

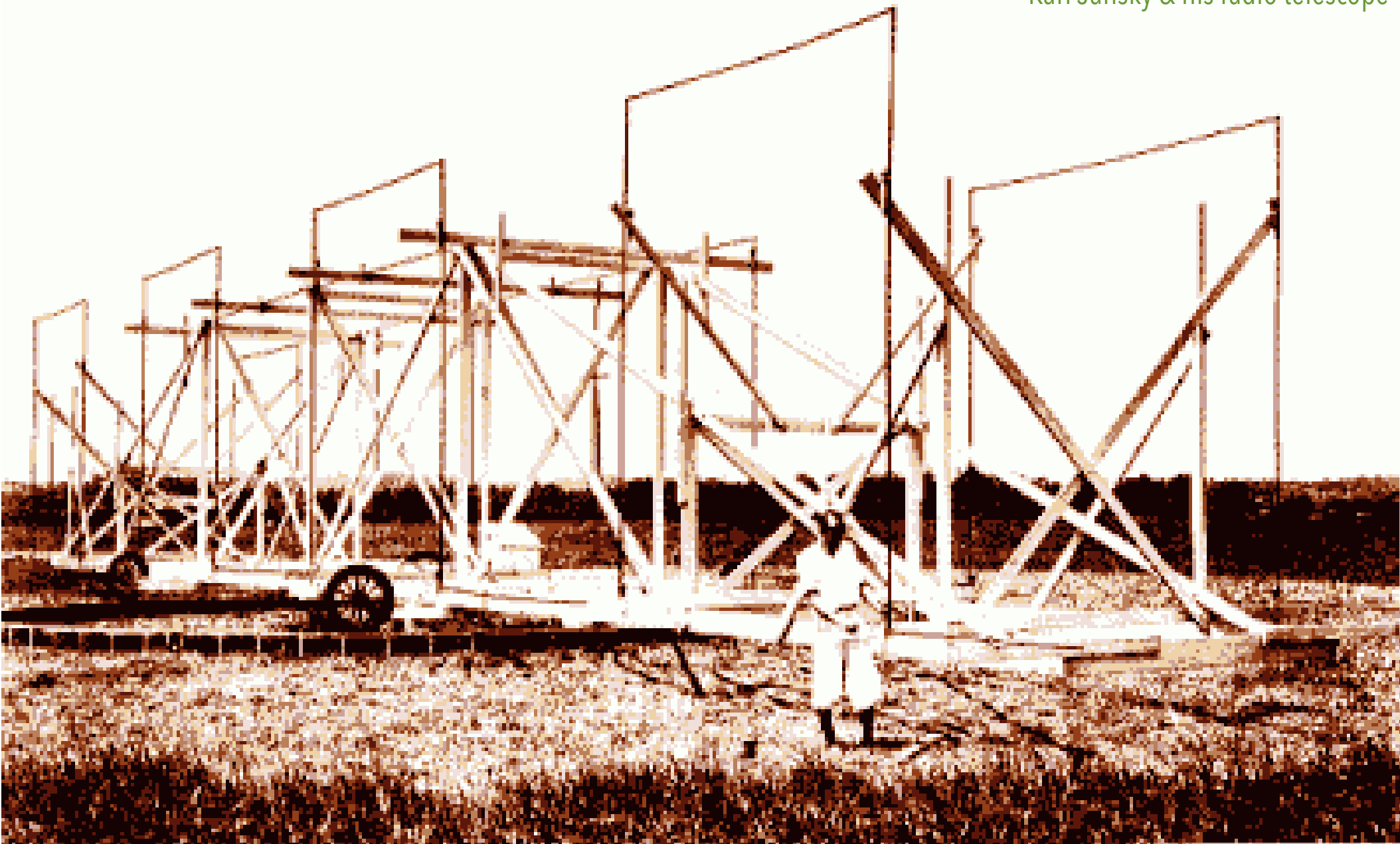
Instruments for Radioastronomy

(current & future)

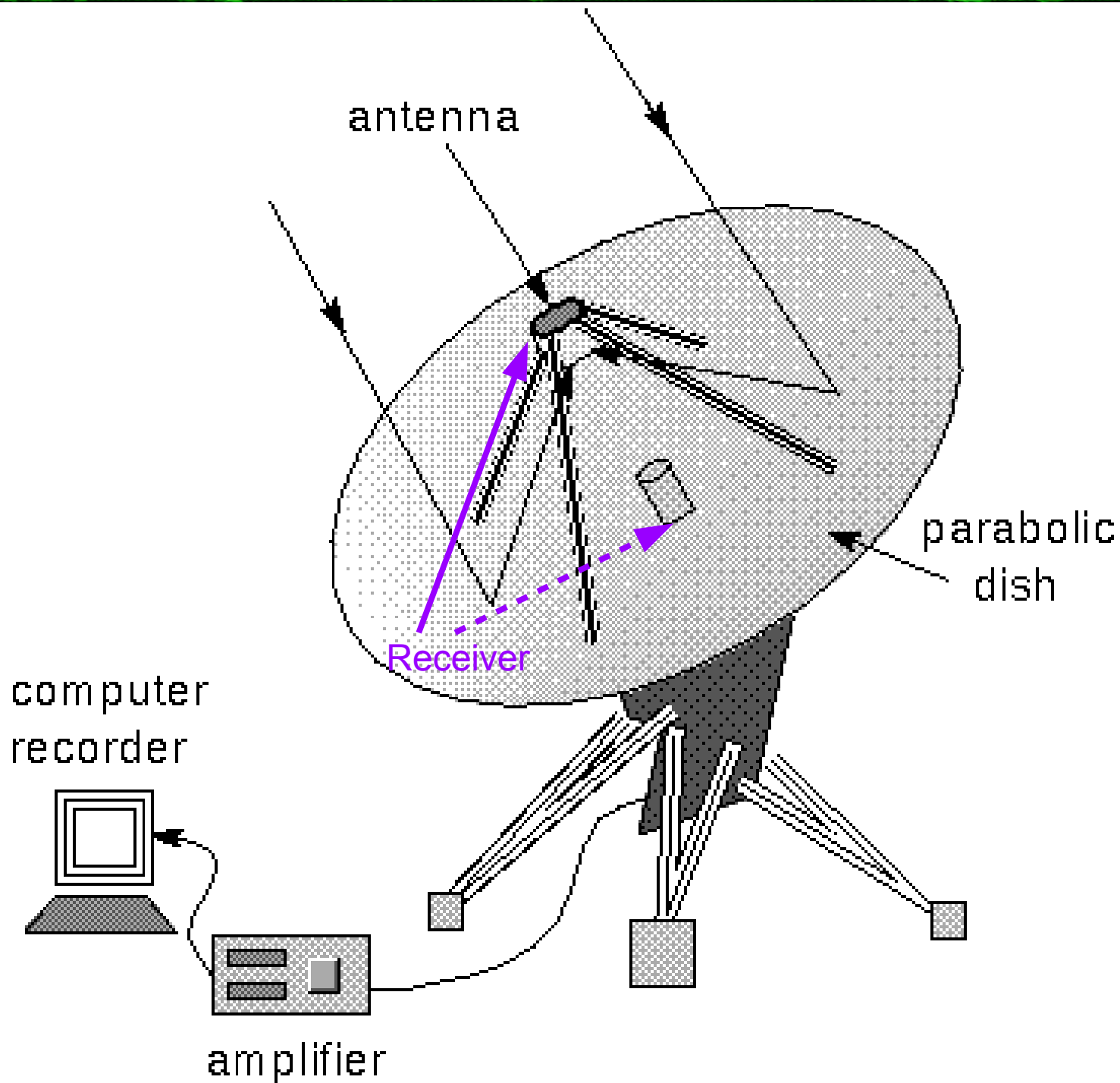
1. Summary of useful concepts
2. Single Dishes
3. Interferometers
4. The past, present and future....

Once upon a time

Karl Jansky & his radio telescope



Elements of a radio telescopes: Mirror, signal path and instrumentation



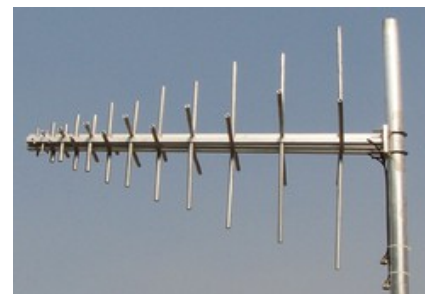
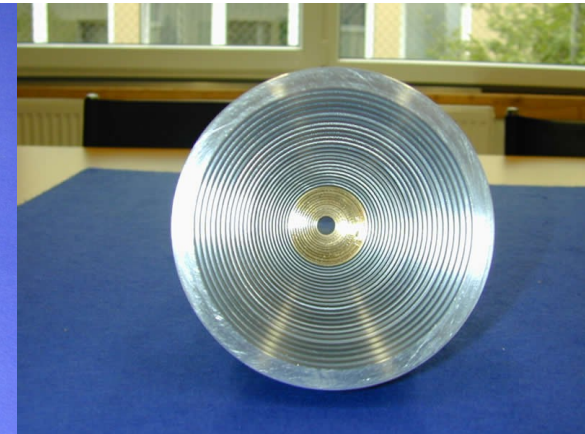
Detection of low-energy radiation:

use the wave formalism (not enough energy for photoelectric effect)

Hardware:

A (main) **mirror/collector**, a secondary mirror (subreflector) and possibly more, drive the radiation onto a given place (focus).

A **detector** must be sensible to an incoming electromagnetic wave. In particular, the easiest component to detect is the **electric field** of the wave (**feeds** are shown aside).

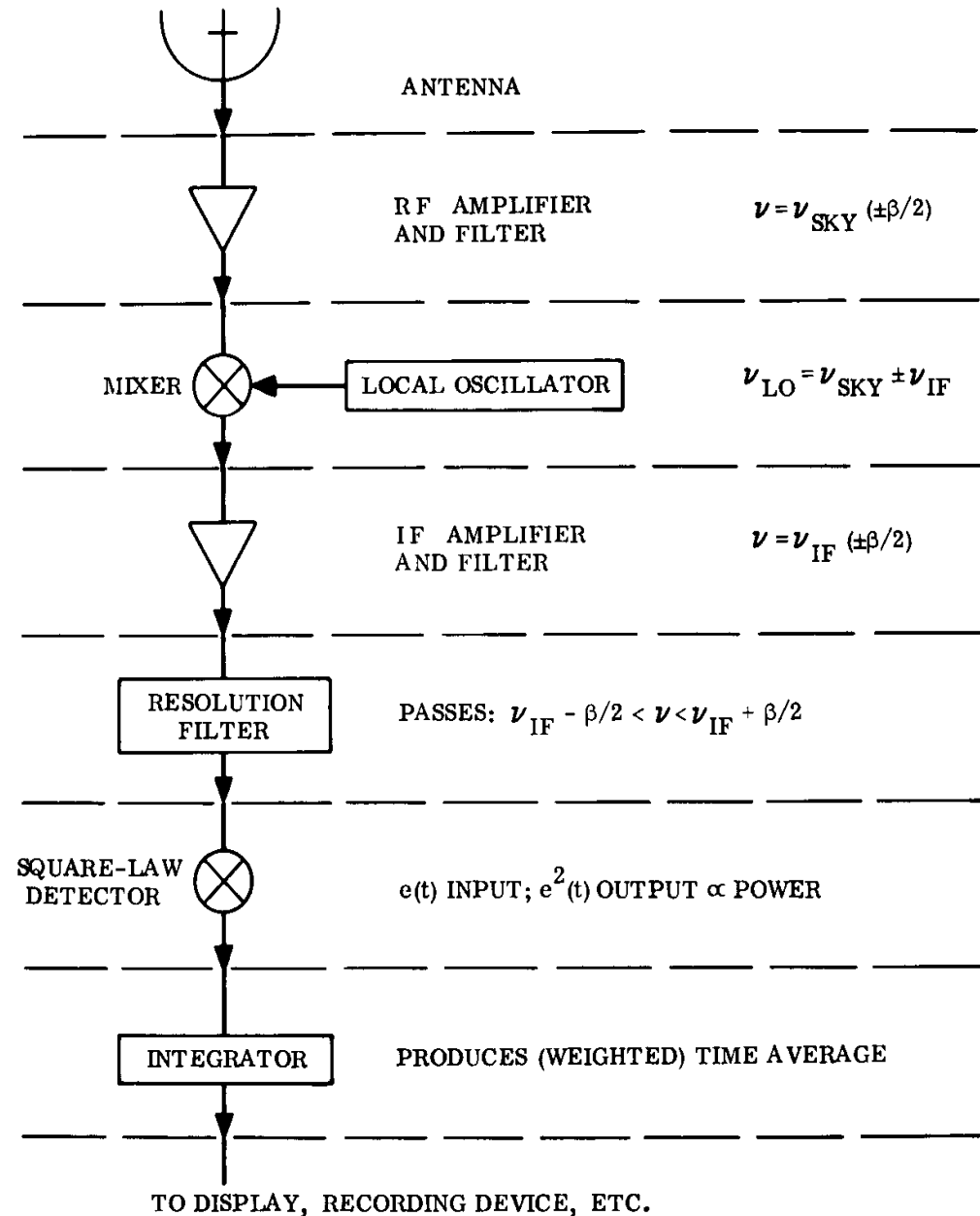


Incoming signal made of rapidly varying (oscillating)
E & B fields (10s of MHz to 10s of GHz!)

- **Sampled** faster than @ Nyquist rate
- If **broadband** (& wide field) obs, then the full bandwidth has **sub-bands** [IFs (spws) and channels]
- Dual polarization (**X + Y**, or **R + L**)

$$V(t)_R = E_R^o \sin(\omega t + \phi_R)$$

$$V(t)_L = E_L^o \sin(\omega t + \phi_L)$$



Elements of a Radio Telescope – 3 –

The incoming signal is a rapidly varying field

- Sampled & detected (**single dish**) (SQLD)
- Sampled & recorded

- Sampled & sent to a "correlator" (**interferometry**) to produce $V(u,v)$

$$V(t)_R^i = E_R^o \sin(\omega t + \phi_R)$$

$$V(t)_L^i = E_L^o \sin(\omega t + \phi_L)$$

For each i-th antenna

[Many antennas, real time \Rightarrow **see aside**]

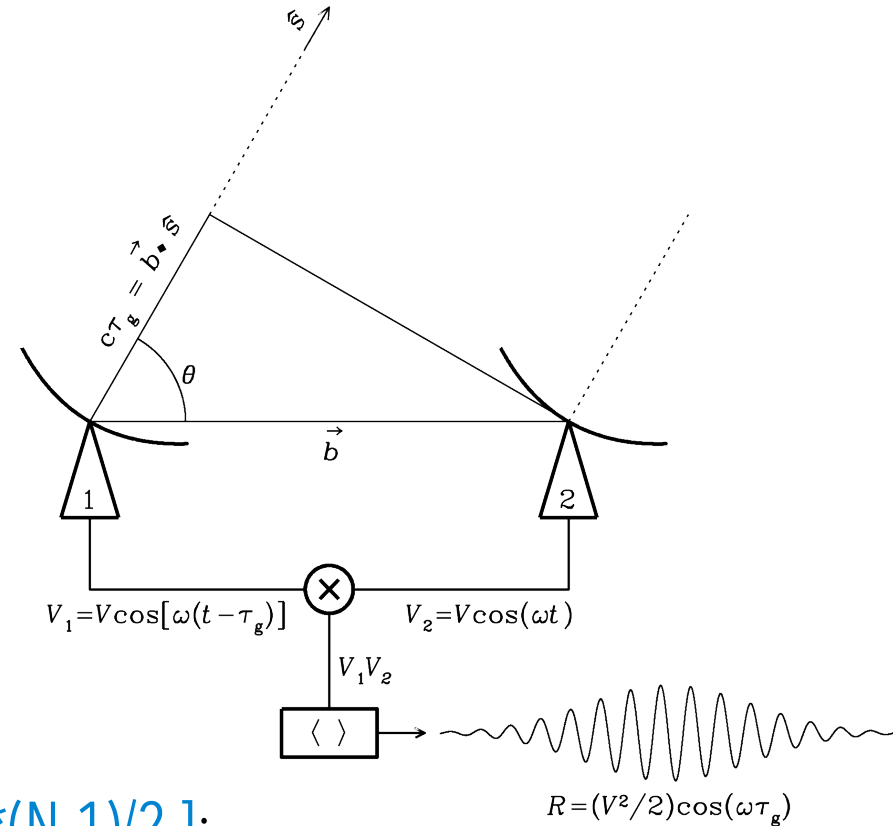
[Many antennas, off-line (VLBI)]



ALMA correlator with over 134 million CPUs. It performs up to 17 quadrillion operations per second, a speed comparable to the fastest general-purpose supercomputer in operation today.

- Atmosphere is transparent (troubles at MHz and tens of GHz) as well as ISM & IGM in general
- Low energy photons, detected as a "wave"
- Diffraction limited instruments: $\Delta\vartheta \approx \lambda/D$

⇒ Single dishes have limited resolution but can achieve excellent sensitivity ($A_e \sim D^2$)



⇒ Need for Interferometers [pairs of antennas = $N*(N-1)/2$]:
excellent resolution, but limited sensitivity, diffraction limited instruments: $\Delta\vartheta \approx \lambda/B_{MAX}$

- ⇒ Radiotelescopes measure the visibility function $V(u,v)$, which is the FT of the sky brightness distribution $B(\vartheta, \varphi)$

Relevant facts – 2 –

- *Atmosphere is transparent (troubles at MHz and tens of GHz) as well as ISM & IGM in general*
- *Low energy photons, detected as a “wave”*
- *Diffraction limited instruments: $\Delta\vartheta \approx \lambda/D$*

Single dishes have limited resolution but can achieve excellent sensitivity ($A_e \sim D^2$)

Need for interferometers: excellent resolution, but limited sensitivity: diffraction limited instruments:

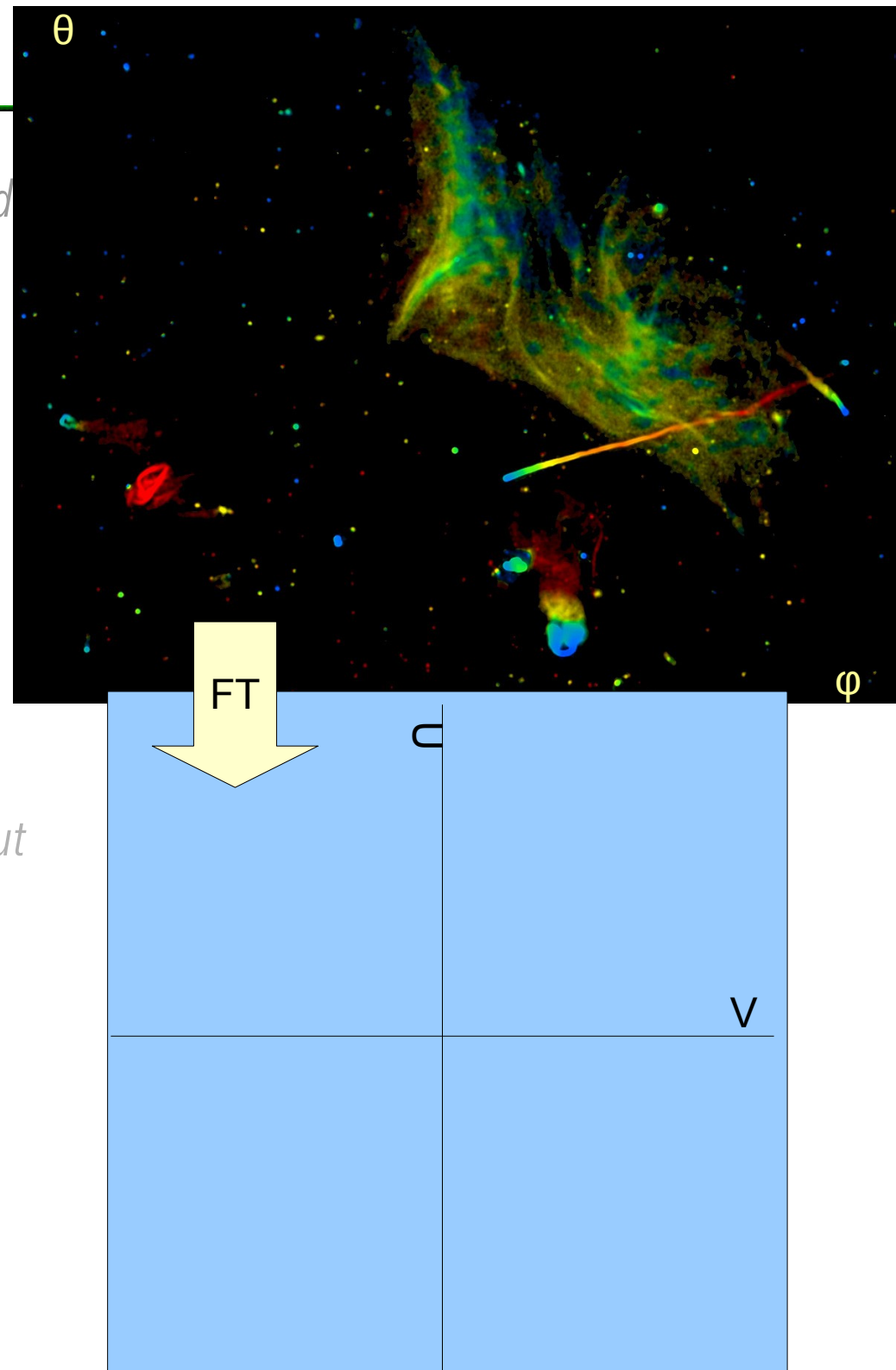
$$\Delta\vartheta \approx \lambda/B_{\text{MAX}}$$

- **Radiotelescopes measure** the **visibility function**

$$\mathbf{V}(\mathbf{u}, \mathbf{v}) \in \mathbb{C}$$

which is the **FT** of the **sky brightness distribution**

$$\mathbf{B}(\vartheta, \varphi) \in \mathbb{R}$$



The uv-plane



It determines

- **the PSF profile**
(which is the FT of the sampling in this plane)
- **where the Visibility function is sampled**

The best would be a continuous sampling
A uniform/regular sampling is good!

