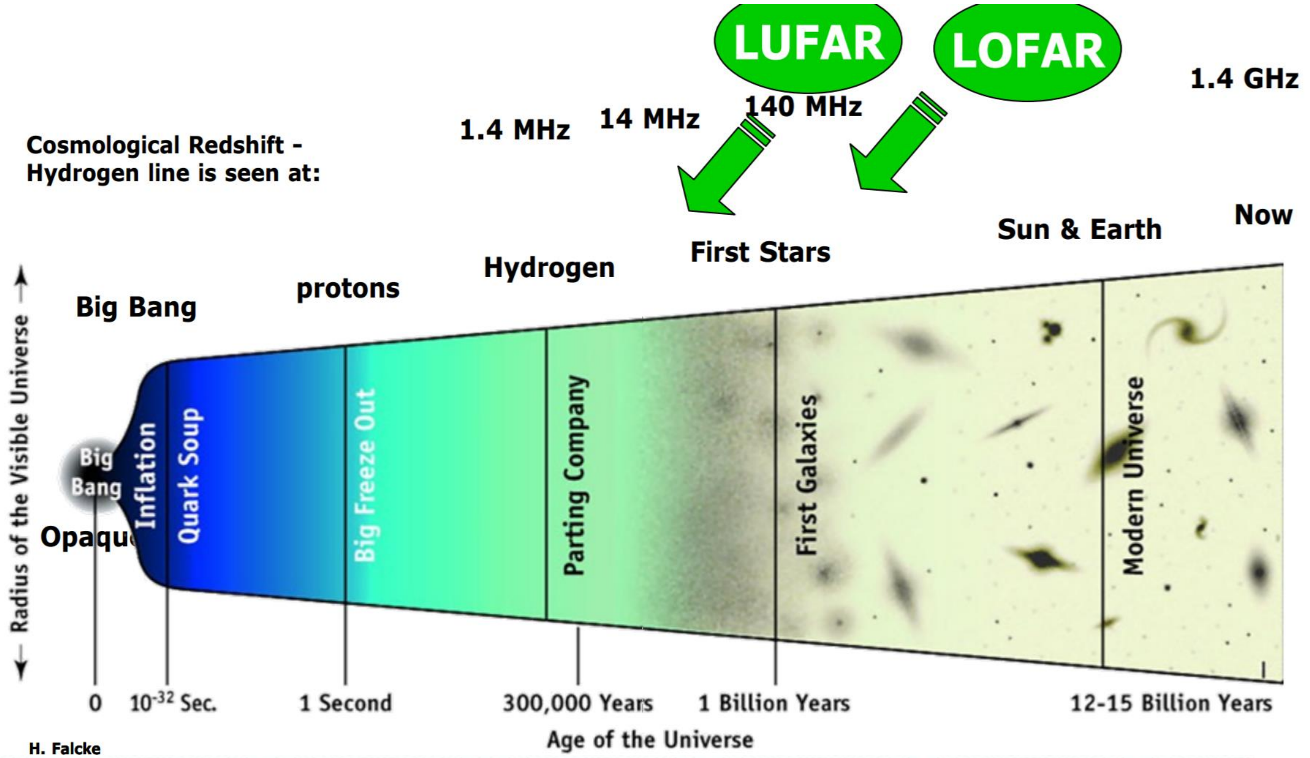
 (Presentation by Heino Falke)

# From the moon we see even further back in time

- Signals that have been redshifted to lower than 30 MHz can tell us how the Universe inflated rapidly in the first trillionth of a trillionth of a trillionth of a second after the Big Bang. Why?
- Because inflation imprints a tiny distortion on HI clouds' distribution.

