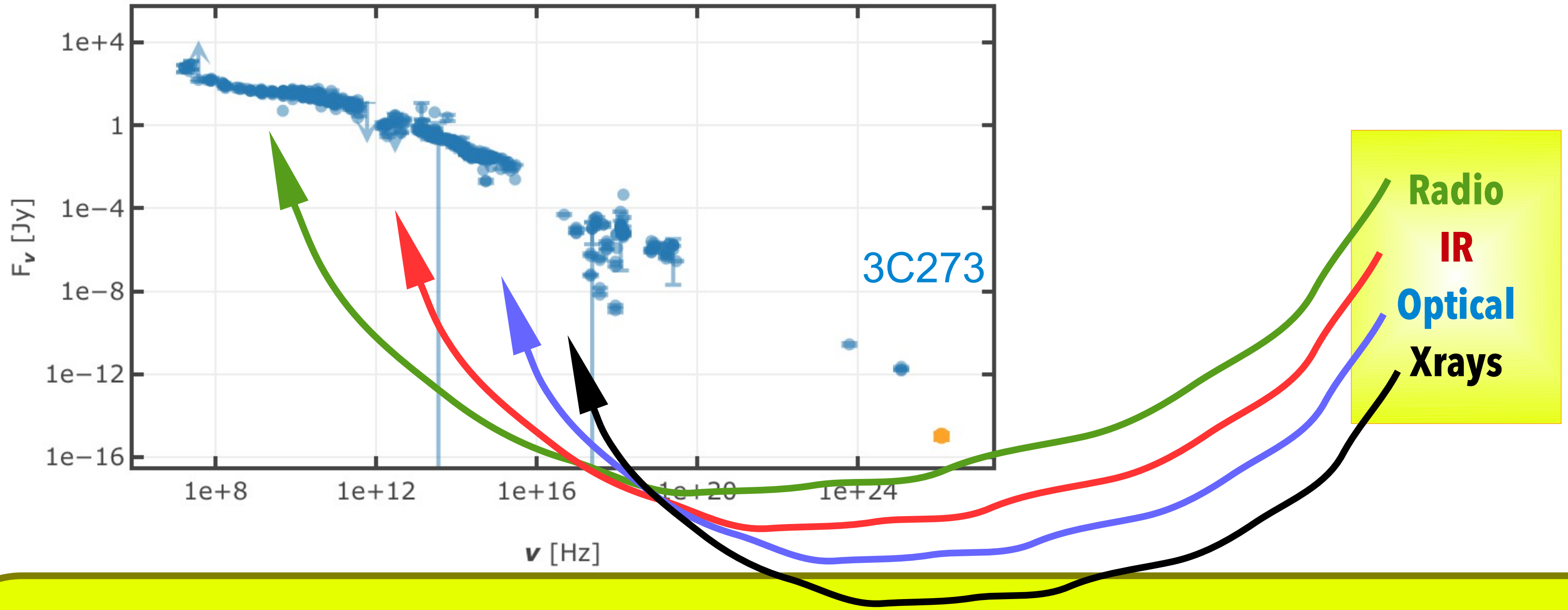
Instruments for Radioastronomy

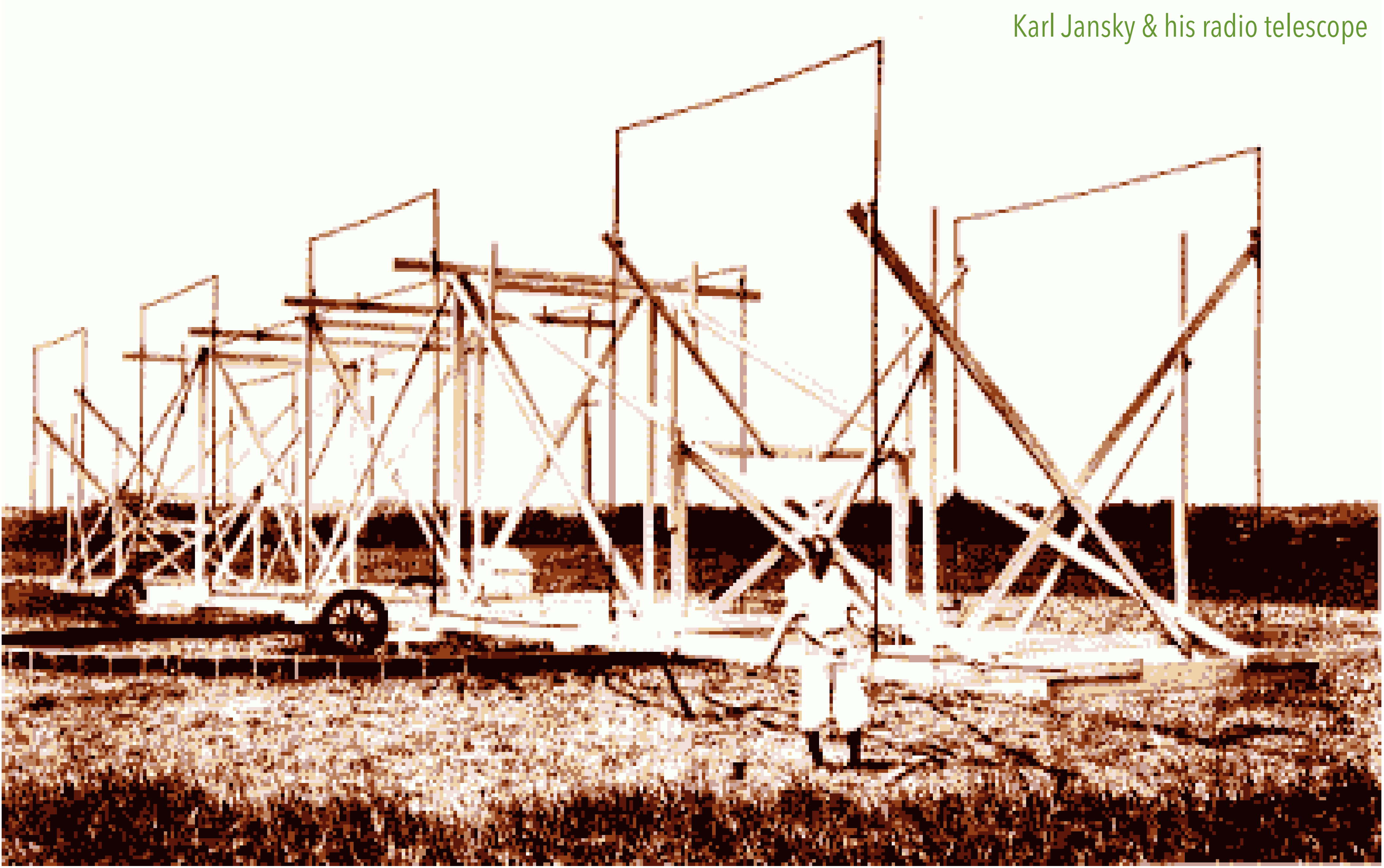
(current & future)

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



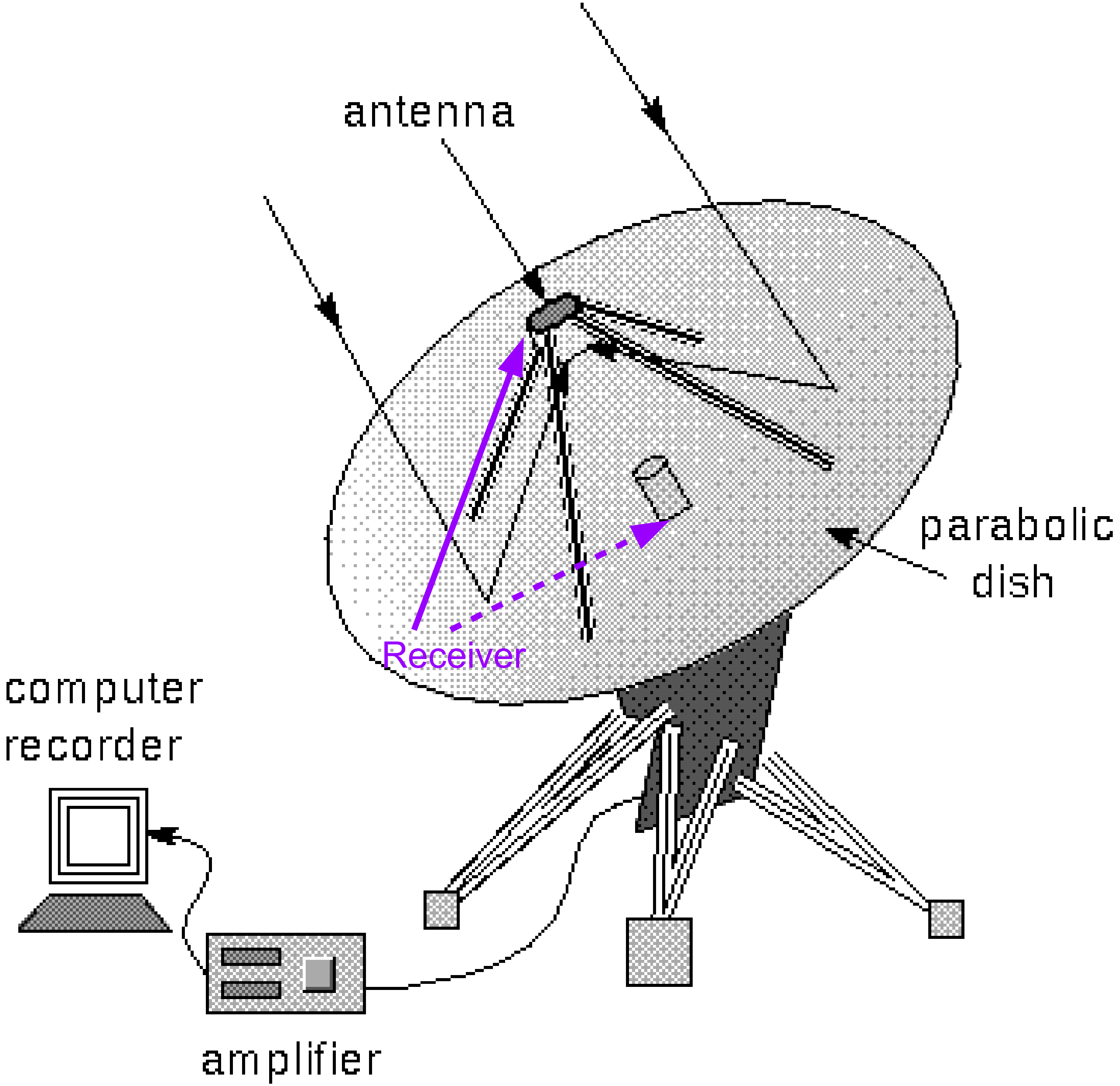
1. Photons do not possess enough energy to produce photoelectric effect
2. There are lot of photons!
3. Wave formalism applies
4. Fraunhofer theory applies
5. Detectors are different from other observing bands/windows