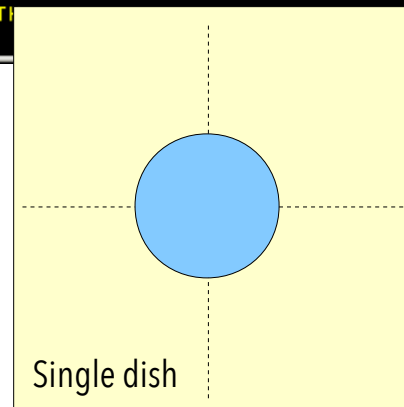
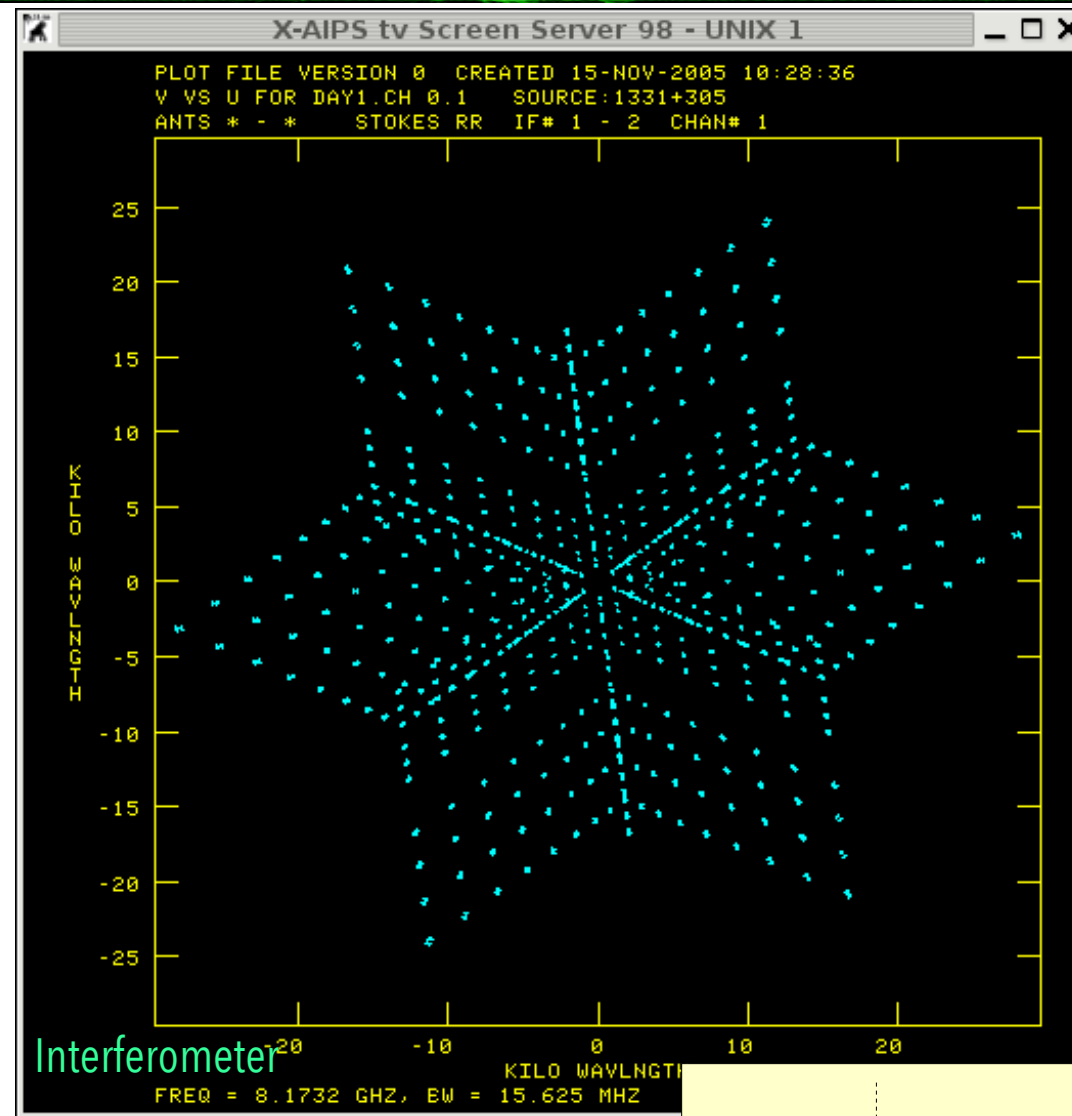
How to improve it?

- increase – number of antennas
 - integration time
 - band-width

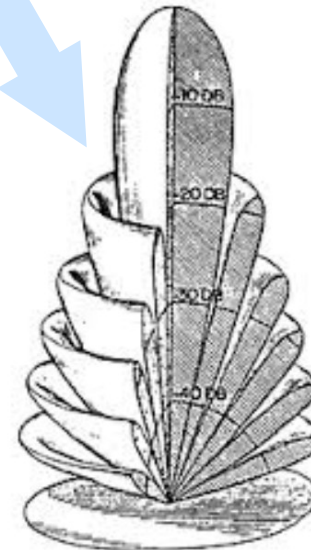
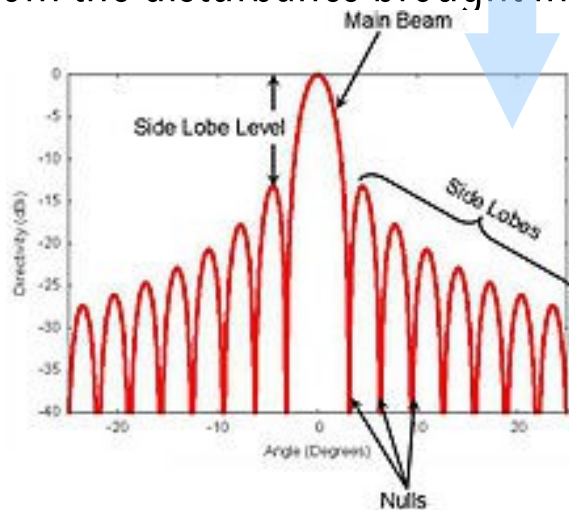
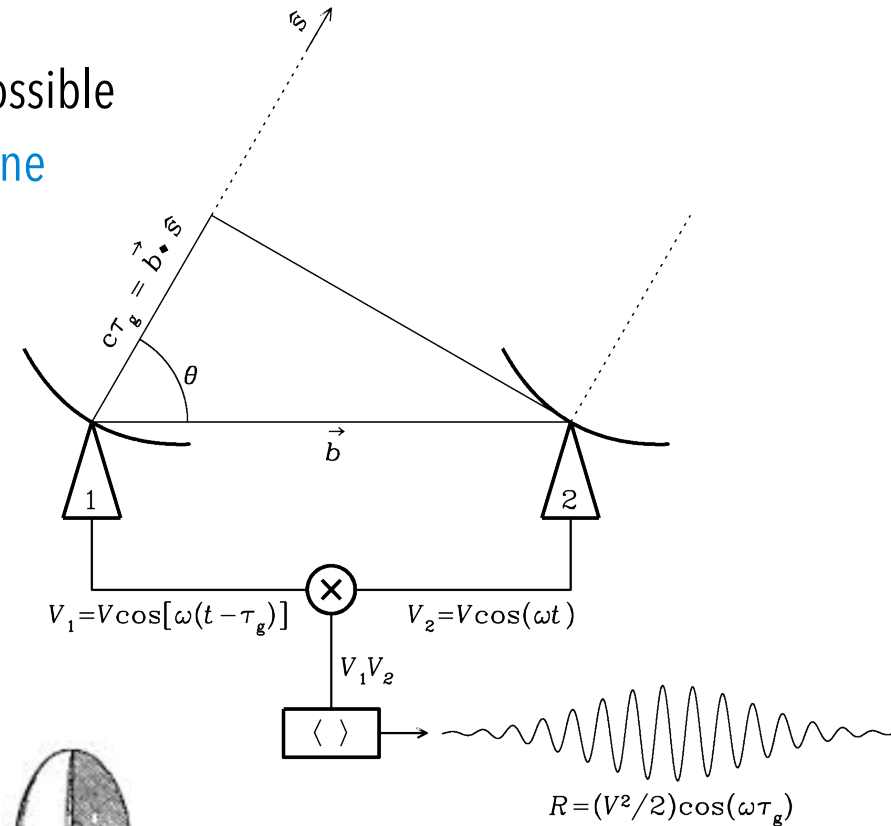
The “sampling problem”

The “invisible distributions” to interferometers

After the FT^{-1} of $V(u,v)$, deconvolution is required.



- A simple interferometer brings in a limited amount of information and does not sample the **total power**
- Ideal interferometers are made up of as many elements as possible and provide excellent (simultaneous) sampling of the **u-v plane**
- The interferometer samples **$V(u,v)$** in the spatial frequency space over a range of baselines
- The u-v sampling determines the **PSF = beam = $P_n(\vartheta, \varphi)$**
- To get the **sky brightness $B(\vartheta, \varphi)$** from an observation is a quite complicated job requiring the deconvolution of the observable from the disturbance brought in by the instrument



Single dishes show

F is small ! Most detectors at secondary focus



Fast



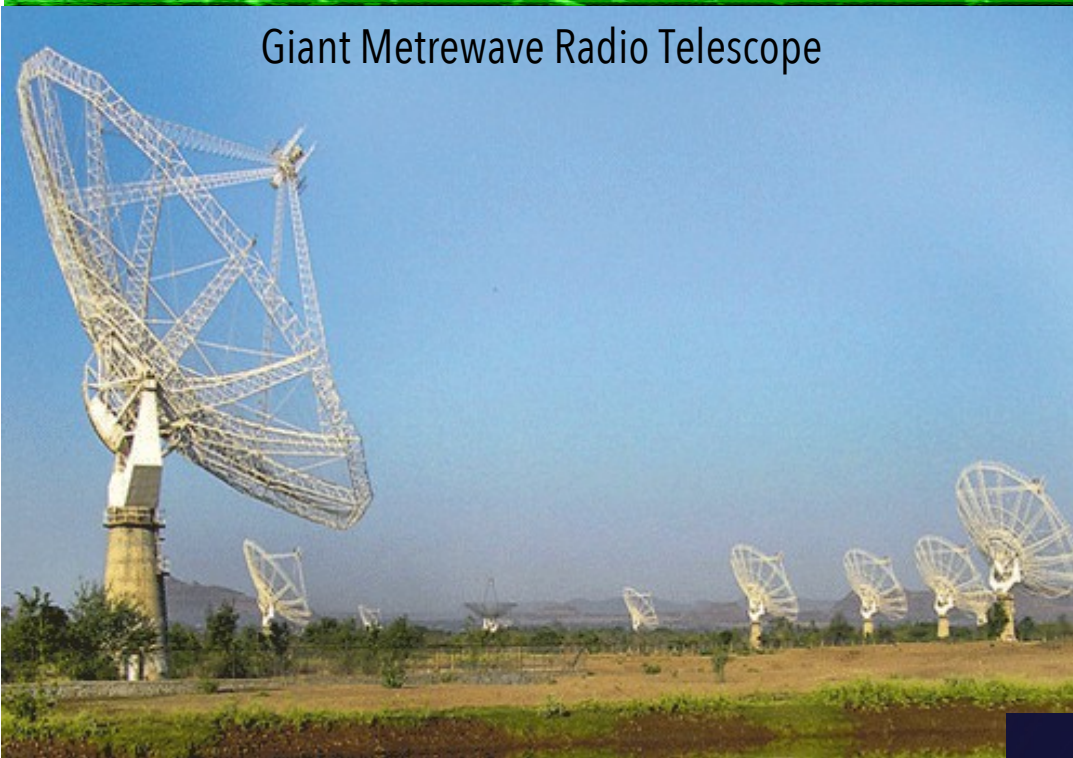
Sardinia Radio Telescope

Parkes (Australia) 64m

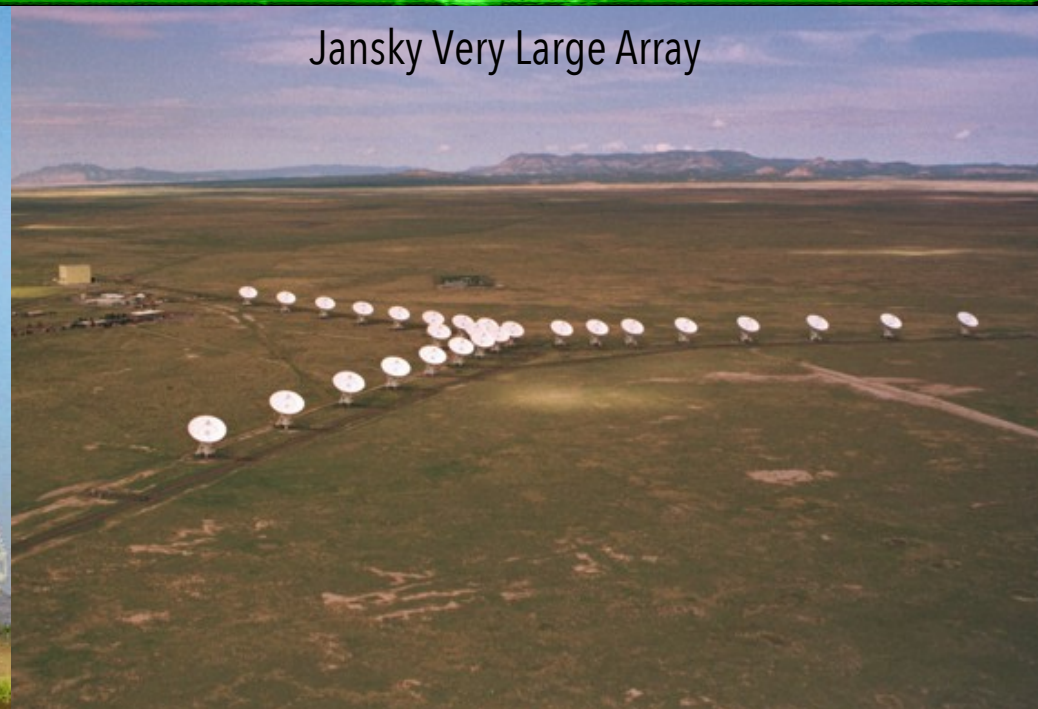


Interferometers

Giant Metrewave Radio Telescope



Jansky Very Large Array



Westerbork Synthesis Radio Telescope



The Global VLBI - Array



Once upon a time



Irregularities in the reflecting surface cannot be corrected for, leading to an unrecoverable signal loss

The radiation reflected from the hatched area gets into the focus at a later time (with some phase delay, $2\epsilon/\lambda$) leading to a reduction of the coherence.

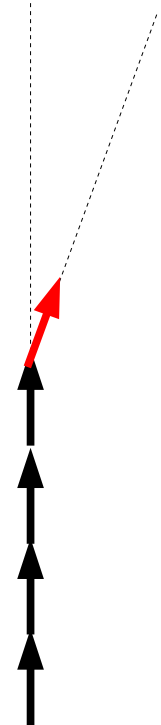
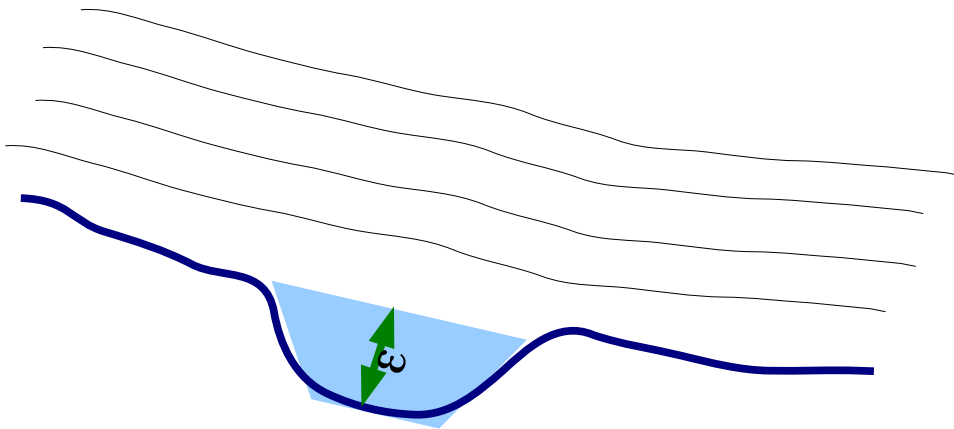
$$\delta = 2 \times 2\pi \left(\frac{\epsilon}{\lambda} \right)$$

$$g(u) = g_o(u) e^{i\delta(u)}$$

$$e^{i\delta(u)} \rightarrow 1 + i\delta - \delta^2/2 + \dots$$

$$\frac{A_e}{A_e^o} = \frac{\left| \int g(u) du \right|^2}{\left| \int g_o(u) du \right|^2}$$

$$\frac{A_e}{A_e^o} = \frac{\left| \int g_o(u) [1 + i\delta - \delta^2/2] du \right|^2}{\left| \int g_o(u) du \right|^2} = 1 - \langle \delta^2 \rangle + \langle \delta \rangle^2$$



The other way round: for a given surface accuracy, we can define a minimum operating wavelength λ_{\min}

$$\frac{A_e(\lambda_{\min})}{A_e^o} = \frac{1}{e}$$

$$\delta = 2 \times 2\pi \frac{\varepsilon}{\lambda_{\min}} = 1 \text{ rad}$$

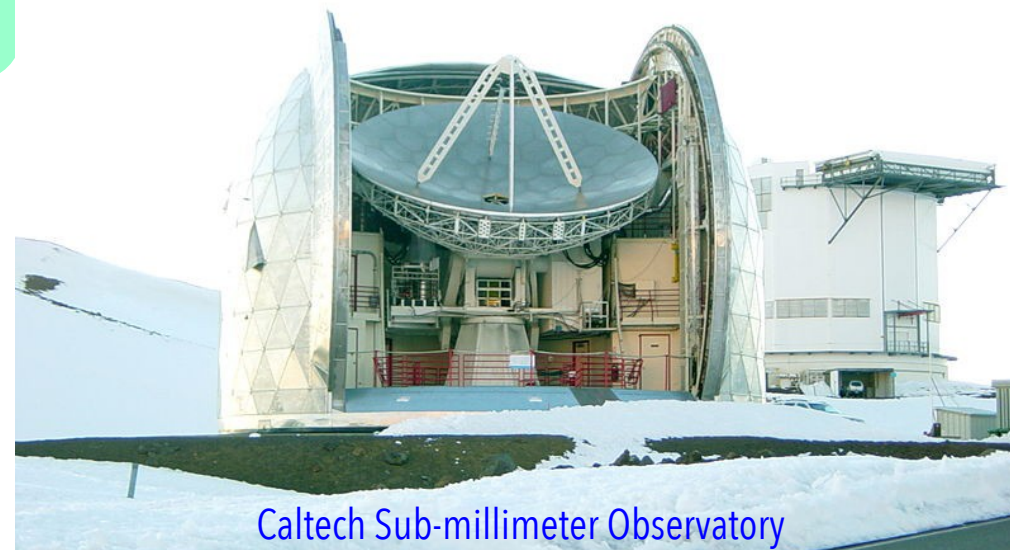
therefore , conservatively, one can chose $\lambda_{\min} = 20\varepsilon$.

Reflecting surface:

Size: big/small (money, weight, running costs)

Accuracy: solid panels, mesh, wires.