This is the only certain signal from the beginning of the Universe

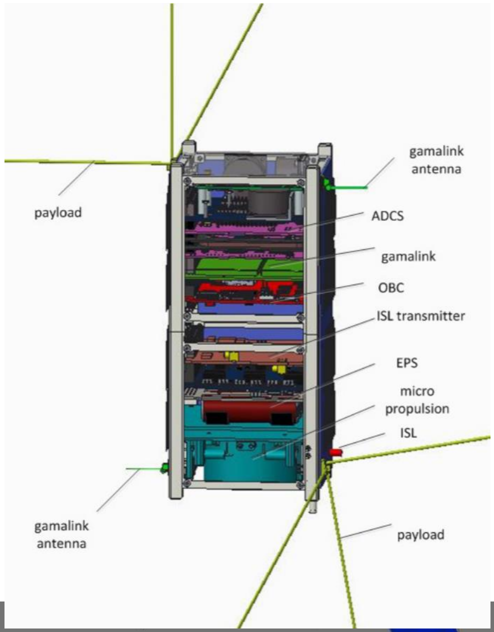




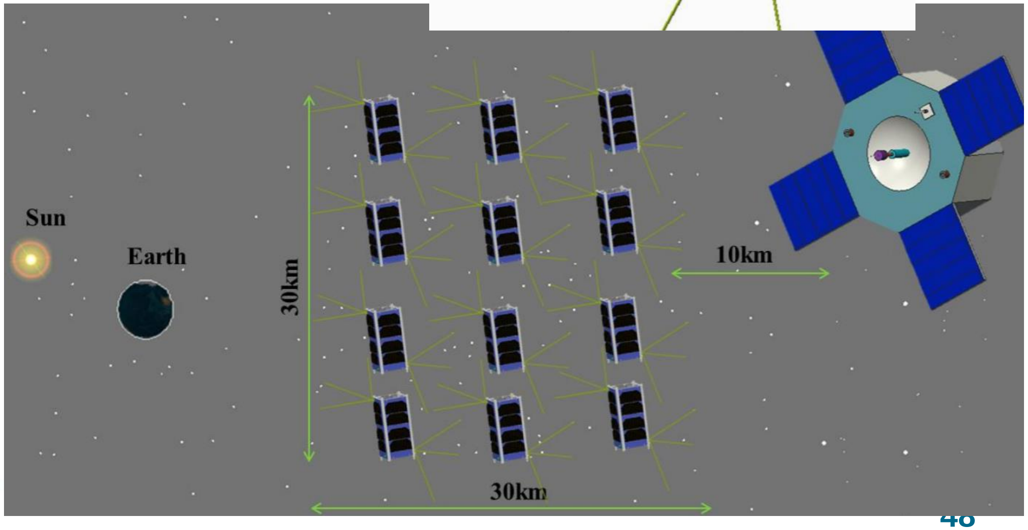

 (Presentation by Heino Falke)

# What about in space itself?

- SULFRO was a concept study to put an array in space
- Constellation consisting of a microsatellite mothership and 12 nanosatellite daughters
- Each equipped with an omnidirectional antenna system. 24/7 all sky imaging
- 1-100 MHz
- Correlation and signal processing done in mothership to reduce data volume before transmission to earth.

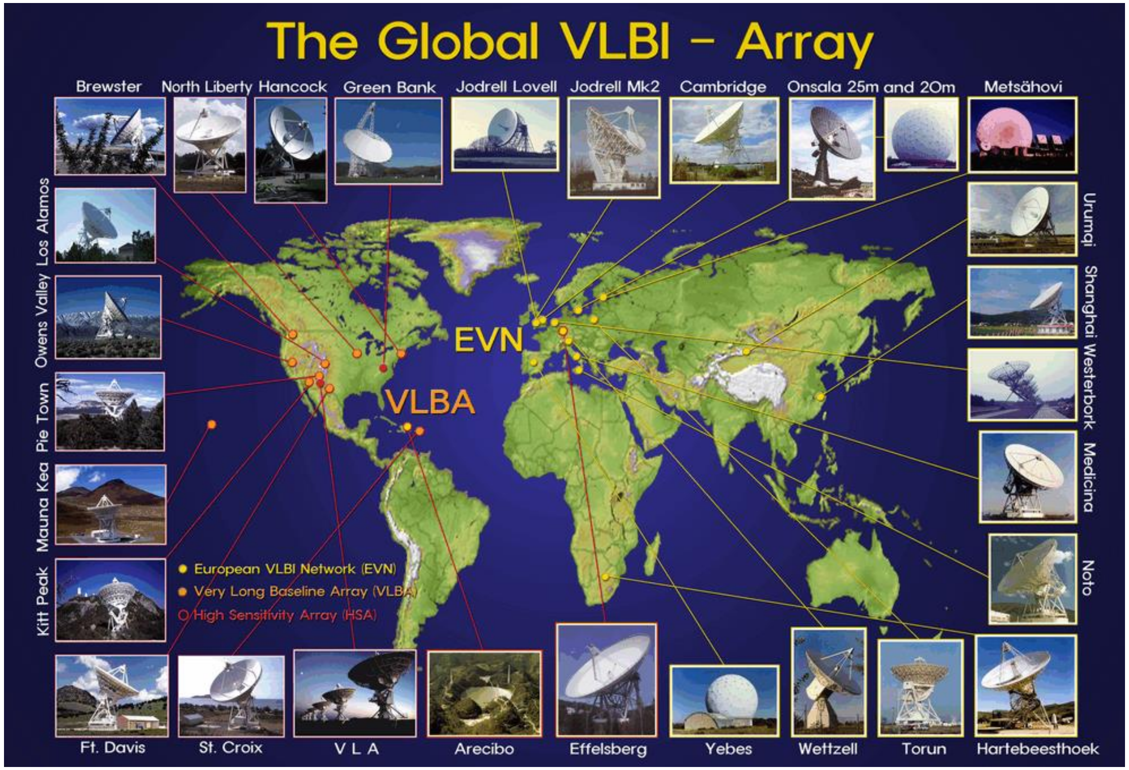



(Shufan Wu et. al)



# Doubling up – VLBI with arrays

**Remember** LOFAR antennas can be beamformed together to form a more sensitive station beam, and multiple station beams can be correlated together.




(Tae-Hyun, Jung (MPIfR, 2004)

But beamformed station beams can be beamformed again, to make **array beams.**

Array beams can then be correlated with array beams/single dish beams from telescopes elsewhere in the world.

This gives you extremely long baselines and fine resolution. More on this in the next talk.

# A final humbling thought

- Arrays have many advantages over single dishes. But there are some things that single dishes can do better Why?
- Single dishes
  - are more sensitive to large scale structure (while arrays have holes around the origin of the U-V plane).
  - Have better brightness temperature sensitivity than an array, on extended sources.
  - Need fewer receivers.
  - Large collecting area with manageable electronic complexity.

# Thank you!