Once upon a time: the first radio telescope



Karl Jansky & his radio telescope

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



Elements of a Radio Telescope -1-

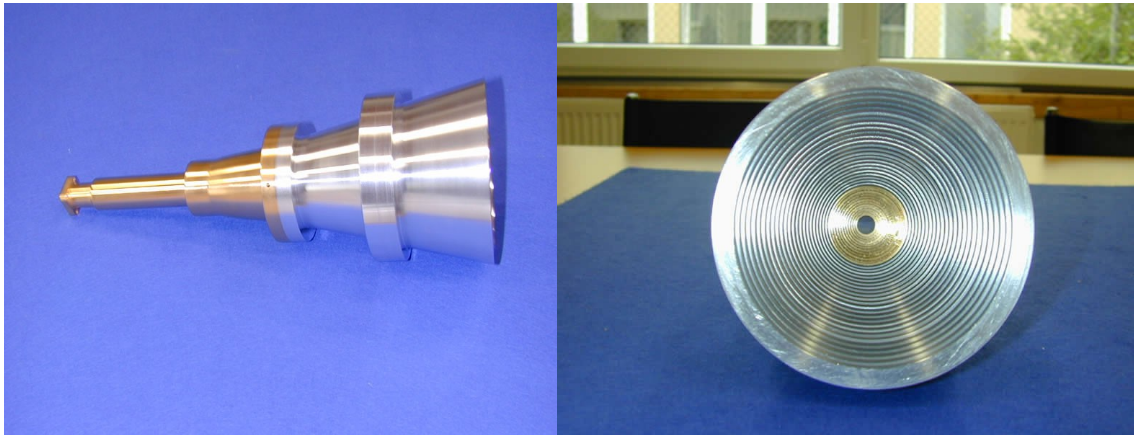
Detection of low-energy radiation:

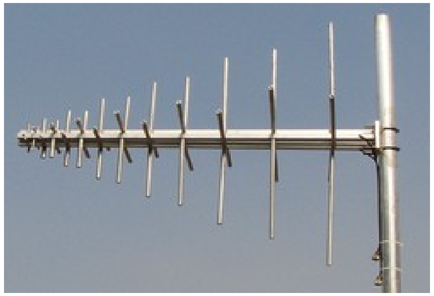
use the wave formalism (not enough energy for photoelectric effect)

Hardware:

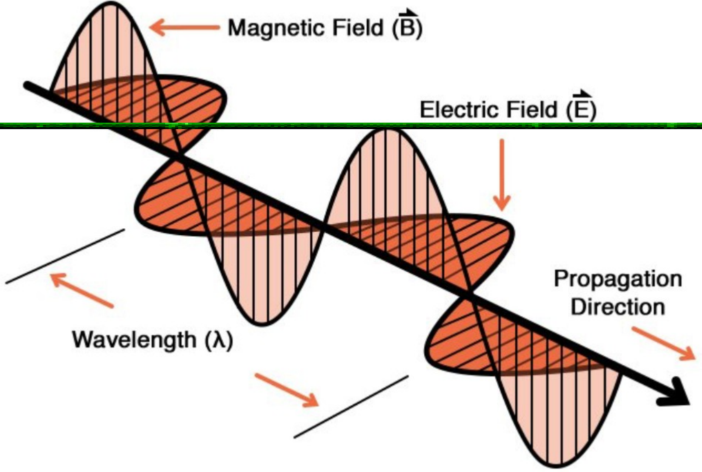
A (main) **mirror/collector,** a secondary mirror (subreflector) and possibly more, drive the radiation onto a given place (focus).

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).