The surface type and telescope characteristics are critical to the main scientific drivers for which a given instrument has been built.



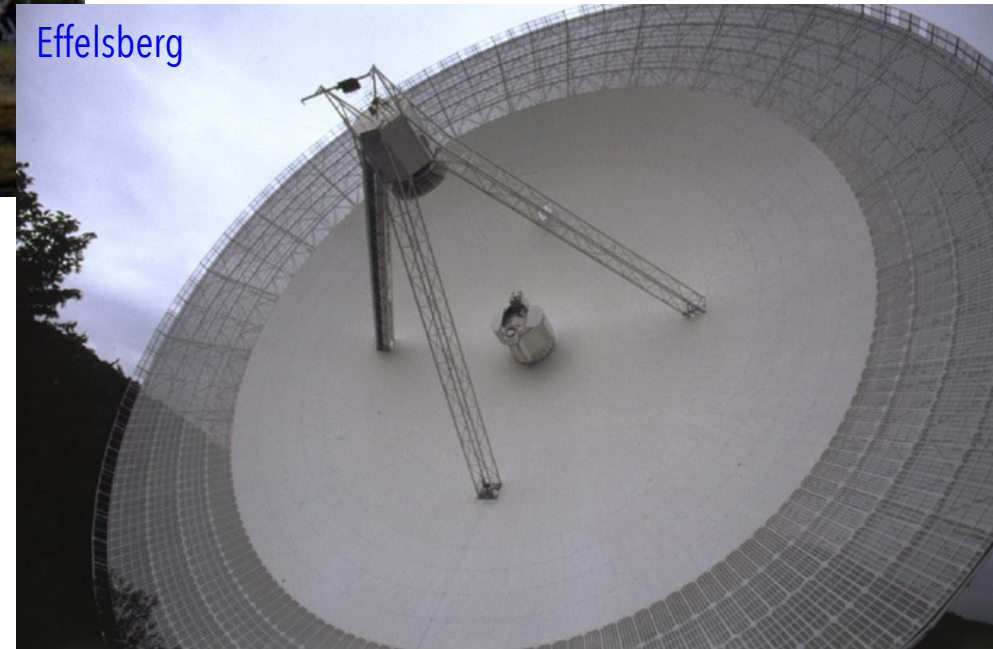
Northern Cross, Medicina



Westerbork Synthesis Radio Telescope



Effelsberg



Modern Radio Telescopes

➤ Each detector can reveal radiation within a given bandwidth centered at a given frequency

In general, the total available bandwidth is a fraction of the reference frequency

➤ Modern receivers can have very large bandwidths.

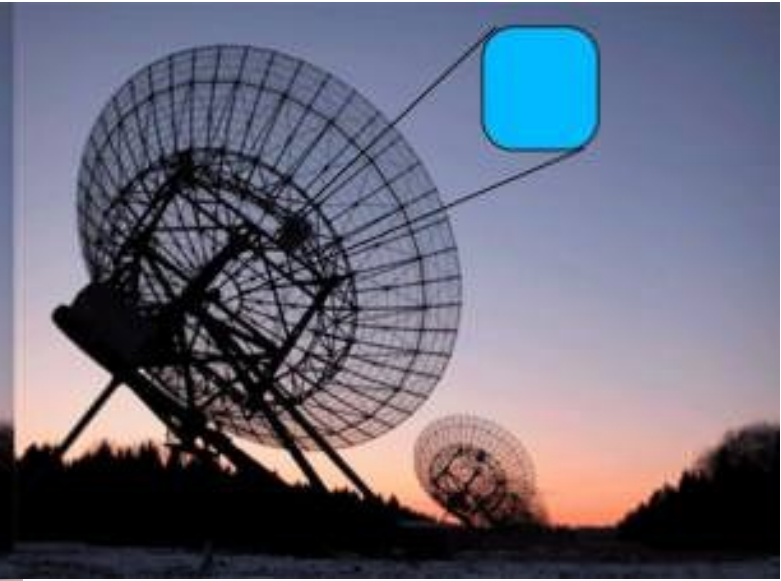
New interferometers:

- Made of low-cost mirrors/collectors, high-cost electronics & infrastructures
- Huge amount of data throughput (storage and data transfer)

(Current) Future radio telescopes aim at

- ➔ continuous (but not simultaneous) frequency coverage
- ➔ wide field imaging (focal plane arrays / field dipoles)
- ➔ high sensitivity

Focal plane arrays



GBT (Green Bank Telescope), Effelsberg, Arecibo, SRT (Sardinia Radio Telescope), FAST (Five-hundred m Aperture Spherical Telescope)

<http://greenbankobservatory.org>

<http://www.mpifr-bonn.mpg.de/en/effelsberg>

<http://www.naic.edu>

<http://www.srt.inaf.it>

<http://fast.bao.ac.cn/en/>

Currently ok for spectroscopic work and pulsar surveys
(where large collecting areas are necessary)



Large mirrors mean good sensitivity.

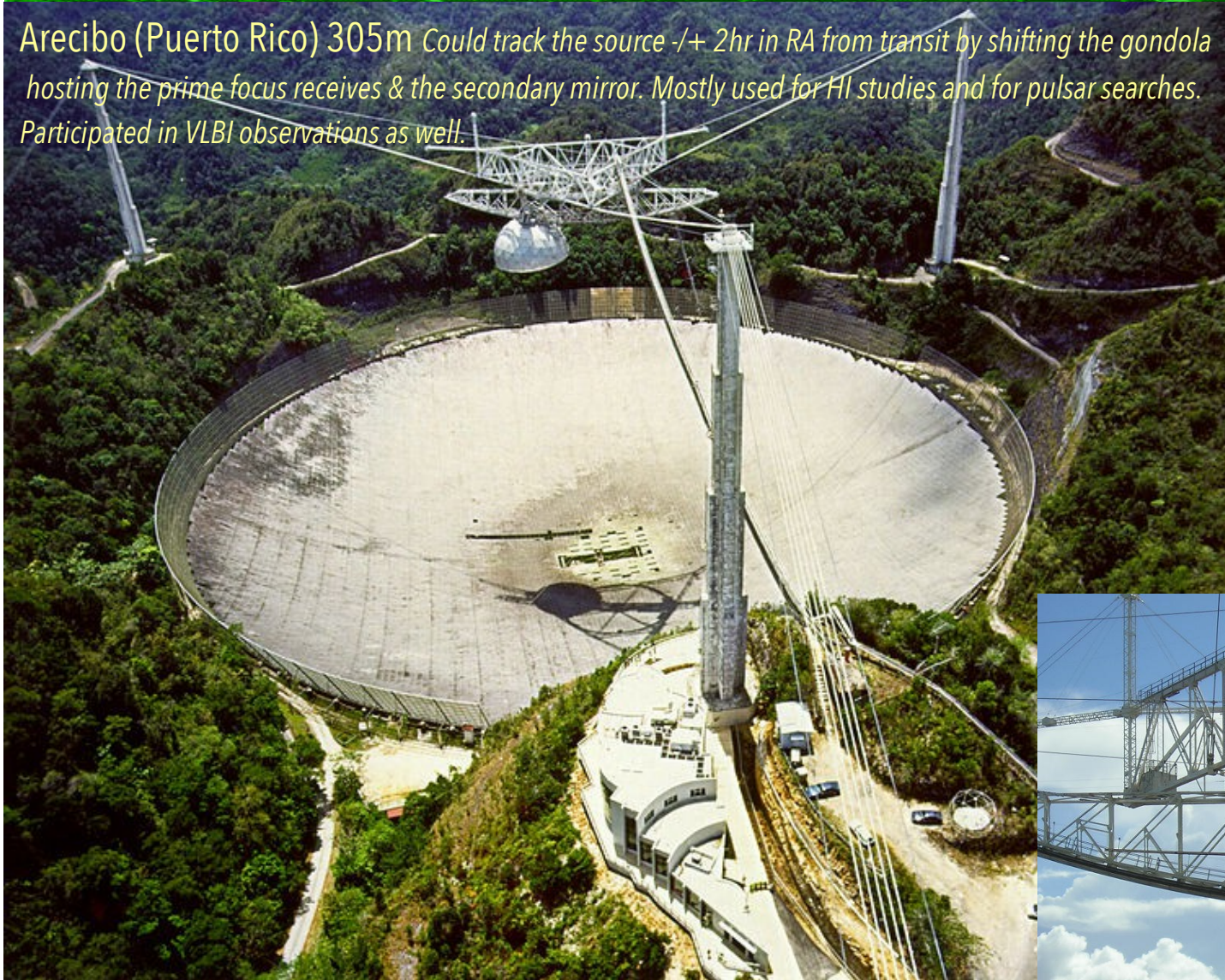
- Arecibo 300 m, partially steerable (secondary mirror) Can't go to high frequencies
- Green Bank Telescope (GBT) 105 m fully steerable 300 MHz – 100 GHz active surface
- Parkes 64m for decimetric work, has a **multi-feed** receiver at L band
- Sardinia Radio Telescope (SRT) 64m has been designed for continuous frequency coverage 300 MHz – 100 GHz but fundings limit to 3 receivers only (a multi-feed at 20 GHz); **active surface**

*Single dishes in the mm and sub-mm at high altitudes and with accurate (and active) surfaces
SEST, IRAM, CSO, ...*

Real Instruments -3 - single dishes



Arecibo (Puerto Rico) 305m *Could track the source ± 2 hr in RA from transit by shifting the gondola hosting the prime focus receives & the secondary mirror. Mostly used for HI studies and for pulsar searches. Participated in VLBI observations as well.*



<https://www.youtube.com/watchv=joLYVix5DLU>

Arecibo (final) collapse on Dec 3rd, 2020

Real Instruments – 4 – single dishes

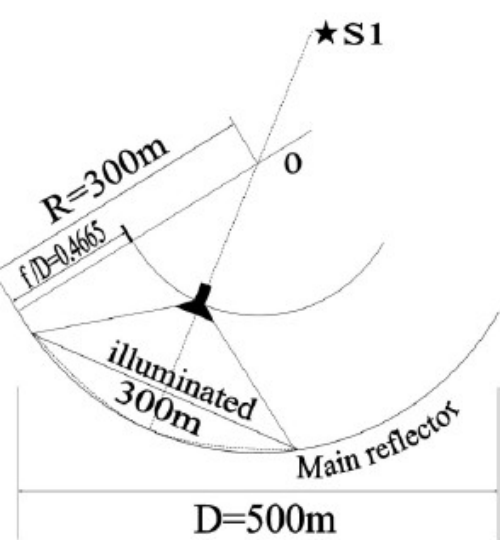


Figure 1: Left: FAST optical geometry, right: FAST 3-D model

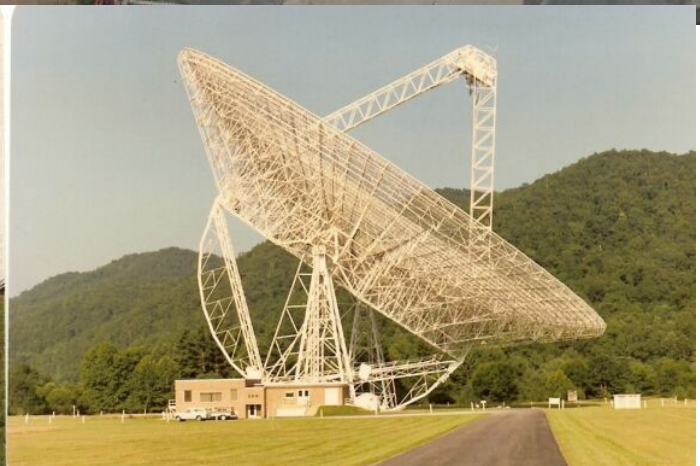
Effelsberg (Germany) 100m



Can track a source for the whole time it is above the horizon (only limitations are hills preventing low elevation [$\sim 10^\circ$] observations. Regularly used in VLBI observations, it is nonetheless mostly used in standalone experiments. Covers frequencies from 300 MHz to 90 GHz, although at high frequencies only a (large) fraction of the mirror is effective. Mostly used for spectral line work (masers either in star forming regions or around evolved stars, HI emission in galaxies) and continuum studies of radio galaxies and quasars (also in polarization) and pulsars.

the Green Bank Telescope (GBT)

The GBT has an unusual shape (off-axis paraboloid) studied to avoid aperture blockage. Designed to work from 300 MHz to 100 GHz, requires an active surface. Building started in 1991, still not fully completed (high frequencies not exploiting the full surface). Used as Effelsberg in both spectral line and continuum studies in standalone mode, and occasionally joins VLBI observations in case a high sensitivity antenna is necessary.



Made of (many) elements (2 at least)

Each "antenna" samples 2 orthogonal polarizations

$$V(t)_R^i = E_R^0 \sin(\omega t + \phi_R)$$

$$V(t)_L^i = E_L^0 \sin(\omega t + \phi_L) \quad \text{For each } i\text{-th antenna}$$

All this is sent to the correlator which performs the "correlation"

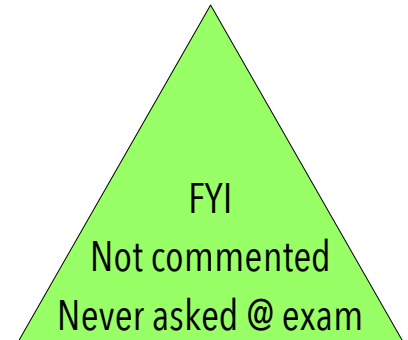
$$V_{i,j}(u,v) = \frac{1}{T} \int_{-T/2}^{T/2} V(t)_R^i V^*(t)_R^j dt$$

This happens

- for every combination of signals: $R_i R_j$, $L_i L_j$, $R_i L_j$, $L_i R_j$
- for each integration time T
- over each bandwidth $\Delta \nu$ (that can be further divided into many smaller intervals)

For an interferometre made of N elements, the number of independent pairs is

$$\frac{N(N-1)}{2}$$



Modern Interferometers: Jansky Very Large Array (JVLA)



Continuous coverage 1 – 50 GHz; Four different configurations, max baseline from 1.1 (D) to 36 km (A)
Reverse Y disposition, excellent for snapshots, still one of the best interferometers in the world at $\lambda \sim \text{cm}$



The JVLA (2)



Congressional approval for the VLA project was given in August 1972, and construction began some six months later. The first antenna was put into place in September 1975 and the complex was formally inaugurated in 1980, after a total investment of USD \$78.5 million.

JVLA consists of 27 antennas (25 m in diameter), in New Mexico, west of Socorro 4 configurations (A, B, C, D) with maximum distance between antennas of 36, 10, 3.5 and 1 km, distributed in 3 arms in reversed Y shape

Built in 1980; sensitivity equivalent to a 125m single dish, originally had a number of bands from 4m to 7mm, maximum bandwidth 100 MHz

EVLA (JVLA) completed in 2013:

Modern correlator (WIDAR) allowing a larger bandwidth (2 – 4 GHz) and more channels

Receivers cover from 1 to 50 GHz. Low frequencies are suspended/under test?

Surveys (carried out in the '90ies):

NVSS (the whole sky north of Dec = -40° ($\sim 75\%$ of the sky), D-Array \Rightarrow HPBW = $45''$, L band
rms ~ 0.45 mJy/beam, about 2 M sources)

FIRST (Polar cap+ ($\sim 25\%$ of the sky), B – Array \Rightarrow HPBW $5''$, L band, rms ~ 0.15 mJy/beam, nearly 1 M sources)

ongoing **VLASS** (HPBW $2.5''$, 2 – 4 GHz, 16 – 128 MHz data cubes, sky north of Dec = -40° ($\sim 75\%$ of the sky),
rms 0.12 mJy/beam, 3 epochs separated by 32 months, ~ 5 M sources)

Receivers Available at the (OLD) VLA

	4 Band	P Band	L Band	C Band	X Band	U Band	K Band	Q Band
Frequency (GHz)	0.073-0.0745	0.30-0.34	1.34-1.73	4.5-5.0	8.0-8.8	14.4-15.4	22-24	40-50
Wavelength (cm)	400	90	20	6	3.6	2	1.3	0.7
Primary beam (arcmin)	600	150	30	9	5.4	3	2	1
Highest resolution (arcsec)	24.0	6.0	1.4	0.4	0.24	0.14	0.08	0.05
System Temp (K)	1000-10,000	150-180	37-75	44	34	110	50-190	90-140

Configuration	A	B	C	D
B_{\max} (km)	36.4	11.4	3.4	1.03
B_{\min} (km)	0.68	0.21	0.035	0.035

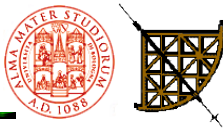
Frequency (GHz)	Band Name Approximate Wavelength	System Letter Code	Antenna Temperature (K)	Efficiency (%)	Number Antennas (VLA+EVLA)	RMS (10 min) Sensitivity (mJy)
0.073 - 0.0745	400 cm	4	1000-10000	15	5+20	160
0.3 - 0.34	90 cm	P	150-180	40	< 1	>4
1.24 - 1.70	20 cm	L	35	55	5+20	0.061
4.5 - 5.0	6 cm	C	45	69	5+20	0.058
8.1 - 8.8	3.6 cm	X	35	63	5+20	0.049
14.6 - 15.3	2 cm	U	120	58	5+0	1.0
22.0 - 24.0	1.3 cm	K	50 - 80	40	5+20	0.11
40.0 - 50.0	0.7 cm	Q	80	35	5+20	0.27

FYI

Not commented

Never asked @ exam

The new EVLA



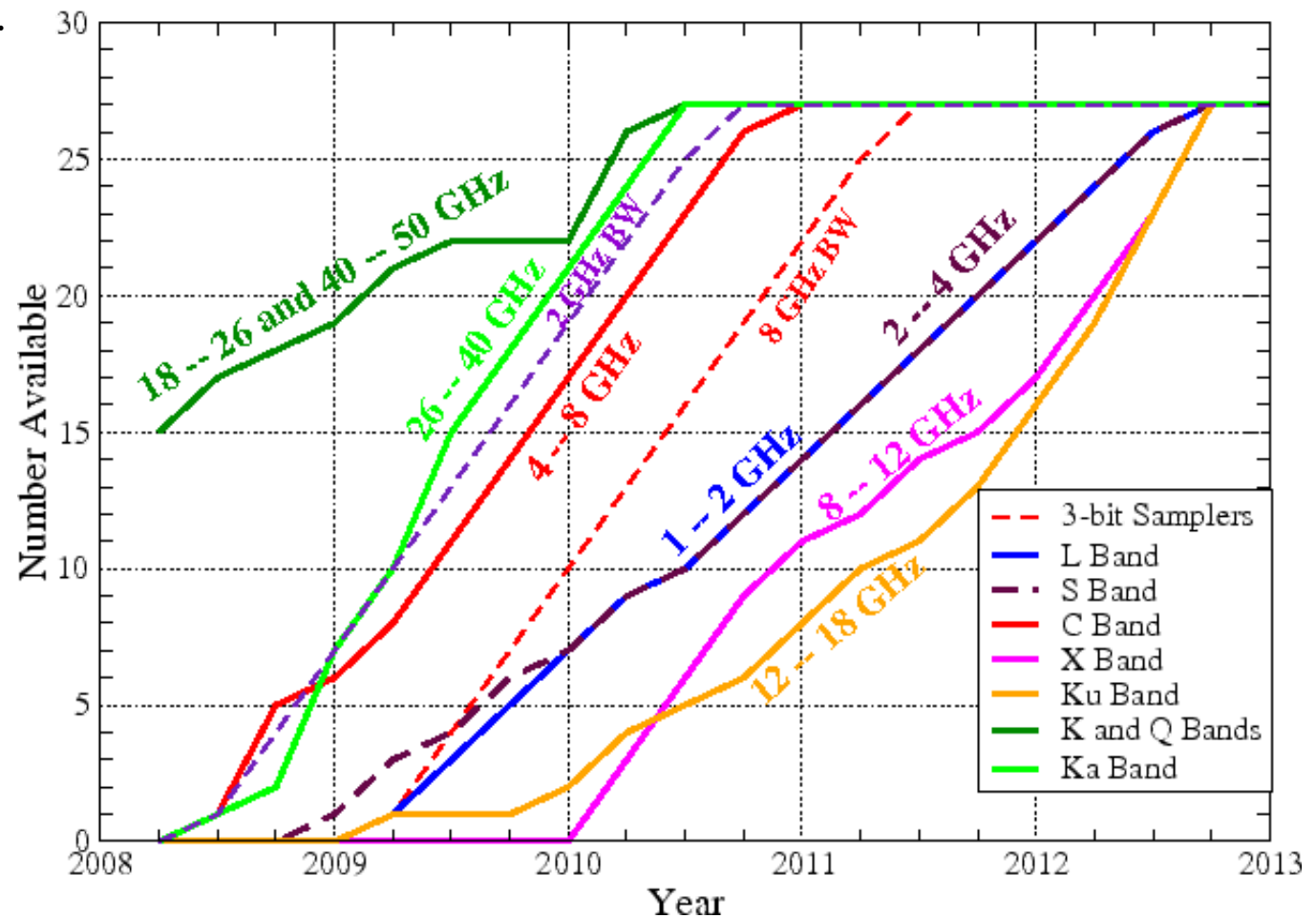
It has the same configurations as the old one.