Elements of a Radio Telescope – 2 –



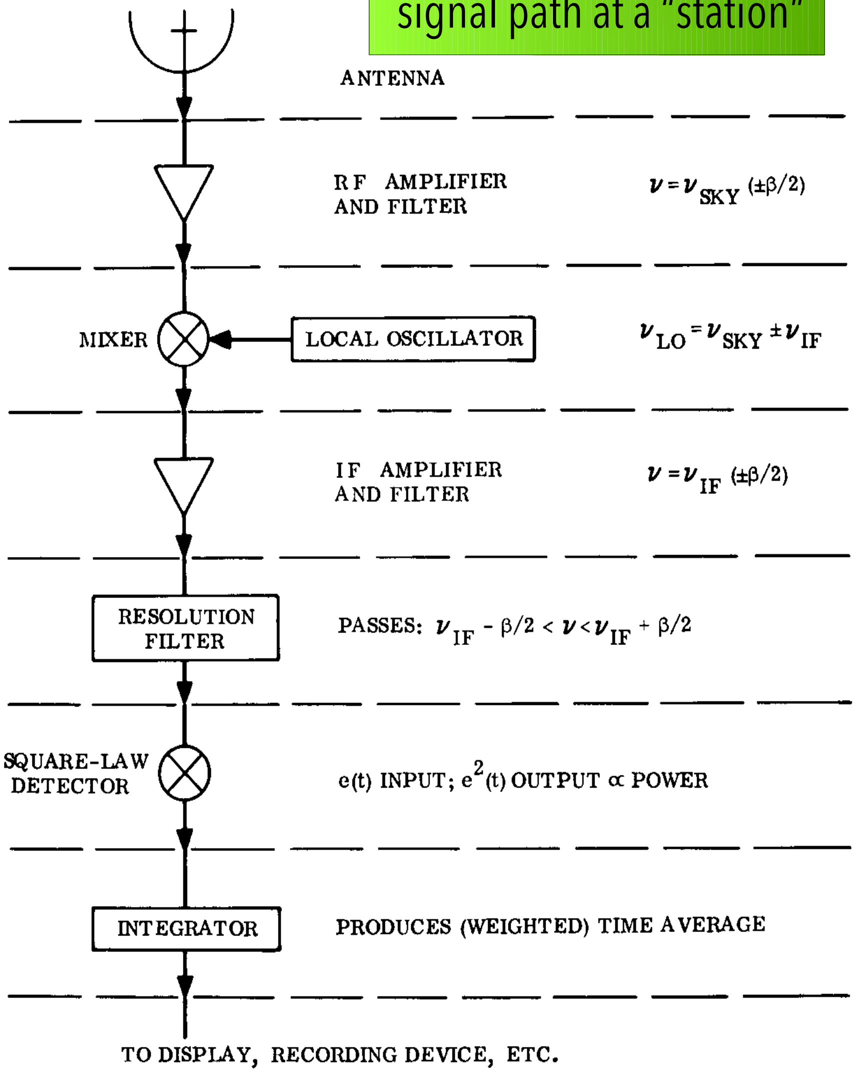
Incoming signal is an e-m wave:
E & B fields oscillate @ ~10s of MHz to ~10s of GHz

- Sampled faster than @ Nyquist rate (2 x frequency)
- If broadband (& wide field) obs, then the full bandwidth has sub-bands [IFs (spws) and channels]
- **Dual polarization** (X + Y, or R + L)

$$V(t)_R = E^o_R \sin(\omega t + \phi_R)$$

$$V(t)_L = E^o_L \sin(\omega t + \phi_L)$$

Simple scheme of the signal path at a “station”