The receiving system and the correlator have been (are being) completely refurbished. The total maximum bandwidth has been increased from 50 to 128 MHz per IF. It can be further sampled in a large number of smaller channels for spectral line work. Below it is shown the planned schedule for the receiver replacement. The EVLA-PhaseII would add 6 new stations for a better resolution and a lower confusion limit, but no funds have been allocated to date.

FYI
Not commented
Never asked @ exam

EVLA Wideband Receiver Availability

Prepared Dec 2008



Built in 1970 the Westerbork Synthesis Radio Telescope (**WSRT**) can be considered the oldest interferometer still in use. 14 antennas in E-W with equatorial mount, 10 in fixed positions (144m spacings) and 4 on movable tracks to provide short spacings variable in length (36, 72, 90 m). **Redundant interferometer**, good for calibration, bad for uv-coverage. E-W baselines provide bad N-S resolution at low declination, and require a full 12-hr synthesis to have a uniformly sampled uv-plane. Maximum baseline of 3.5 km. Frequencies from 120 MHz to 5 (8.3) GHz.

Surveys: **WENSS**

The Westerbork Northern Sky Survey (WENSS) is a 325 MHz (92cm) radio survey that covers the sky north of declination +28.5 degrees to a limiting flux density of about 18 mJy (5x the noise).

The survey has a resolution of $54'' \times 54'' / \sin(\text{dec})$

WHISP

It is a survey of the neutral hydrogen component in spiral and irregular galaxies with the WSRT. Its aim is to obtain maps of the distribution and velocity structure of HI in several hundreds of nearby galaxies, increasing the number of well-analyzed HI observations of galaxies by an order of magnitude. This uniform database will serve as a basis for research in many areas, for example: the structure of dark halo's as a function of galaxy mass and type, and the effects of environment on the structure and growth of HI disks.

FYI
Not commented
Never asked @ exam



The Australia Telescope Compact Array (**ATCA**), at the Paul Wild Observatory, is an array of six 22-m antennas used for radio astronomy. It is located about 25 km west of the town of Narrabri in rural NSW (about 500 km north-west of Sydney). Max E-W baseline ~ 6000 m

www.narrabri.atnf.csiro.au/observing/users_guide/html/new_atug_4.html#The-Australia-Telescope-Compact-Array

FYI

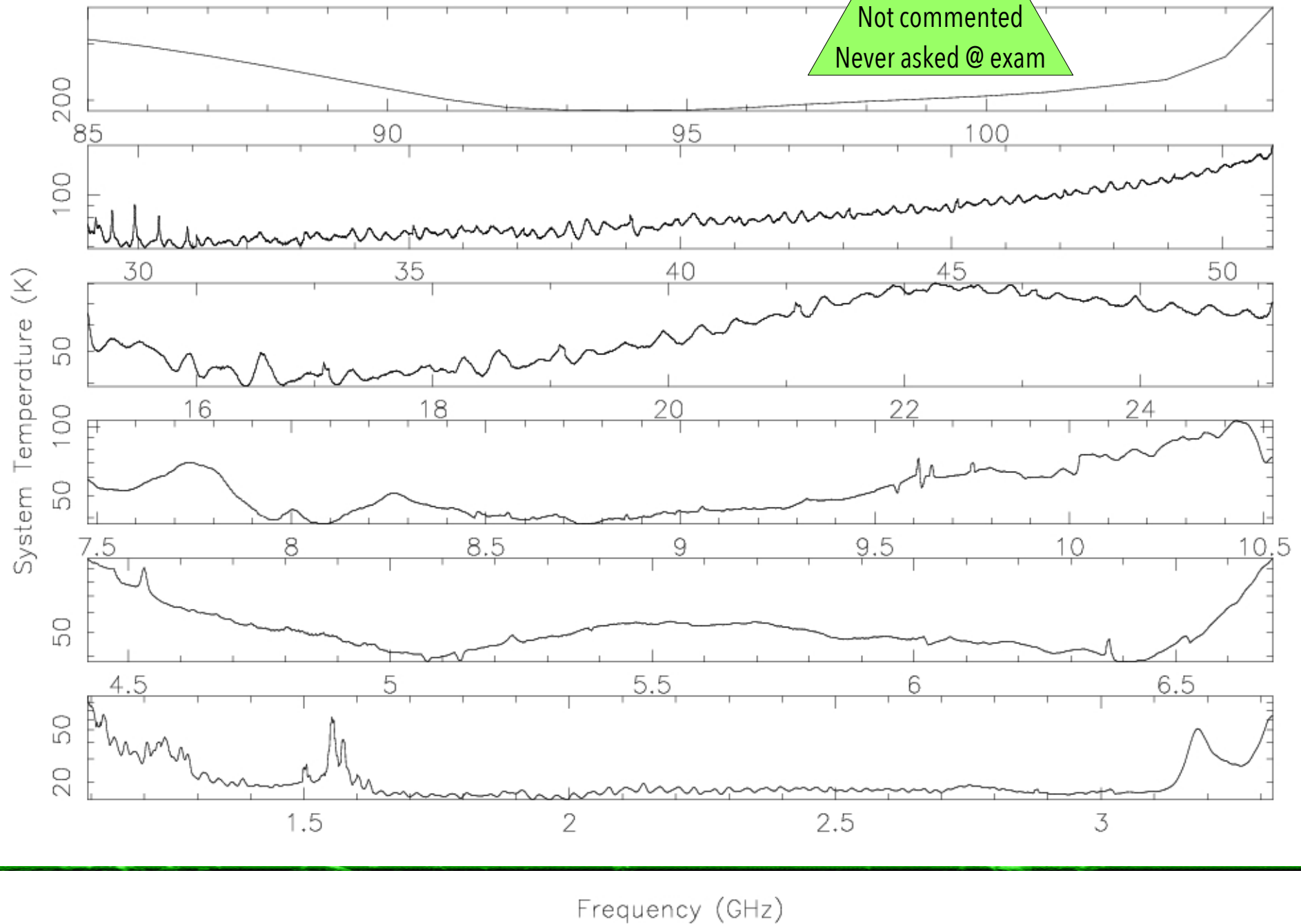
Not commented
Never asked @ exam



ATCA: T_{SYS} .vs.frequency coverage

FYI

Not commented
Never asked @ exam



The Giant Metrewave radio telescope (GMRT) operates 30 antennas, 45m in diameter, at 5 frequency bands, 150, 233, 327, 610, and 1420 MHz, maximum baseline ~25 km. Operations started in 1995

uGMRT has receivers and electronics upgraded to support wide-band operations

120-250 250-500 500-900 1000-1400 MHz

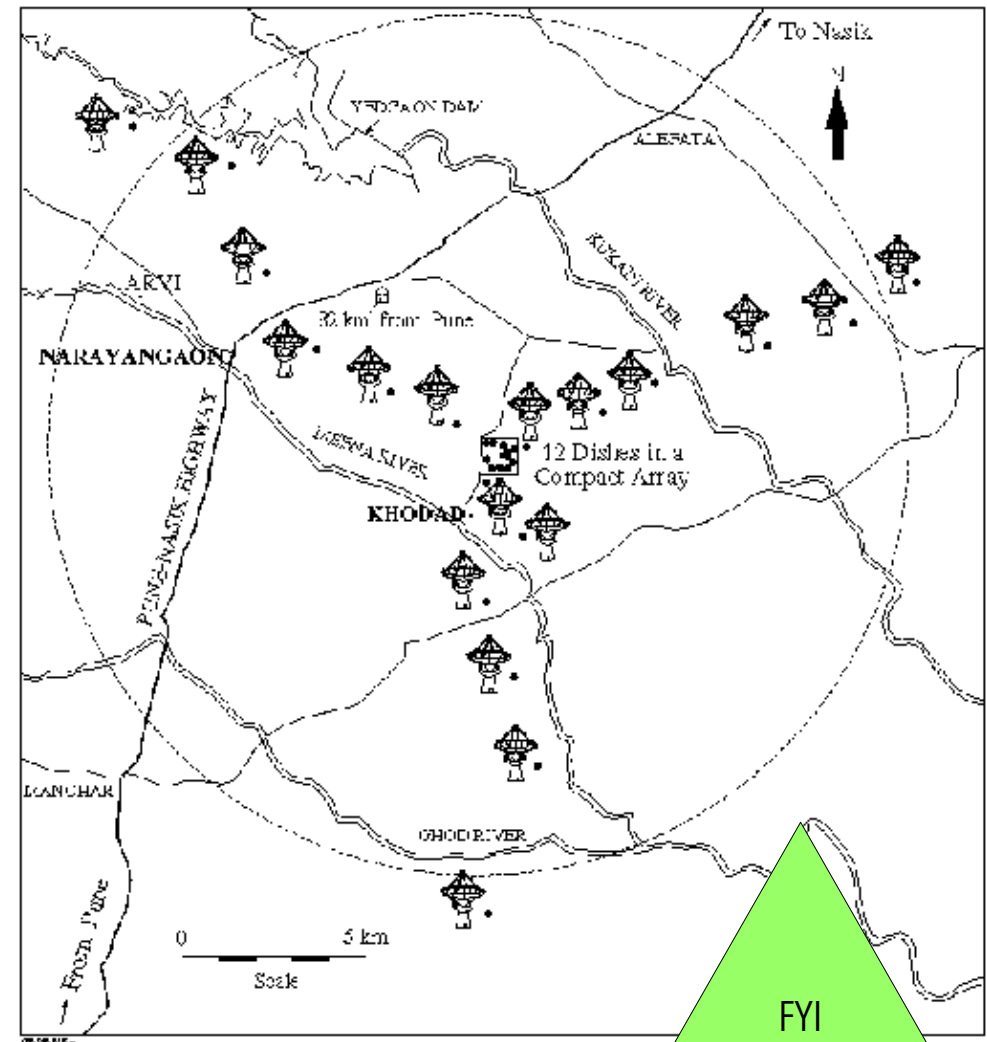
<http://gmrt.ncra.tifr.res.in/>

Survey: TGSS at 150 MHz, ongoing



Megan Argo 2005

LOCATIONS OF GMRT ANTENNAS (30 dishes)



FYI

Not commented
Never asked @ exam

LOFAR (LOw Frequency Array)

- operates between **30-80 (LBA)** and **120-240 (HBA)** MHz
- low-cost antennas and much more expensive electronics (fibers, computing)

Each **station** is an **array of detectors** spread over an area, whose signal is combined to get a "station beam", and then such signal is transferred via optical fiber to a super computer (IBM – Blue Gene P).

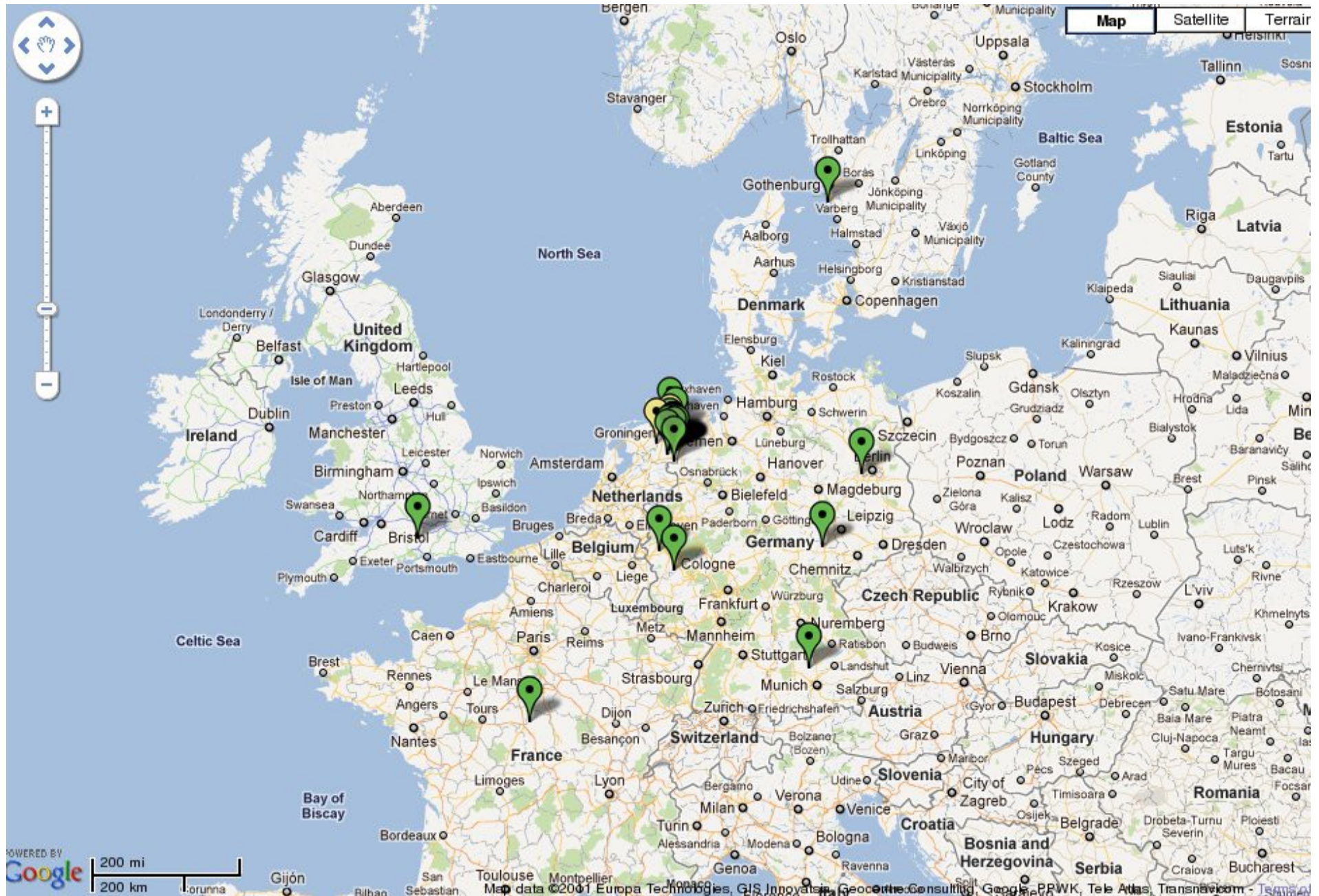
The FoV is very large (about 120° in diameter) and many sources are visible at any time. The low frequency sky is dominated by the "A-team" (Cas A; Cyg A; Vir A;...) and by 3C sources. The PSF is of the order of $1''$. [...]

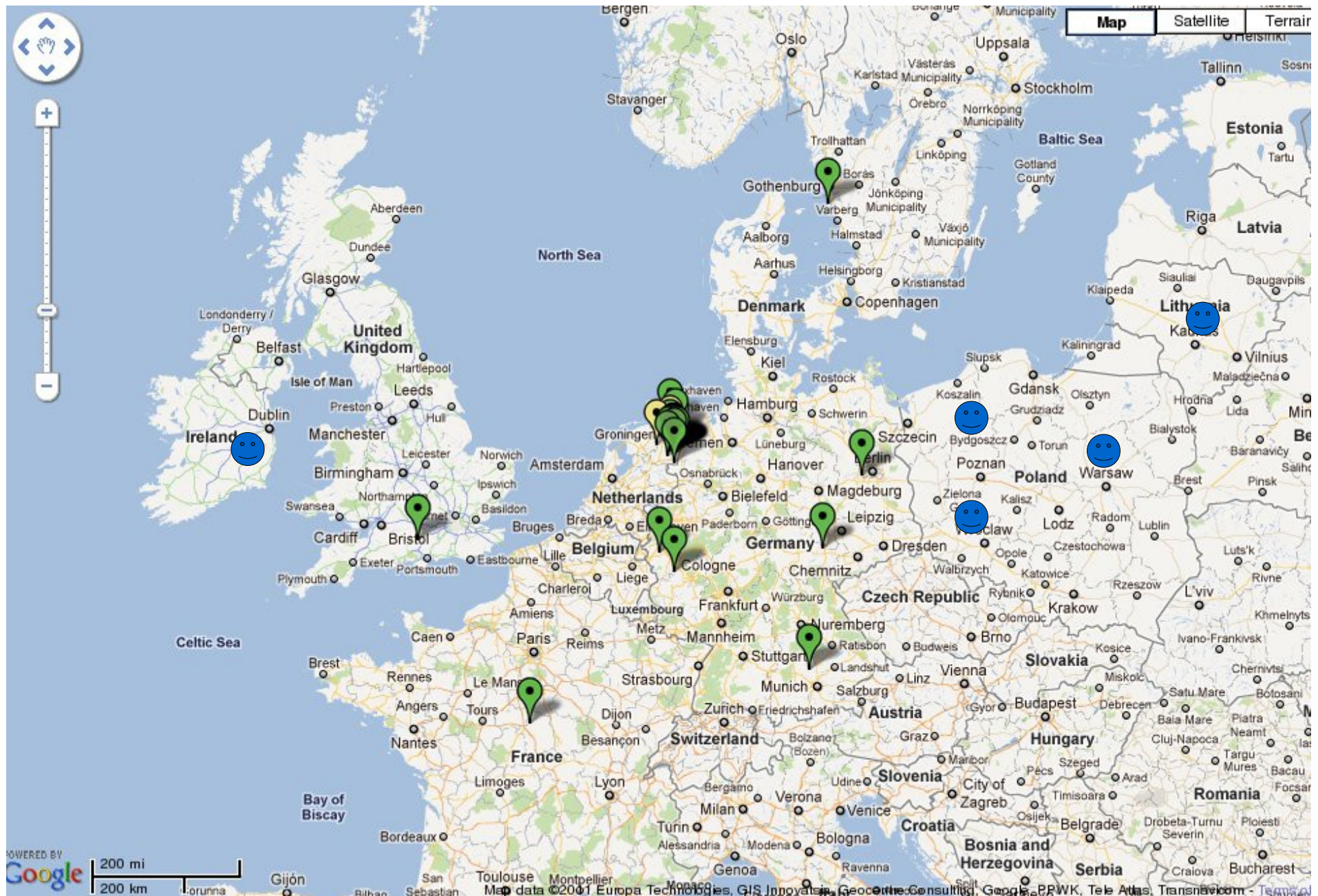
Science: organized in a number of key-projects (transients, EoR, surveys, cosmic magnetism) which will employ most of the observing time in the first years of operations.

LOFAR was intended as a precursor/demonstrator of SKA (but now the frequency range is different).

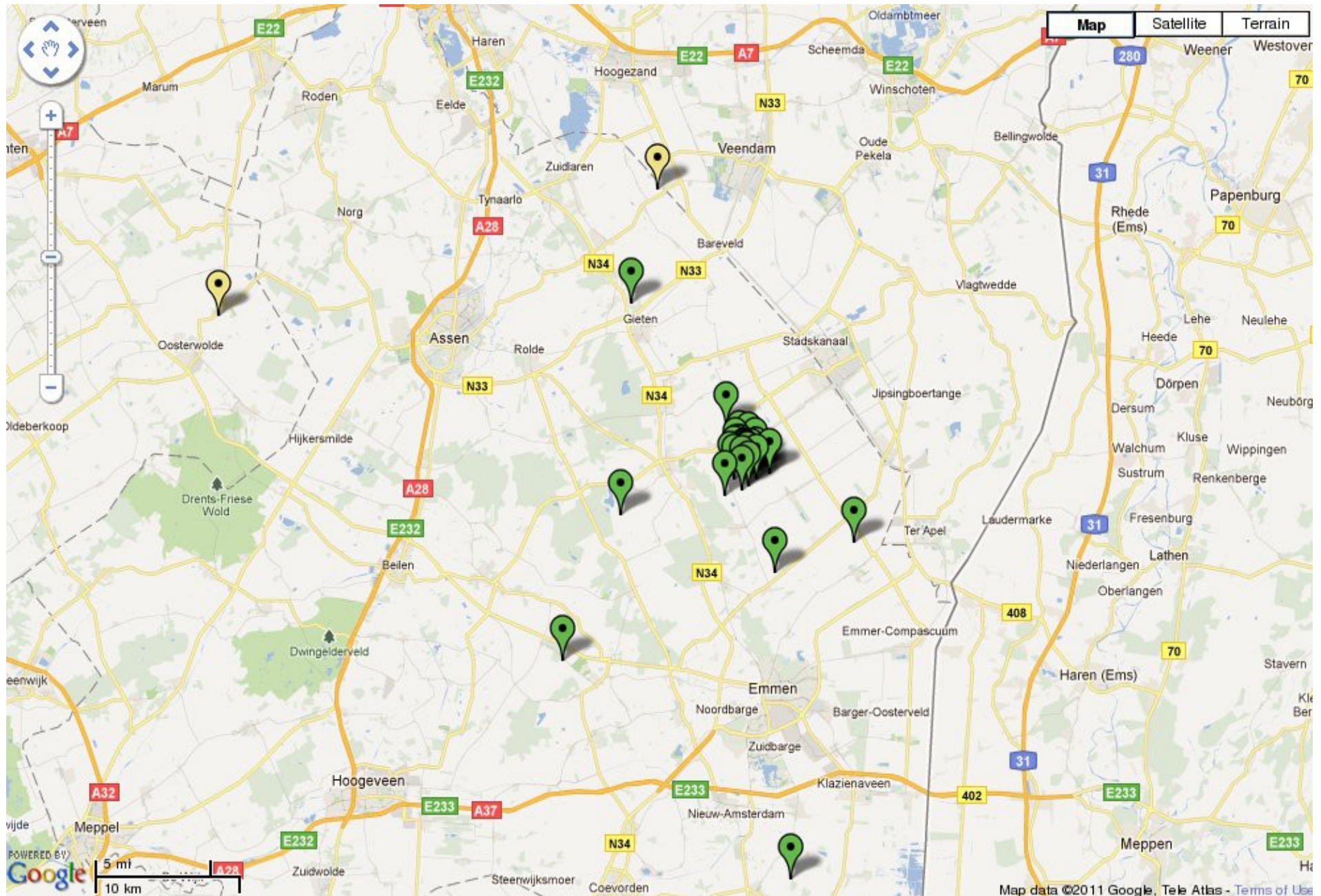
Survey images are already available.

Huge data throughput, only "real" time images are archived?

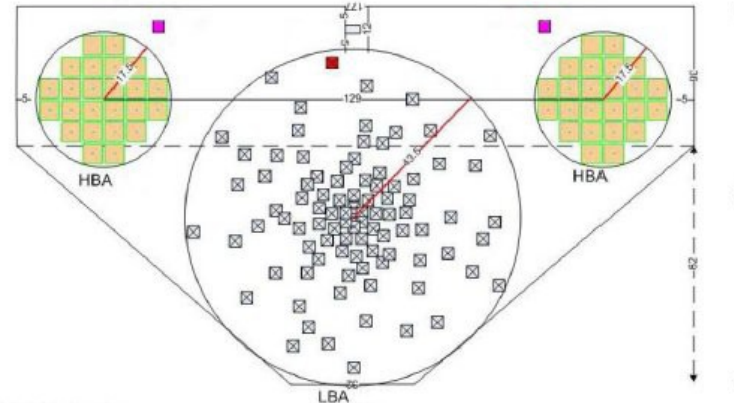
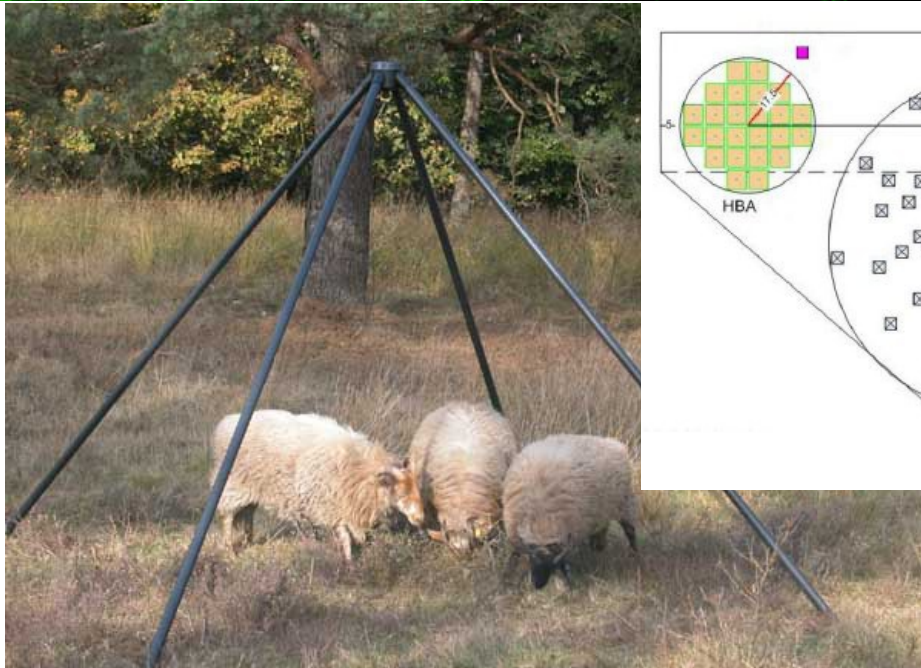




Present/Future Instruments -1- LOFAR : the location of the inner stations



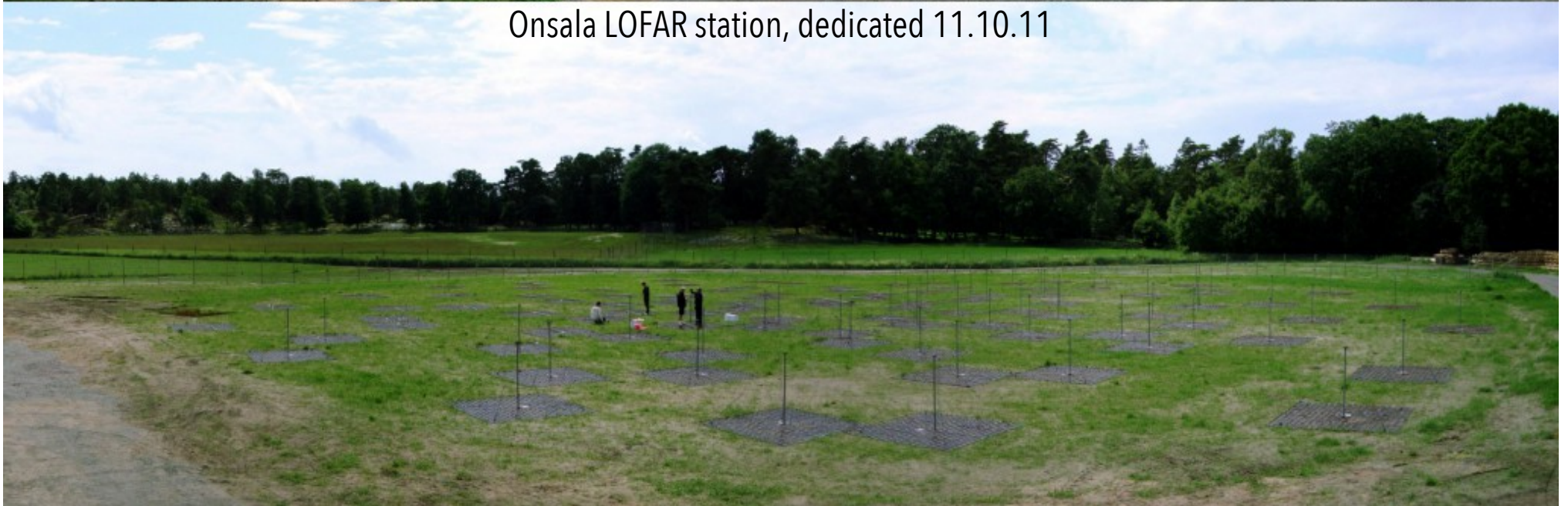
Present/Future Instruments -1- LOFAR: details of the station(s)

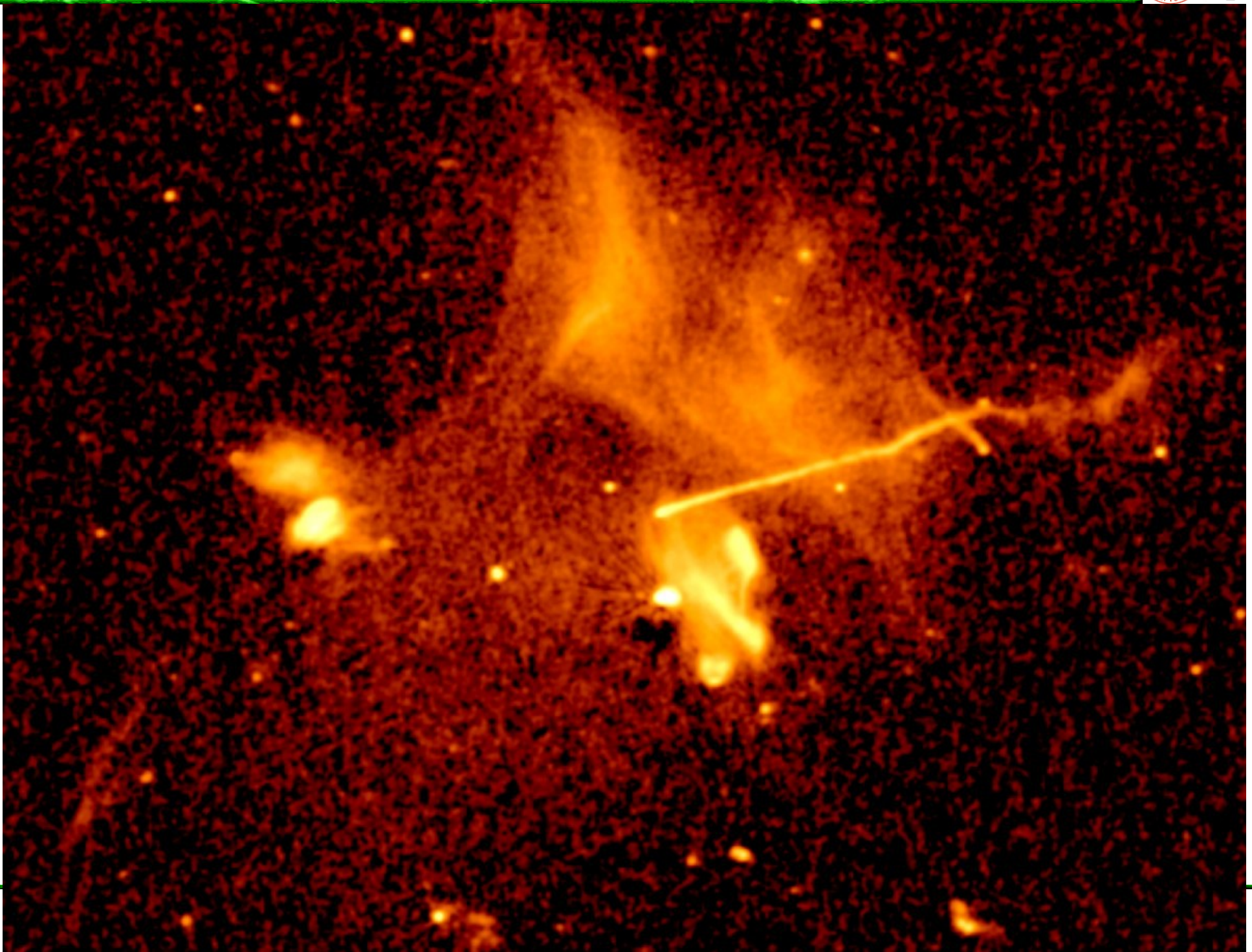






Onsala LOFAR station, dedicated 11.10.11





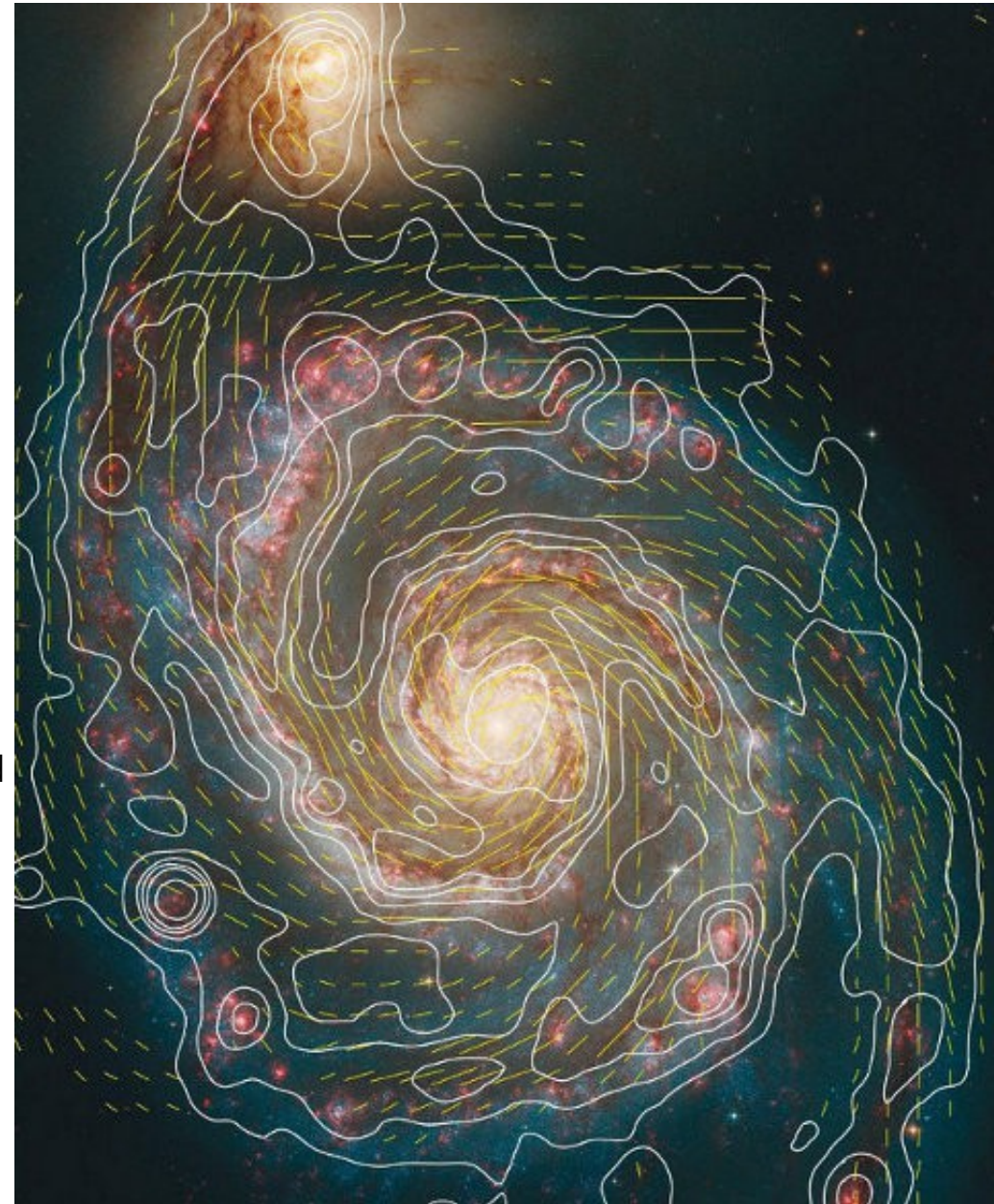
Cosmic Magnetism Key Science Project

The International Key Science Project "Cosmic Magnetism of the Nearby Universe" studies magnetic fields in the Universe by observing polarized radio synchrotron emission with LOFAR.

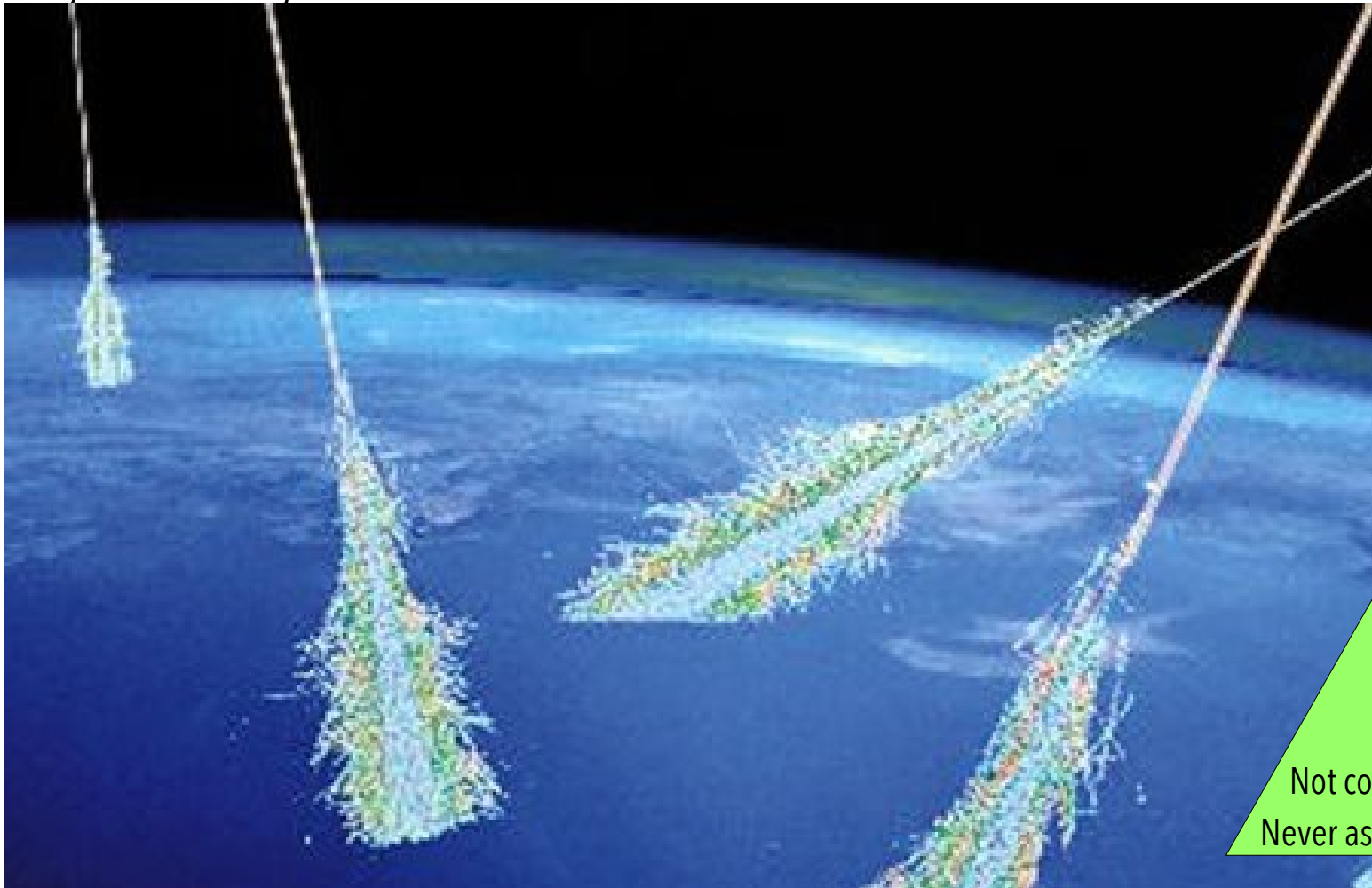
Faraday screens and rotation measure synthesis/Faraday tomography will be used to investigate the 3-D structure of local magnetic fields in the Milky Way and probe the magneto-ionic structure of the very local ISM surrounding the Sun.

Spectro-polarimetry with LOFAR will allow study of the so far unexplored domain of very small Faraday rotation measures and weak magnetic field strengths. It will address the astrophysics of objects such as dwarf galaxies, galaxy halos, nearby galaxy clusters, and intergalactic filaments related to the formation of large-scale structures, through ultra-deep observations of the diffuse polarized emission and Faraday rotation of polarized background sources.

For the first time we might detect magnetic fields and tenuous warm gas in the intergalactic medium.