ANTENNA

RF AMPLIFIER AND FILTER $\nu = \nu_{SKY}\ (\pm\beta/2)$

MIXER

LOCAL OSCILLATOR $\nu_{LO} = \nu_{SKY} \pm \nu_{IF}$

IF AMPLIFIER AND FILTER $\nu = \nu_{IF}\ (\pm\beta/2)$

RESOLUTION FILTER

PASSES: $\nu_{IF} - \beta/2 < \nu < \nu_{IF} + \beta/2$

SQUARE-LAW DETECTOR

e(t) INPUT; e^2(t) OUTPUT $\propto$ POWER

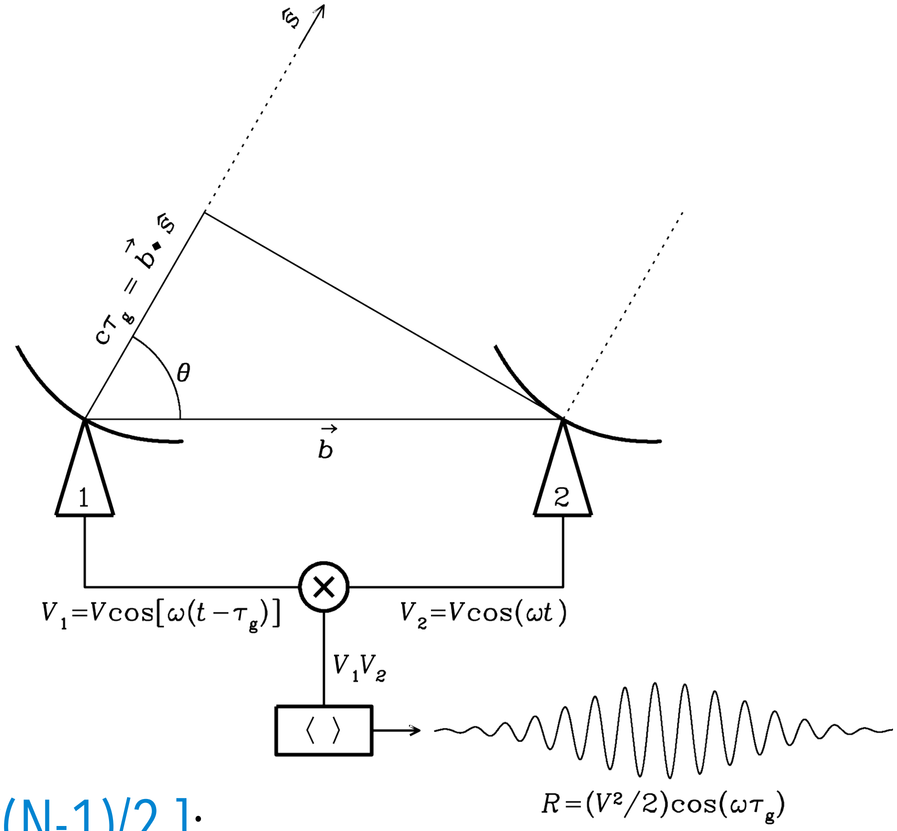
INTEGRATOR

PRODUCES (WEIGHTED) TIME AVERAGE

TO DISPLAY, RECORDING DEVICE, ETC.

Relevant facts

- 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(ϑ,φ)**

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)

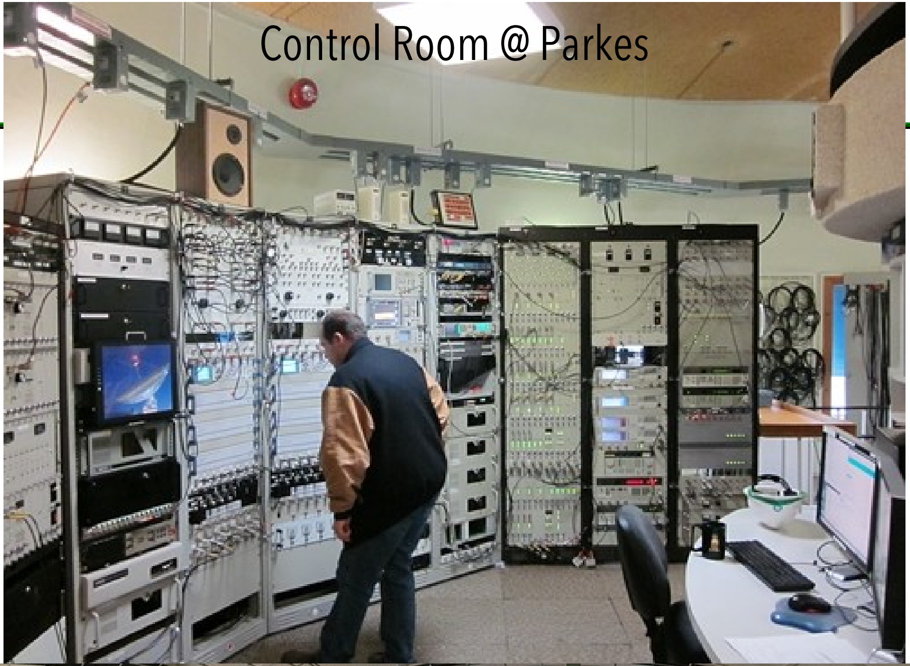
$$V(t)^i_R = E^o_R \sin(\omega t + \phi_R)$$

$$V(t)^i_L = E^o_L \sin(\omega t + \phi_L)$$

For each i-th antenna

[Many antennas, real time ⟹ see aside]

[Many antennas, off-line (VLBI)]



Control Room @ Parkes

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.

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:

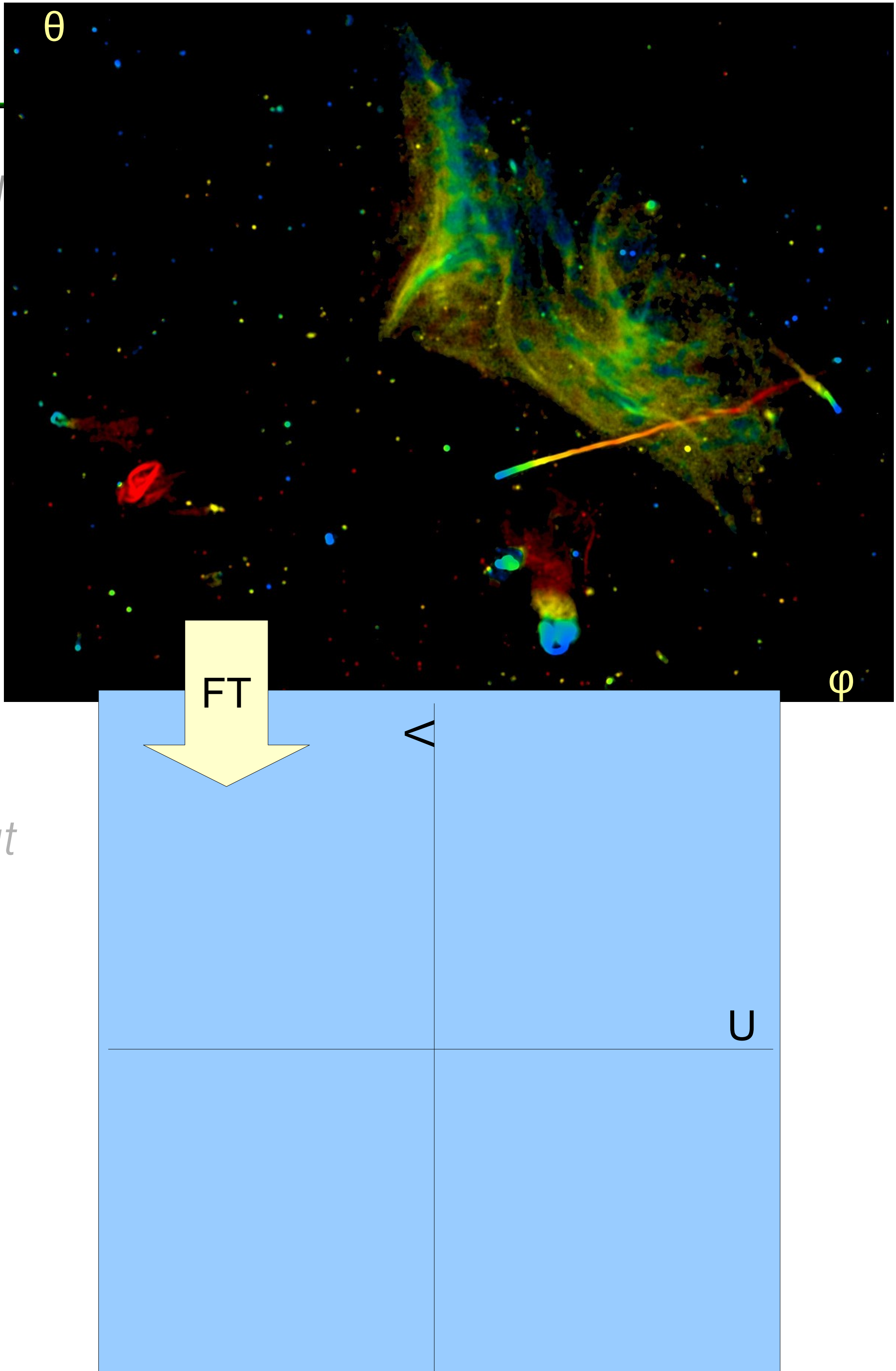
$$\Delta\vartheta \approx \lambda/B_{MAX}$$

- Radiotelescopes measure the visibility function

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

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)

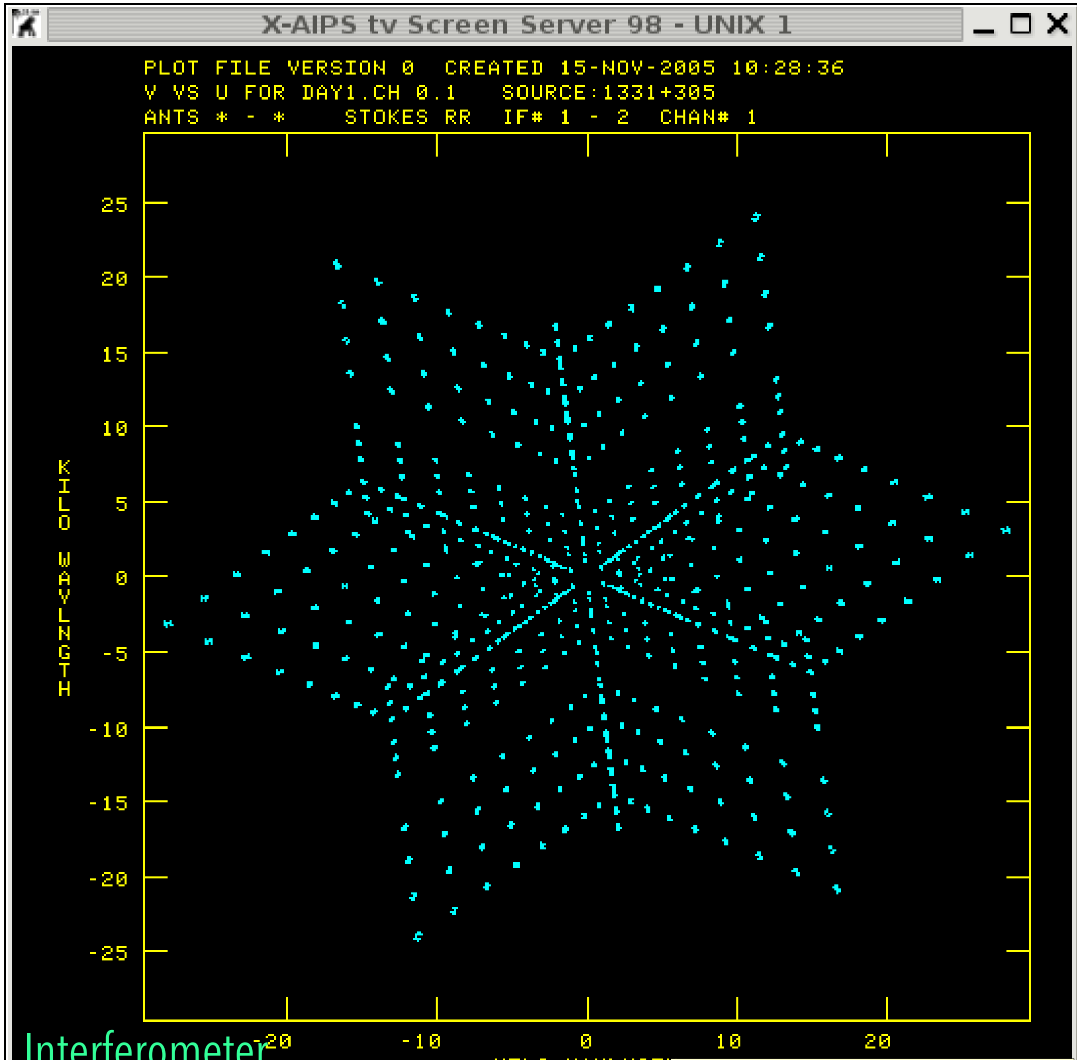
- **where the Visibility function is sampled**
  The best would be a continuous sampling
  A uniform/regular sampling is good!