Cosmic Rays Key Science Project

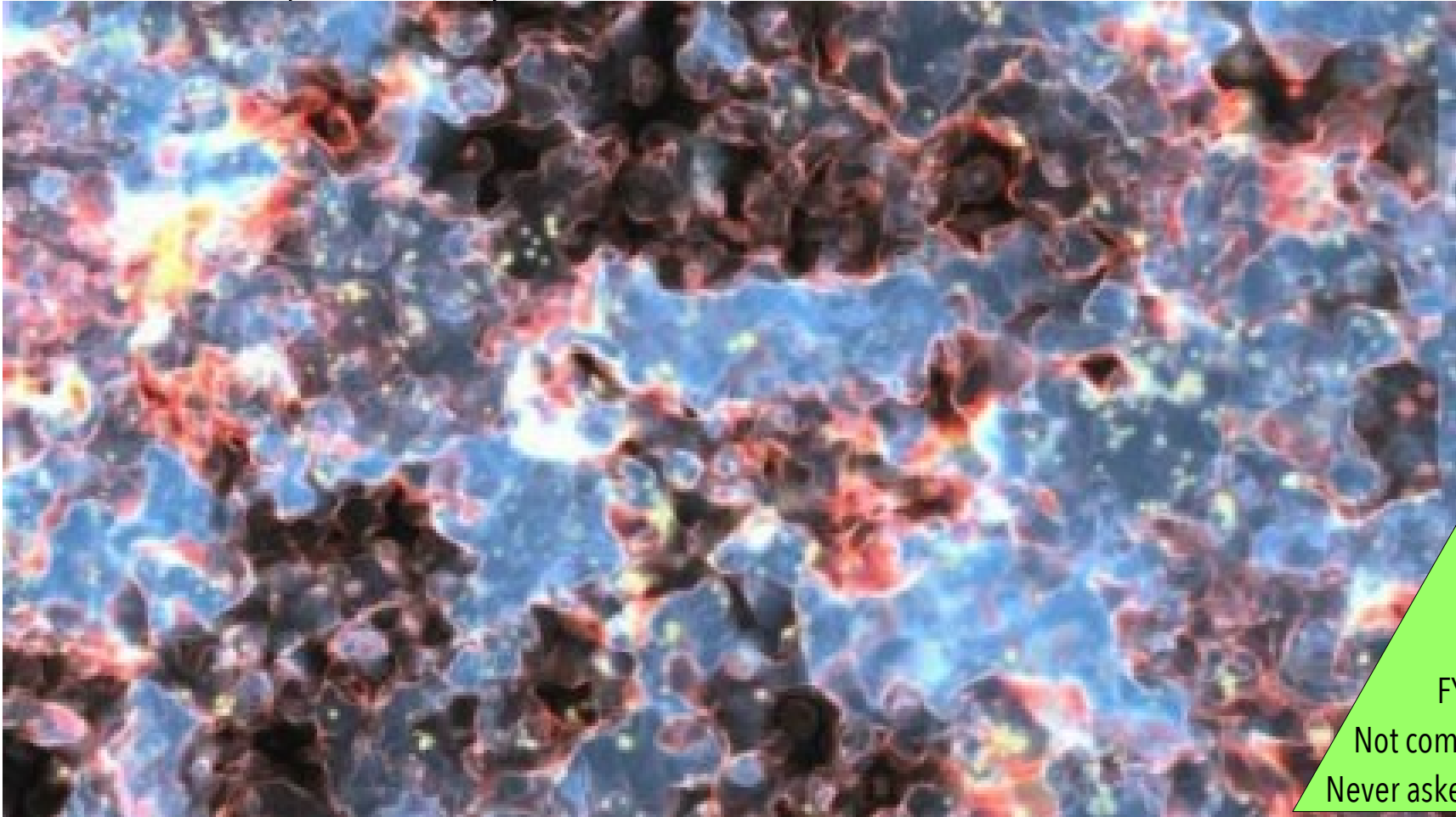


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LOFAR offers a unique possibility in particle astrophysics for studying the origin of high-energy cosmic rays (HECRs) at energies between 10^{15} - $10^{20.5}$ eV through the detection of air showers of secondary particles caused by interaction of cosmic rays with the Earth's atmosphere.

Both the sites and processes for accelerating particles are unknown. Possible candidate sources of these HECRs are shocks in radio lobes of powerful radio galaxies, intergalactic shocks created during the epoch of galaxy formation, so-called Hyper-novae, Gamma-ray bursts, or decay products of super-massive particles from topological defects, left over from phase transitions in the early Universe.

Epoch of Reionisation Key Science Project



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One of the most exciting applications of LOFAR will be the search for redshifted 21cm line emission from the Epoch of Reionisation (EoR). It is currently believed that the Dark Ages, the period after recombination when the Universe turned neutral, lasted until around redshift $z=20$. Wilkinson Microwave Anisotropy Probe (WMAP) polarisation results appear to suggest that there may have been extended, or even multiple phases of Reionisation, the start possibly being around $z\sim 15-20$ and ending at $z\sim 6$. Using LOFAR the redshift range from $z=11.4$ (115 MHz) to $z=6$ (180 MHz) can be probed.

For more information about the Epoch of Reionisation KSP <http://www.lofar.org/astronomy/eor-ksp/epoch-reionization>

Solar Physics and Space Weather with LOFAR



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The KSP "Solar Physics and Space Weather with LOFAR" is a European LOFAR activity. The KSP aims at using LOFAR for Solar and Space Weather studies. This includes the definition of solar observing modes, the development of the necessary software infrastructure, and making the observations available to the scientific community.

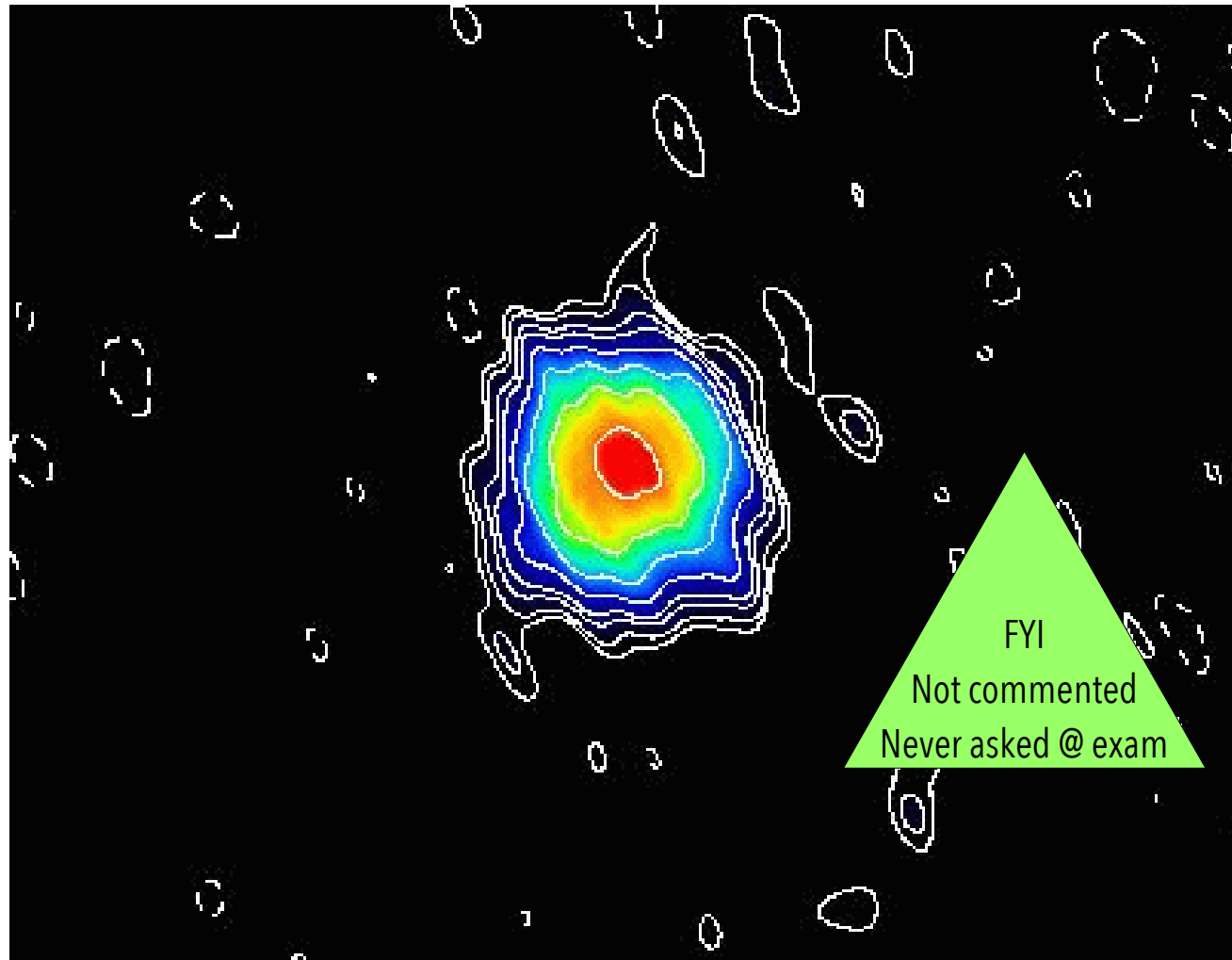
For information about solar and heliospheric science with LOFAR, <http://www.aip.de/groups/osra/sksp/>

Transients Key Science Project

Transient sources are one of the Key Projects of LOFAR. Under its remit come all time-variable astronomical radio sources, including pulsars, gamma-ray bursts, X-ray binaries, radio supernovae, flare stars, and even exo-planets. With its continuous monitoring of a large area of sky, it is hoped that LOFAR will detect many new transient events, and provide alerts to the international community for follow-up observations at other wavelengths. The project has been subdivided into five basic scientific working groups:

- * Jet sources: AGN, GRBs, accreting white dwarfs, neutron stars and stellar-mass black holes
- * Pulsars: classical radio pulsars, AXPs, RRATs
- * Planets: solar system objects and exoplanets
- * Flare stars: M, L, and T dwarfs and active binaries
- * Serendipity: hitherto unexplored parameter space

Public web page: <http://www.transientskp.org/>



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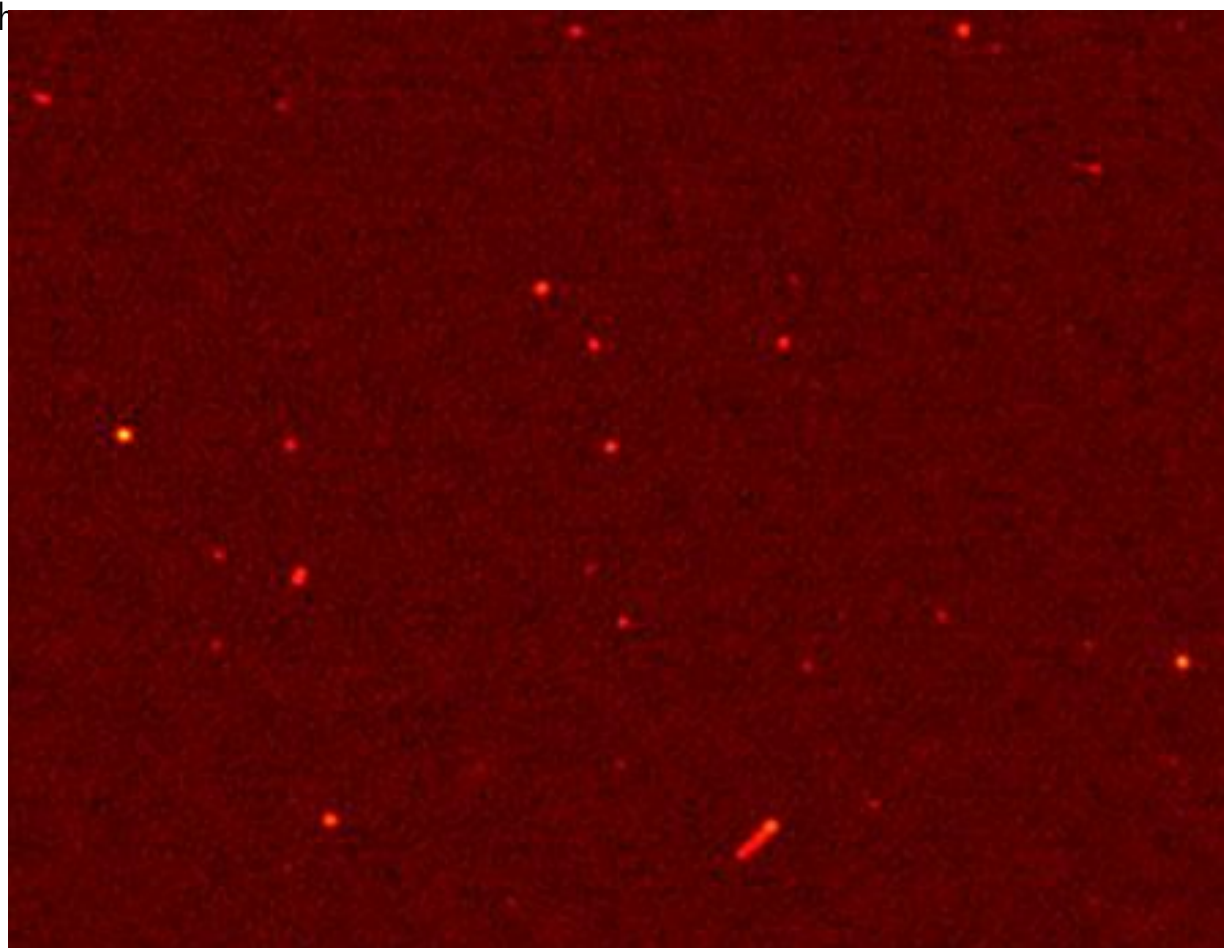
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Surveys Key Science Project

An important goal that has driven the development of LOFAR since its inception is to explore the low-frequency radio sky by means of a series of unique surveys. Low-frequency radio telescopes are ideally suited for carrying out large-sky surveys, because of their large instantaneous fields of view and the all-sky nature of their calibration. Four topics have been identified as drivers for the proposed surveys. Three of these are fundamental areas of astrophysics for which LOFAR is likely to make substantial contributions. The

- * 1. Formation of massive galaxies, clusters and black holes using $z \geq 6$ radio galaxies as probes,
- * 2. Intercluster magnetic fields using diffuse radio emission in galaxy clusters as probes,
- * 3. Star formation processes in the early Universe using starburst galaxies as probes,
- * 4. Exploration of new parameter space for serendipitous discoveries.

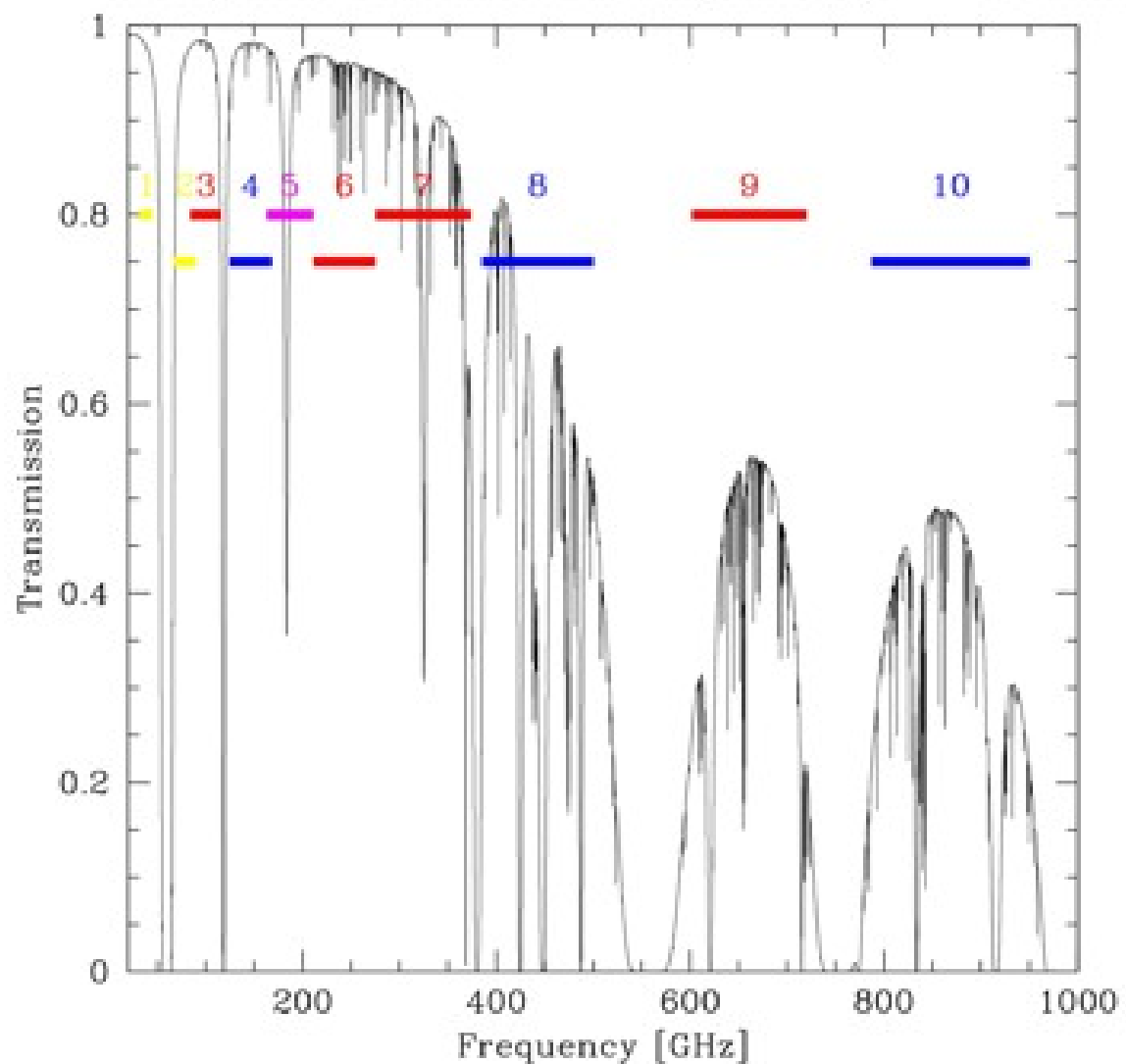
In addition to these, a broad range of topics are expected to be addressed by the surveys team. They span from magnetic fields and the interstellar medium in nearby galaxies, to physics of radio sources (their initial and final stages in the evolution), up to large scale structure of the Universe and its evolution, using clustering of radio sources, baryonic oscillations and gravitational lensing.



ALMA

(Atacama Large Millimeter Array). Joint instrument of ESO, NRAO, Japan and Chile. ALMA is a single telescope of revolutionary design, composed of 66 high (50 +4 are 12m dishes, with the addition of 12 antennas 7m in diameter) precision antennas located on the Chajnantor plateau, 5000 meters altitude in northern Chile.

Atmospheric transmission at Chajnantor, pwv = 0.5 mm



A number of bands from many millimeters to hundreds microns

Totally new instrument

Baselines up to 16 km.

A "compact core" made up by 4 12m antennas and 12 7m antennas will be used for studies of "extended structures"

Overview of ALMA's Scientific Potential

ALMA provides an unprecedented combination of sensitivity, angular & spectral resolution and imaging fidelity at the shortest radio wavelengths for which the Earth's atmosphere is transparent.

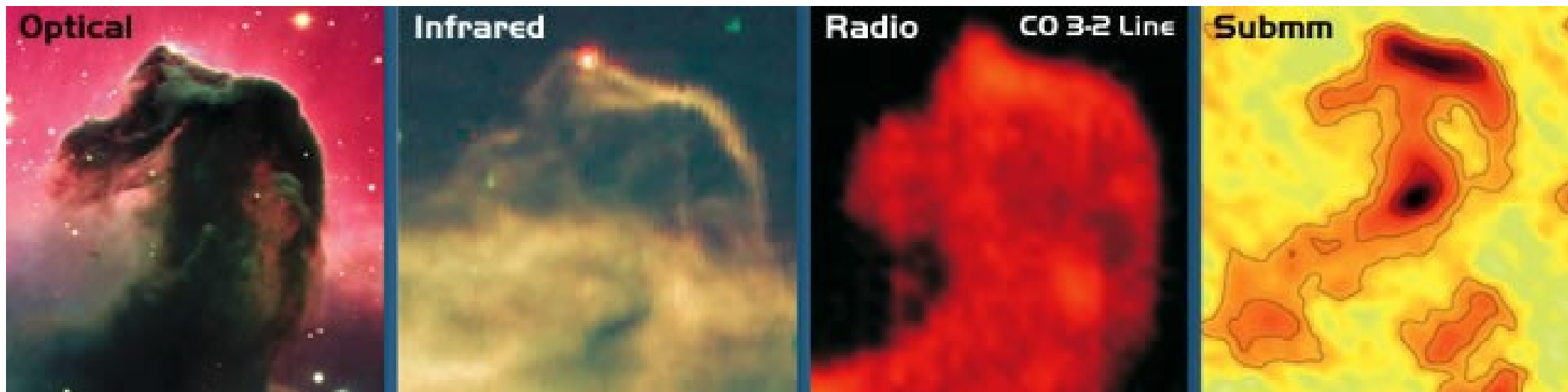


1. ALMA is a premier tool for studying the first stars and galaxies that emerged from the cosmic "dark ages" billions of years ago. These objects now are seen at great cosmic distances, with most of their light stretched out to millimeter and sub-millimeter wavelengths by the expansion of the Universe.
2. In the more nearby Universe, ALMA provides an unprecedented ability to study the processes of star and planet formation. Unimpeded by the dust that obscures visible-light observations, ALMA can reveal the details of young, still-forming stars, and can show young planets still in the process of developing/forming.
3. In addition, ALMA allows scientists to learn in detail about the complex chemistry of the giant clouds of gas and dust that spawn stars and planetary systems.

Many other astronomical specialties also will benefit from the new capabilities of ALMA, such as:

- * Map gas and dust in the Milky Way and other galaxies.
- * Investigate ordinary stars.
- * Analyze gas from an erupting volcano on Jupiter's moon, Io.
- * Study the origin of the solar wind.

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Nebulae

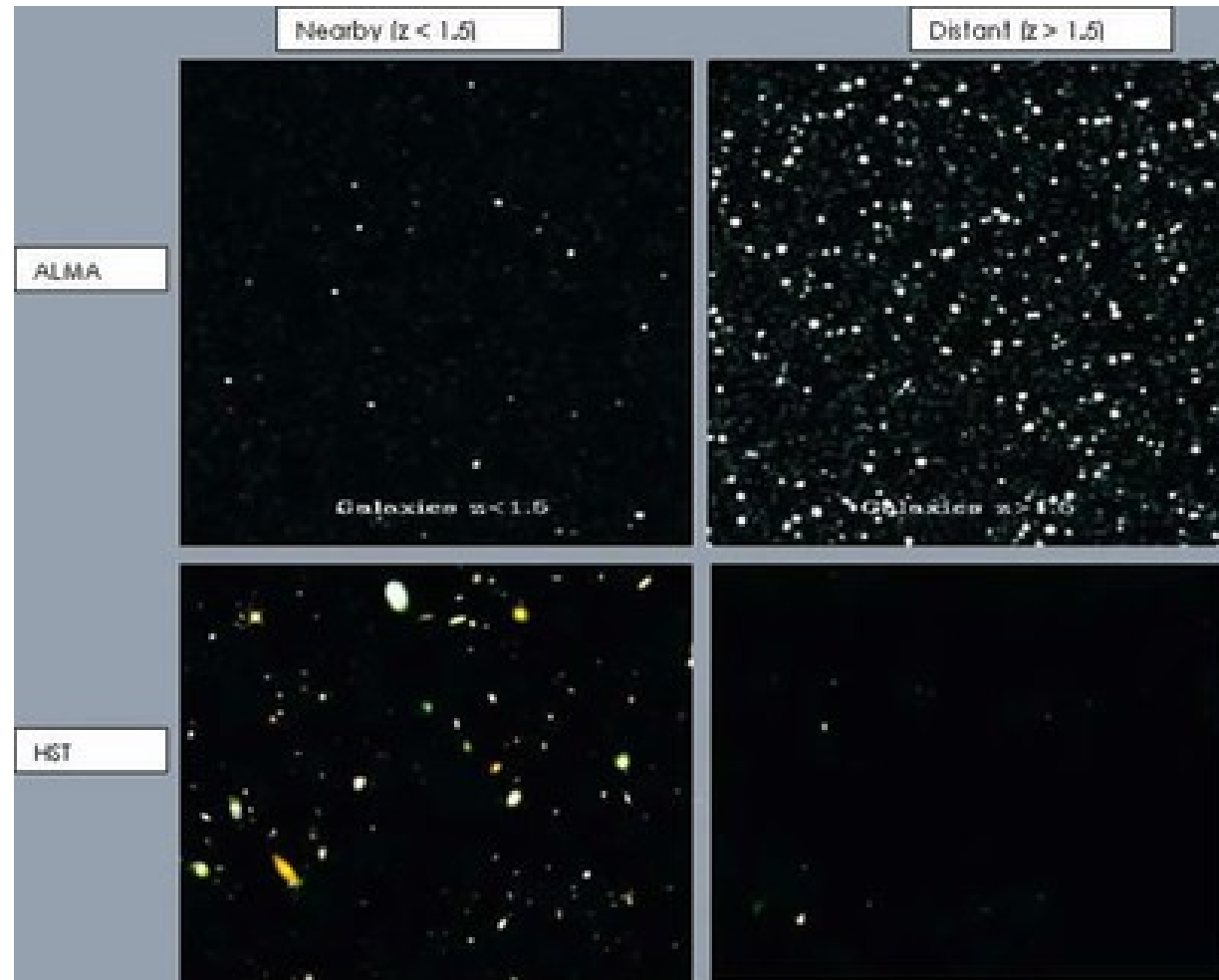
Here are parallel pictures of the Horsehead Nebula in the optical/radio. The Horsehead Nebula at different wavelengths: in the optical, dust obscures star-forming activity. In the infrared, the hot, thin layer of dust around the cloud glows.

At radio wavelengths, both dust and molecules glow, providing a wealth of information on regions that are otherwise invisible in the optical range.

ALMA Deep Field:

Most of the galaxies that will be detected in sensitive ALMA images will have large redshifts. This is illustrated in the top row that shows the number of low redshift ($z < 1.5$) and high redshift ($z > 1.5$) galaxies expected from a simulated deep ALMA observation. Although the high redshift galaxies are more distant, much more of the dominant emission from warm dust is redshifted into the ALMA frequency bands.

The bottom row shows that with an optical image, such as the Hubble Deep Field, most of the detections are of galaxies with $z < 1.5$. In stark contrast to the optical image, 80 percent of the ALMA detected galaxies will lie at high redshifts.



Top images from Wootten & Gallimore (2000, ASP Conf. Ser. Vol. 240, pg. 54).

Bottom images from K. Lanzetta, K. Moore, A. Fernandez-Soto, and A. Yahil (SUNY). © 1997 Kenneth M. Lanzetta.

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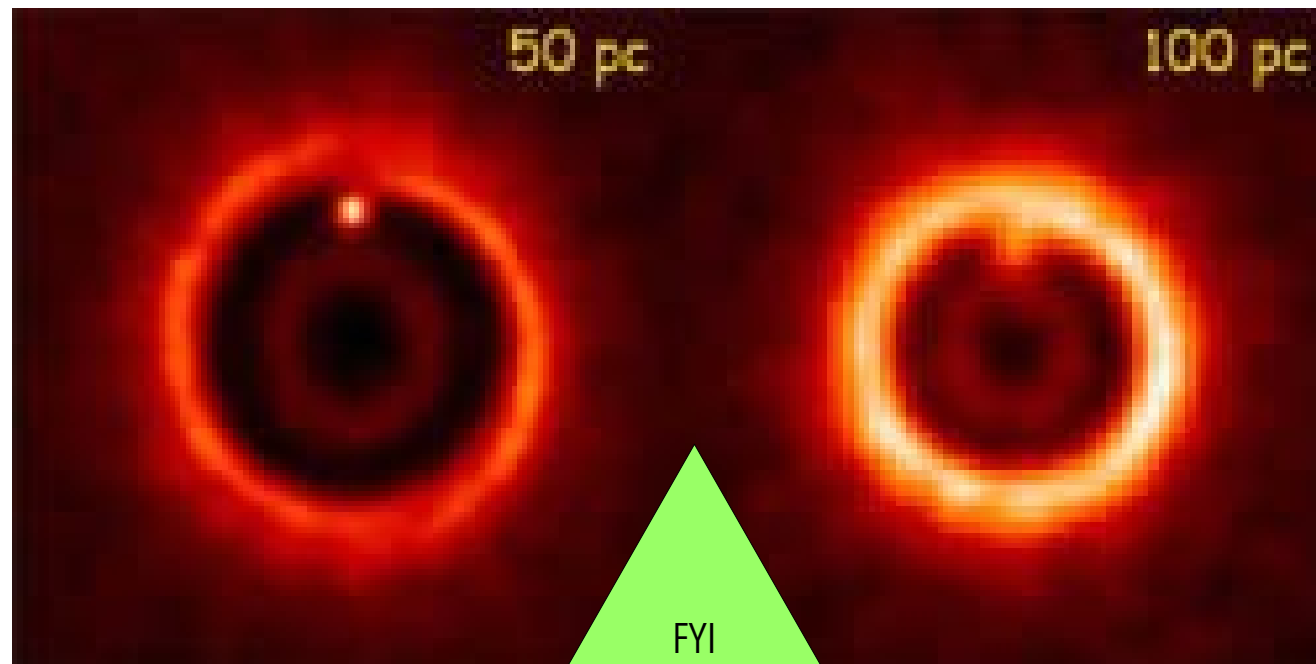
Star and Planet Formation

Star formation is the mechanism which controls the structure and evolution of galaxies, the buildup of heavy elements in the Universe with time, and which is responsible for the creation of the planetary environments in which life in the universe has become possible.

ALMA will be unique in its ability to detect the signature of proto-stellar collapse on solar-system size scales. We know that star formation involves gravitational collapse, but infall motions forming a new star have yet to be found. To observe unambiguous evidence for collapse, we require high spatial and velocity resolution (to map the velocity field across small structures) and high sensitivity (to take advantage of the spatial and velocity resolution). Furthermore, this must be available at a wavelength at which the collapsing object emits, and at which the surrounding material is transparent. Of current and planned instruments, only ALMA has these characteristics.

Further, ALMA will be ideal for studying the diversity of objects and physical processes involved in star formation. Its excellent mapping precision will allow astronomers to study the characteristics of parent molecular clouds from which stars form. Its sensitivity, angular and velocity resolution, and high frequency performance will allow the study of smaller structures, including proto-stellar fragments, outflows, and disks.

A simulation (Wolf & D'Angelo 2005) of ALMA observations at 950 GHz of a disc shows an embedded protoplanet of 1 Jupiter Mass around a 0.5 Solar Mass star (orbital radius: 5AU). The assumed distance is 50 pc or 100 pc as labeled. The disc mass is set to that of the Butterfly Star (IRAS 04302+2247) in Taurus. Note the reproduced shape of the spiral wave near the planet and the slightly shadowed region behind the planet in the left image. Image courtesy S. Wolf.



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Detecting Extrasolar Planets with ALMA

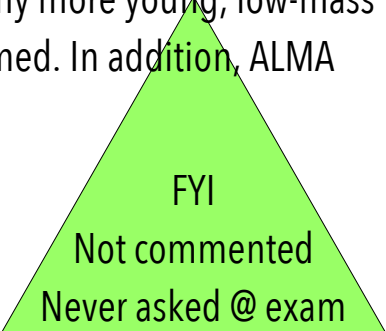
Detecting planets circling other stars is a particularly difficult task. In order to answer fundamental questions about planetary systems, such as their origin, their evolution, and their frequency in the Universe, scientists need to find and study many more extrasolar planets. According to scientists, ALMA will provide valuable information about extrasolar planetary systems at all stages of their evolution.

Millimeter and submillimeter waves occupy the portion of the electromagnetic spectrum between radio microwaves and infrared waves. Telescopes for observing at mm & submm wavelengths make use of advanced electronic equipment similar to that used in radio telescopes observing at longer wavelengths.

Millimeter/submillimeter-wave observations offer a number of advantages in the search for extrasolar planets. Multi-antenna mm/submm-wave telescope such as ALMA can provide much higher resolving power, or ability to see fine detail, than current optical or infrared telescopes. Observations in mm & submm wavelengths would not be degraded by interference from the "zodiacal light" reflected by interplanetary dust, either in the extrasolar system or our own solar system. Another important advantage is that, at mm & submm wavelengths, the star's brightness poses less of a problem for observers because, while it is still brighter than a planet, the difference in brightness between the two is far less. Because of the physical nature of the objects themselves, proto-planets in different stages of formation could readily be detected by ALMA.

ALMA is capable of imaging planetary systems in the earliest stages of their formation. It can also detect many more young, low-mass stellar systems and examine them to determine if they have the disks from which planetary systems are formed. In addition, ALMA could be used to examine the properties of these disks in detail.

The properties that could be examined include size, temperature, dust density and chemistry.

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FYI
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Evolved Stars and dust

Large surveys of emission from the carbon monoxide (CO) molecule and other molecules show that evolved stars are losing mass in the form of stellar winds at relatively low outflow speeds like 20 km/s. The current observations suggest that, roughly speaking, the winds are isotropic and that the mass loss rates and outflow velocities are constant with time. Mass loss rates are derived by model fitting to observed CO profiles, to OH maser radii, to IR spectra and to HI and optical measurements. Generally, the values agree fairly well, so that in principle one should be able to study mass loss as a function of stellar parameters, in particular of location on the Hertzsprung-Russell (HR) diagram. As is the case with evolutionary studies in general, observations of very large numbers of stars will be required, perhaps of thousands of stars.

Stardust: Molecules escape a dying star

Winds from cool evolved stars are probably the dominant source of refractory dust grains in the interstellar medium. They are the stardust from which we and our planet was formed. The grains manifest themselves through thermal emission extending from the far infrared through mm-wavelengths. At around 1 mm wavelength the emission is certainly optically thin, so that high-resolution maps of the thermal continuum from such winds will be an excellent tracer of the dust distribution. The high continuum sensitivity of the Atacama Large Millimeter/submillimeter Array (ALMA) will make possible direct imaging of the dust condensation zone for giant (AGB) stars within a few hundred parsecs at resolutions $< 0.1''$. High-frequency performance of the ALMA is especially critical here, since the dust emission increases at least like ν^3 and since the angular resolution scales as $\nu^{2.1}$. Grain growth is expected to be most rapid at distances of a few $\times 10^{14}$ cm, so such observations will require the best possible resolution.

The ALMA will measure the angular sizes of circumstellar CO envelopes which will result in statistical studies of the distances to evolved (old) stars. Careful measurements of the angular extents of nearby evolved stars, whose distances may be known by independent means, will yield a typical linear size for the CO emitting regions; in these bloated aged stars, this can amount to thousands of times the distance from the Earth to the Sun. Statistical distance estimates of other stars can then be made by synthesis imaging with the ALMA. At resolutions of approximately $0.1''$, the ALMA can image CO envelopes well beyond the distance to the Galactic center. An interesting project will be to compare the distances measured in this manner with kinematic distances for the same objects, since the centroid of the CO profile is an excellent indicator of the stellar radial velocity, ALMA data will also provide the input for the kinematic distance determinations. Measurements of distances to a large numbers of these objects will indicate their spatial density and distribution in the Galaxy.

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The high resolution available with the millimeter array will allow the detailed study of many such shells. This will allow the study of photochemistry in these environments; it will allow the observation of the shell kinematics and it will allow an examination of the evolutionary history of the star during its transition to the PN stage, since the molecular shell was emitted during the AGB phase and therefore contains information about that phase. Finally, the measurement of the shell masses of a large number of planetary nebulae, coupled with an examination of their luminosities and galactic kinematics, should allow a good value to be set for the upper progenitor mass limit for a white dwarf stars, or, conversely, for the lower mass limit for supernova progenitors.

Astrochemistry

The first interstellar molecule was discovered serendipitously in 1934 in an optical absorption spectrum. The first radio detection was of OH, again in absorption, in 1963. Since then radioastronomers have discovered an increasing number of gas-phase molecules in the space between the stars as well as surrounding both old and young stars. The average gas density is about 1 atom cm^{-3} and the gas coexists with tiny dust particles. The interstellar gas and dust are concentrated into large regions known as molecular clouds. These clouds are the birthplaces of new stars. Even the highest interstellar densities are very low by laboratory standards, however, and atoms only rarely collide. In addition, the low temperature of most interstellar gas (10-50 K) means that most collisions do not lead to chemical reactions.

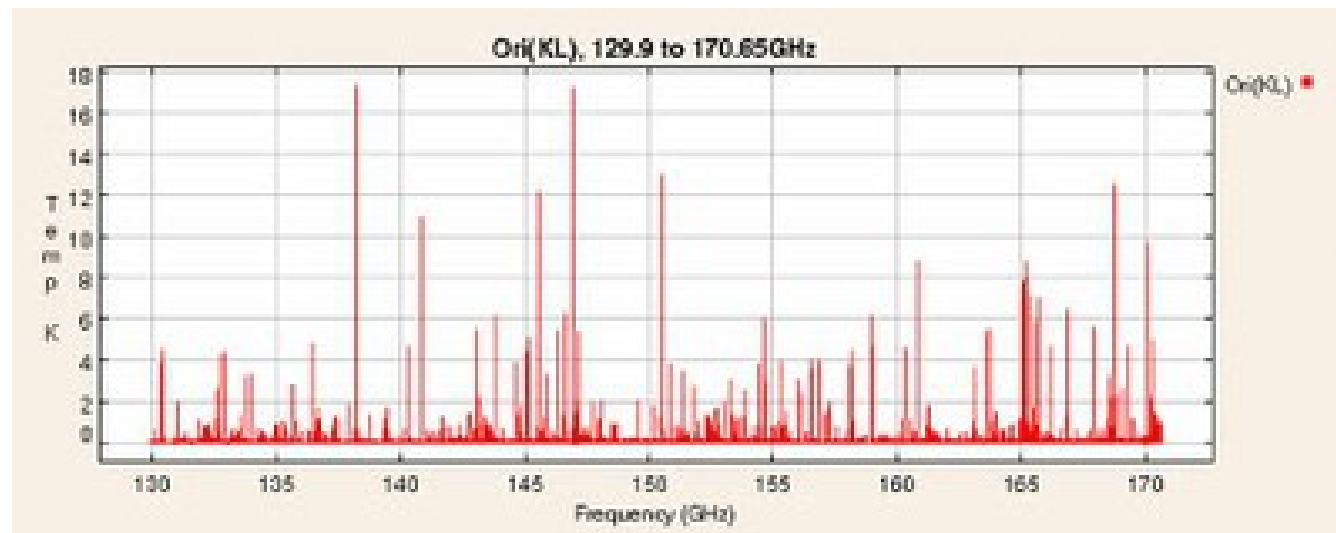
Molecules are synthesized very slowly from atoms by two mechanisms in interstellar clouds. Molecular hydrogen, the most abundant molecule in the gas phase, is formed when two hydrogen atoms stick to the surface of a dust grain and diffuse until they coalesce to form a molecule. Most molecules detected in the gas phase are, however, produced via sequences of special types of reactions known as ion-molecule reactions.

Gas-phase interstellar molecules are detected mainly by high-resolution radio astronomy observations. The molecules can be observed in emission as well as absorption. After colliding with other molecules they emit characteristic wavelengths of radiation, typically in the mm or submm wavelength range, that are associated with quantized levels of rotation of the molecules. Infrared astronomy is used to detect vibrationally excited molecules.

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More than 160 different kinds of molecules have been unambiguously detected, ranging in size from diatomic species to thirteen-atom species. After molecular hydrogen the most abundant molecule is carbon monoxide (CO), which astronomers use to map out interstellar clouds in nearby as well as in distant galaxies. Most of the molecules are organic (carbon-containing), comprising both standard organic molecules and a strange assortment of species unstable in the terrestrial environment. There is also evidence for much larger molecules such as polycyclic aromatic hydrocarbons, which resemble the soot from automobile emission. Broad visible spectra suggest the existence of large carbon cluster molecules, perhaps as straight chains or soccer-ball structures (fullerenes).

The widespread existence of varied forms of organic molecules in space could have interesting implications for life in the Universe. Our solar system is derived from an interstellar cloud, which collapsed to form the Sun, the planets, and all the smaller structures. Some of the molecules observed in space could have been involved in the early steps of the development of life.



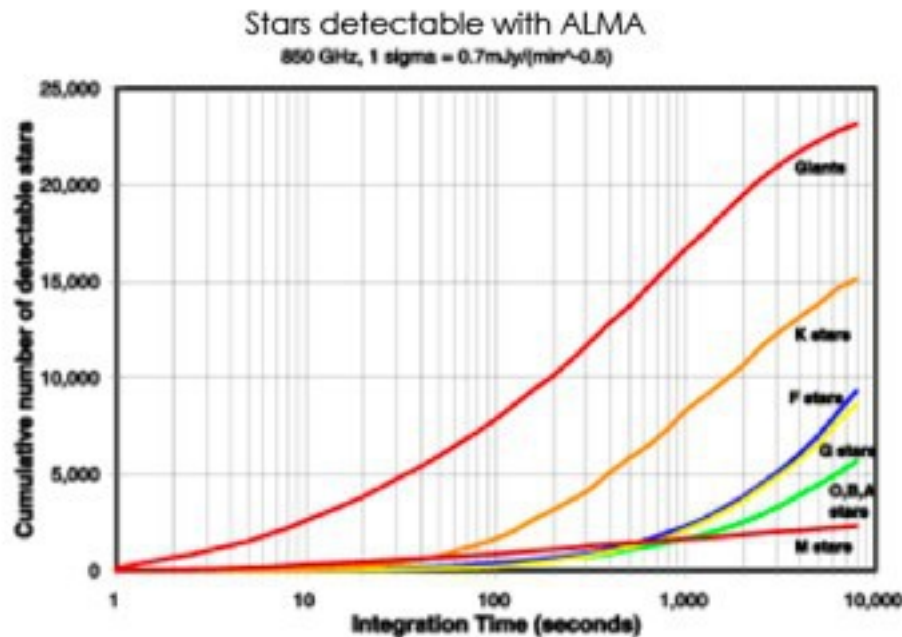
Most of the observed transitions of the 160 known interstellar molecules lie in the mm/submm spectral region. Here some 17,000 lines are seen in a small portion of the spectrum at 2mm. Spectrum courtesy B. Turner (NRAO).

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The Stars

ALMA will allow scientists to determine the radius and the rotation of stars and identify the chemical composition of dust being emitted from red supergiant stars (a star which is 10 to 1,000 times the diameter of our Sun, such as Betelgeuse).

One way in which a star is classified is by color (or spectra). Stars were first categorized in the 1890s by Annie Cannon. She used letters to classify the different spectra of light stars emitted. Originally the letters used were A through Q, since then, astronomers have narrowed and rearranged the classification index to the letters O, B, A, F, G, K, M. O representing the hottest stars and M the coolest.



Aside is a list of common stars and their attributes, the graph above represents how quickly the Atacama Large Millimeter Array will be able to detect these different stars.

Spectral Class	Color Emitted	Approximate Temperature	Star Example	Constellation
O	bluest	40,000K	Alnitak	Orion
			Mintaka	Orion
B	bluish	18,000K	Spica	Virgo
			Rigel	Orion
			Bellatrix	Orion
			Regulus	Leo
A	bluish-white	10,000K	Mimosa	Ursa Major
			Sirius	Canis Major
			Castor	Gemini
			Vega	Lyra
F	white	7,000K	Deneb	Cygnus
			Polaris	Ursa Minor
			Canopus	Carina
			Procyon	Canis Minor
G	yellowish-white	5,500K	Dabih	Capricorn
			Sadr	Cygnus
			The Sun	
			Capella	Auriga
K	orangish	4,000K	Muphrid	Bootes
			Nekkar	Bootes
			Matar	Pegasus
			Edasich	Draco
M	reddish	3,000K	Kochab	Ursa Minor
			Izar	Bootes
			Dubhe	Ursa Major
			Pollux	Gemini
			Aldebaran	Taurus
			Betelgeuse	Orion
			Mirach	Andromeda
			Menkar	Cetaurus
			Antares	Scorpio
			Scheat	Pegasus

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The Sun

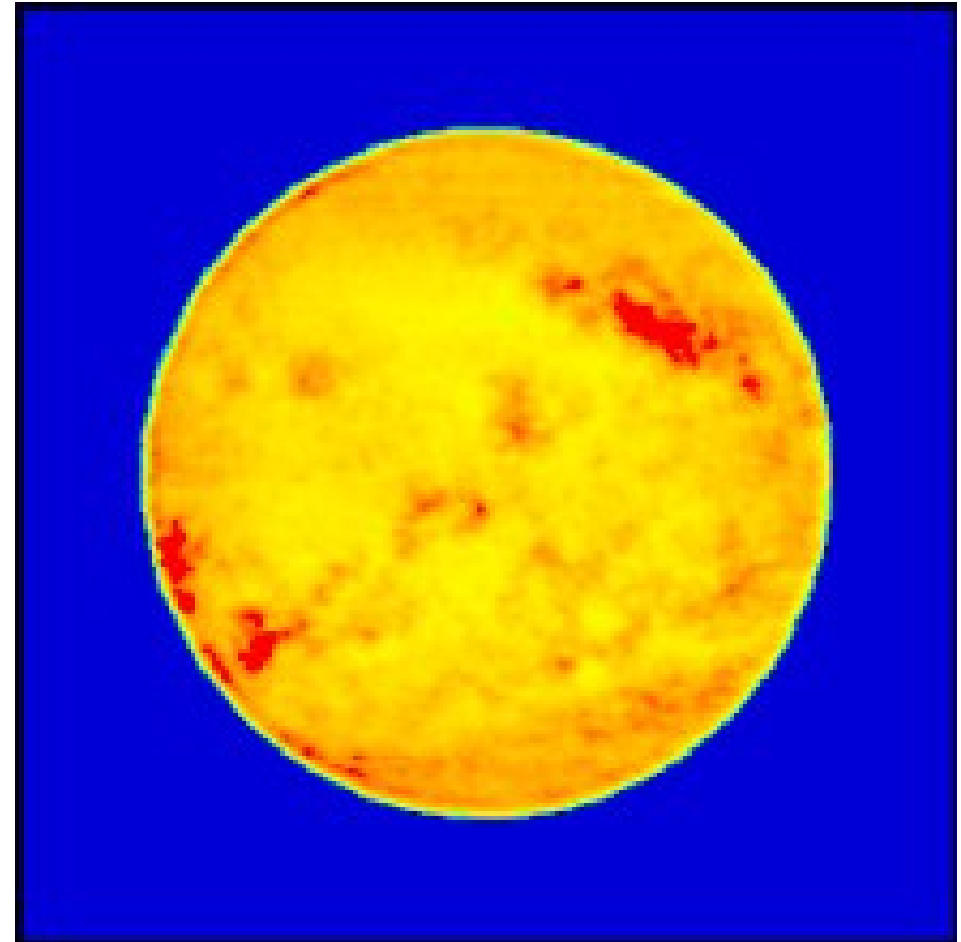
ALMA can observe a wide variety of phenomena on the Sun:

- * The structure of the quiet solar atmosphere.
- * Coronal holes (where vast solar winds originate because of diverging magnetic fields)
- * Solar active regions
- * Active and quiescent filaments
- * Energetic phenomena like filament eruptions and flares.

Significant progress will be made in the following scientific areas:

Flares: Solar flares involve the catastrophic release of energy in the low-solar corona which heats plasma and accelerates ions and electrons to relativistic energies on short timescales. The ALMA will probe emissions from the most energetic electrons, shedding light on the questions of when, where, and by what mechanism are electrons promptly accelerated to high energies.

Filaments: Solar prominences and filaments are, as their name suggests, large filamentary structures composed of relatively cold ($\sim 6500\text{K}$), dense plasma suspended in the hot, 3 million degree solar corona. They occur along magnetic neutral lines in both active and quiet regions of the Sun. Some simply fade away after a lifetime of days to weeks; others are expelled from the Sun in spectacular eruptions. Their birth and death is still mysterious in many ways. The ALMA will span those wavelengths at which filaments become optically thin. Their structure and evolution will be more accessible to the ALMA than any other instrument.



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Structure of the low solar atmosphere: One of the great mysteries of the Sun is why it has a solar corona. At the height of the photosphere (the visible surface of the Sun), the temperature is $\sim 5880\text{K}$. The temperature then decreases with height for several hundred kilometers. But then something amazing occurs: at greater heights, the temperature increases, gradually at first, and then suddenly to ~ 3 million degrees! The ALMA will probe the "temperature minimum" region of the manifest. By imaging this region of the solar atmosphere at various mm and submm wavelengths, the ALMA will offer a means of characterizing the structure and evolution of the low solar atmosphere and how that structure is maintained. The ALMA will also be able to exploit helioseismology to explore the details of the structure of the low solar atmosphere since the hydromechanical waves cause brightness variations in the mm and submm emission.

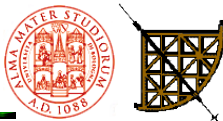
New spectral line diagnostics: At wavelengths longward of $\sim 1\text{mm}$, no spectral lines are available for diagnostic purposes. Pressure and Zeeman broadening (due to the presence of magnetic fields) is so extreme as to render them undetectable. At submm wavelengths, however, it should be possible to detect high- n radio recombination lines of hydrogen and certain ions. These offer the possibility of constraining the temperature, density, magnetic field strength, and mass motions in the low solar atmosphere, layers of the atmosphere that are inaccessible by other means.

ALMA Design Reference Science Plan

The ALMA Design Reference Science Plan (DRSP) is an exercise to see how ALMA can provide science results for a suite of high-priority prototype science projects. The projects assume that ALMA is completed and is thus not directly applicable for the Early Science phase. Note also that the DRSP projects are not approved for execution with ALMA. Nevertheless, the DRSP provides an overview of potential projects and how these can be accommodated within the ALMA design.

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Present/Future Instruments -2- ALMA : some scientific results



The Antennae Galaxies (also known as NGC 4038 and 4039) are a pair of colliding spiral galaxies about 70 million light-years away, in the constellation of Corvus (The Crow). This view combines ALMA observations, made in two different wavelength ranges during the observatory's early testing phase, with visible-light observations from the NASA/ESA Hubble Space Telescope.

The Hubble image is the sharpest view of this object ever taken and serves as the ultimate benchmark in terms of resolution. ALMA observes at much longer wavelengths which makes it much harder to obtain comparably sharp images. However, when the full ALMA array is completed its vision will be up to ten times sharper than Hubble.

Most of the ALMA test observations used to create this image were made using only twelve antennas working together — fewer than will be used for the first science observations — and much closer together as well. Both of these factors make the new image just a taster of what is to come. As the observatory grows, the sharpness, efficiency, and quality of its observations will increase dramatically as more antennas become available and the array grows in size. This is nevertheless the best submillimeter-wavelength image ever taken of the Antennae Galaxies and opens a new window on the submillimeter Universe.

While visible light — shown here mainly in blue — reveals the newborn stars in the galaxies, ALMA's view shows us something that cannot be seen at those wavelengths: the clouds of dense cold gas from which new stars form. The ALMA observations — shown here in red, pink and yellow — were made at specific wavelengths of millimeter and submillimeter light (ALMA bands 3 and 7), tuned to detect carbon monoxide molecules in the otherwise invisible hydrogen clouds, where new stars are forming.

Massive concentrations of gas are found not only in the hearts of the two galaxies but also in the chaotic region where they are colliding. Here, the total amount of gas is billions of times the mass of the Sun — a rich reservoir of material for future generations of stars. Observations like these will be vital in helping us understand how galaxy collisions can trigger the birth of new stars. This is just one example of how ALMA reveals parts of the Universe that cannot be seen with visible-light and infrared telescopes.

Credit: ALMA (ESO/NAOJ/NRAO). Visible light image: the NASA/ESA Hubble Space Telescope

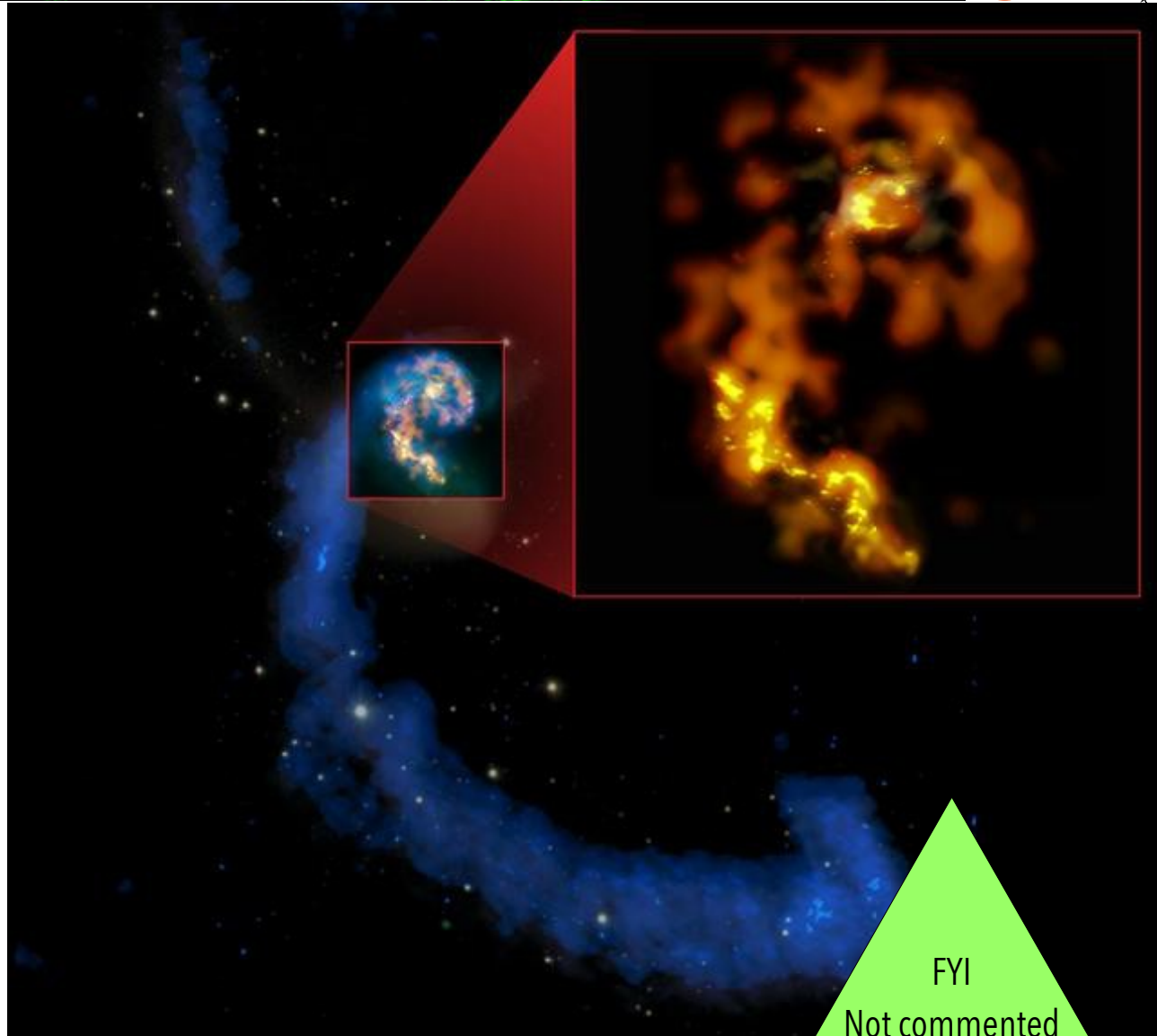


ALMA Early Science: The Antennae Galaxies

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*Multi-wavelength composite of interacting galaxies NGC 4038/4039, the Antennae, showing their namesake tidal tails in **radio (blue)**, past and recent star births in optical (whites and pinks), and a selection of current star-forming regions in mm/submm (orange and yellows). Inset: ALMA's first mm/submm test views, in Bands 3 (orange), 6 (amber), & 7 (yellow), showing detail surpassing all other views in these wavelengths.*



Credit:

(NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO); HST (NASA, ESA, and B. Whitmore (STScI)); J. Hibbard, (NRAO/AUI/NSF); NOAO/AURA/NSF.

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Visit the website <https://www.skatelescope.org> for updated information

SKA stands for Square Kilometre Array. It is expected to start operations around 2020. It consists of TWO Independent radio telescopes (interferometers) split into SKA-LOW (to be built in Western Australia) and SKA-HIGH (to be built in South Africa and neighboring countries)

SKA specifications

FREQUENCY RANGE ~ 100 MHz TO 10 GHz

SENSITIVITY 400 μ Jy IN 1 MINUTE) between 70 AND 300 MHz

FIELD-OF-VIEW 200 SQUARE DEG BETWEEN 100 AND 300 MHz

1-200 SQUARE DEGREES BETWEEN 0.3 AND 1 GHz

1 SQUARE DEGREE MAXIMUM BETWEEN 1 AND 10 GHz

ANGULAR RESOLUTION <0.1 ARCSECOND

INSTANTANEOUS BANDWIDTH BAND CENTRE \pm 50% SPECTRAL (FREQUENCY) CHANNELS 16 384 PER BAND PER BASELINE

CALIBRATED POLARISATION PURITY 10 000:1 SYNTHESISED IMAGE DYNAMIC RANGE >1 000 000

FINAL PROCESSED DATA OUTPUT 10 GB/SECOND

Nowadays a number of pathfinders and precursors are on place to prepare the way to SKA

Pathfinders

Pathfinder telescopes and systems, dotted around the globe are also engaged in SKA related technology and science studies. These include the famous Arecibo radio telescope in Puerto Rico, which starred in the James Bond movie "Goldeneye", the LOFAR low-frequency array, which is based in Europe, and the EVLA, in North America, which was famously seen in the hit movie "Contact". Here is a list of SKA Pathfinders;

- APERTure Tile In Focus (APERTIF), The Netherlands
- Arecibo Observatory, Puerto Rico
- Allen Telescope Array (ATA), USA
- electronic European VLBI Network (eEVN), Europe
- Electronic MultiBeam Radio Astronomy ConcEpt (EMBRACE), France & The Netherlands
- e-MERLIN, UK
- Expanded Very Large Array (EVLA), USA
- Giant Metrewave Radio Telescope (GMRT), India
- Low Frequency Array (LOFAR), The Netherlands
- Long Wavelength Array (LWA), USA
- NenuFAR, France
- Parkes Telescope, Australia
- SKA Molonglo Prototype (SKAMP), Australia

Nowadays a number of pathfinders and precursors are on place to prepare the way to SKA

Precursor facilities

Australian SKA Pathfinder (ASKAP)	http://www.atnf.csiro.au/projects/askap/index.html
MeerKAT	http://www.ska.ac.za/gallery/meerkat/
Murchinson Widefield Array (MWA)	http://www.mwatelescope.org
Hydrogen Epoch of Reionization (HERA)	http://reionization.org

Precursor telescopes like the South African MeerKAT and HERA, along with the Murchison Widefield Array (MWA) and CSIRO's Australian SKA Pathfinder (ASKAP) are providing SKA scientists with invaluable knowledge to assist in the design of the SKA's main telescopes over the coming decade.

Located at future SKA sites, these precursors are and will be in future carrying out scientific study related to future SKA activities, as well as helping the development and testing of new crucial SKA technologies.

The science driving the construction of SKA is available at <https://skatelescope.org/science/>
Where there is a link to a pdf (pptx) presentation where the state of the art is reported on.

A double volume (>2000 pages, 8.8 kg) contains the science cases worked out by the
Astronomical community.

The Square Kilometre Array (SKA)

Low-frequency detectors (1 Million when completed!)



High-frequency dishes

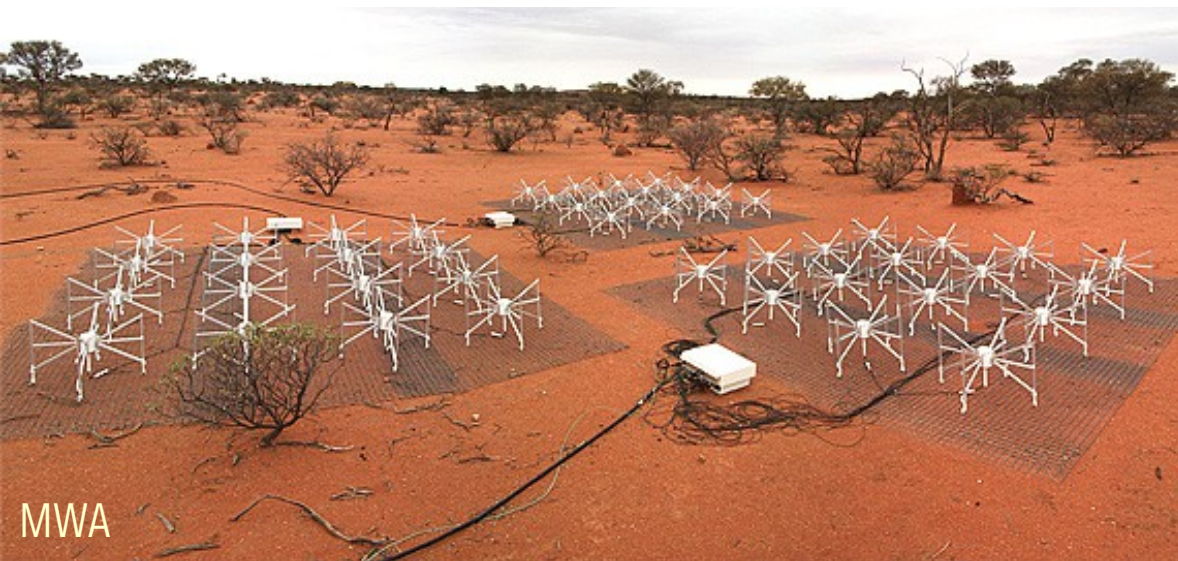
ASKAP



MEERKAT



The most updated news can be obtained visiting the websites of each instrument.
In particular, for precursors and pathfinders, visit the MWA, LOFAR sites where substantial scientific results are already available (e.g. LoTSS and GLEAM surveys)



- A radio telescope has (\sim) the same basic structure of an optical telescope (mirror(s), detectors, recorders)
- It works at the diffraction limit of the aperture (D =diameter), but its resolution is disfavored by λ/D
It samples the FT of the sky brightness.
- Interferometers overcome the low resolution problem. The FoV of the elements of the interferometer determine the FoV of the interferometer.
- Modern interferometers are made of cheap collectors (or array of collectors) and complex and expensive electronics and computing power.
- From 10(s) of MHz (e.g. LOFAR) up to 100s of GHz (e.g. ALMA), the radio-submm sky is being investigated with unprecedented detail [...waiting for SKA **1**?00MHz – 30 GHz]