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.



```
PLOT FILE VERSION 0  CREATED 15-NOV-2005 10:28:36
V VS U FOR DAY1.CH 0.1   SOURCE:1331+305
ANTS * - *     STOKES RR   IF# 1 - 2   CHAN# 1
FREQ = 8.1732 GHZ, BW = 15.625 MHZ
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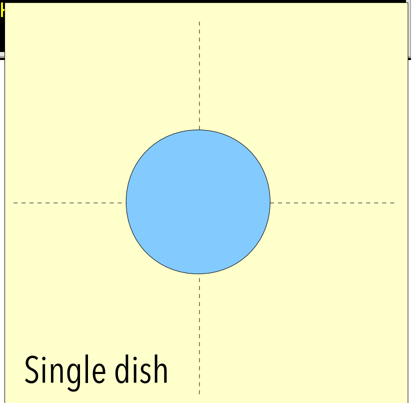
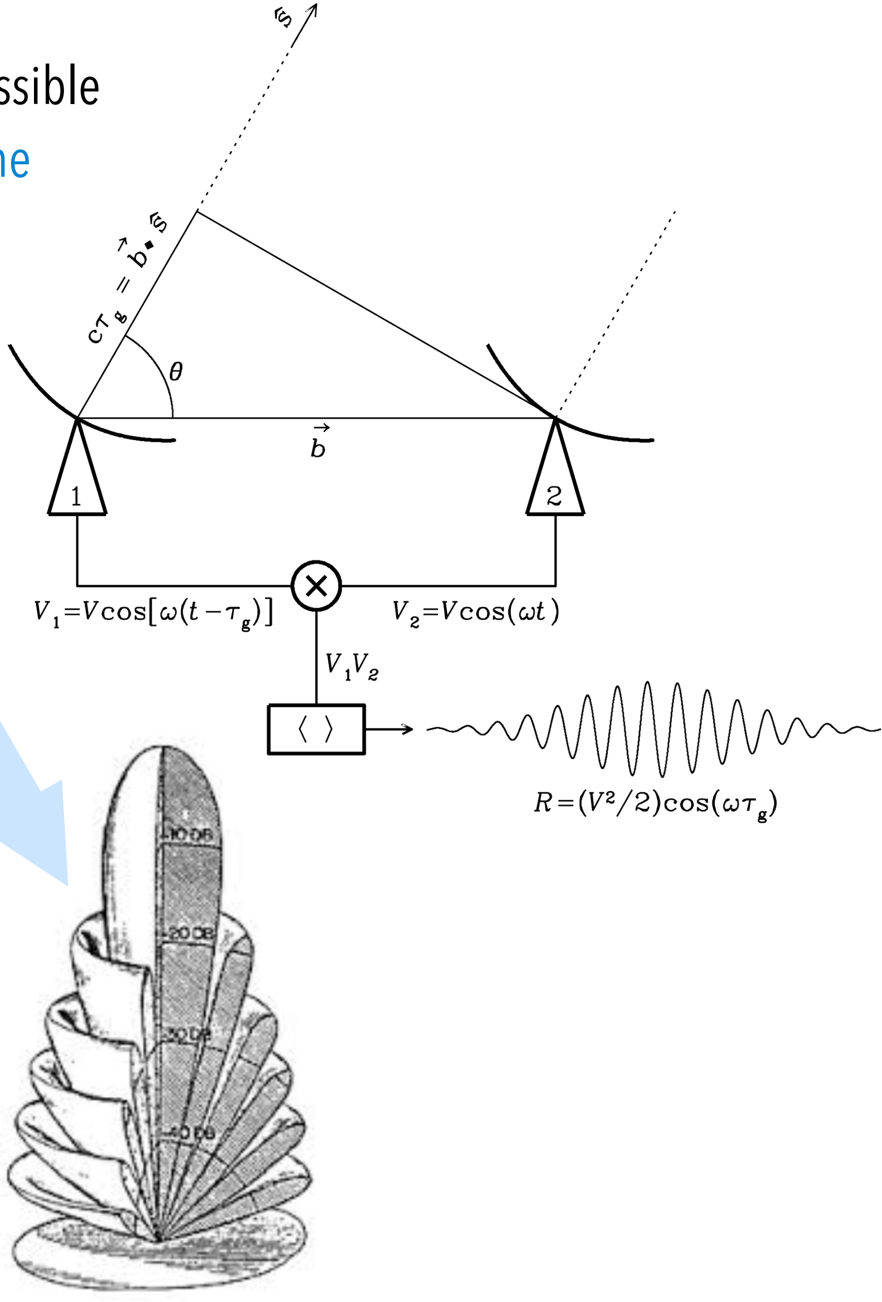
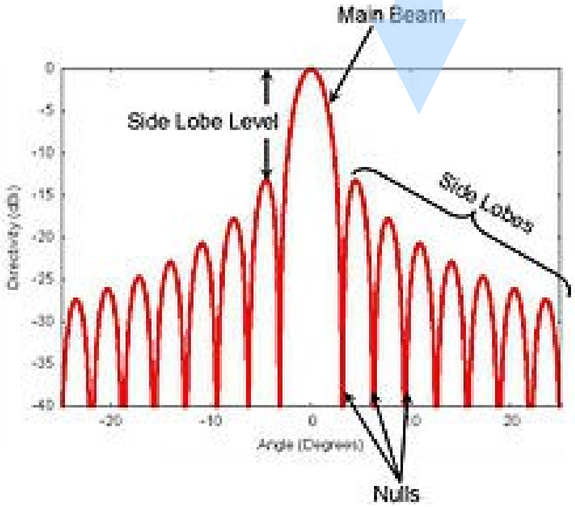


Relevant facts – 3 –

- 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 = $P_n(\vartheta,\varphi)$
- The generation of 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

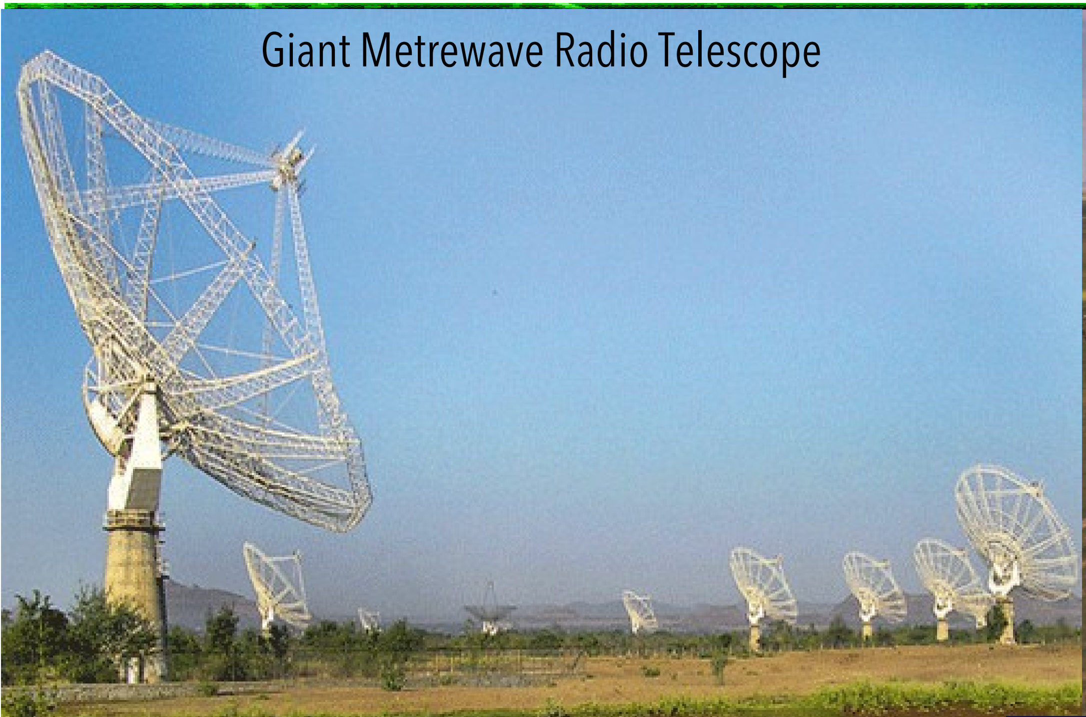
F is small !   Most detectors at secondary focus

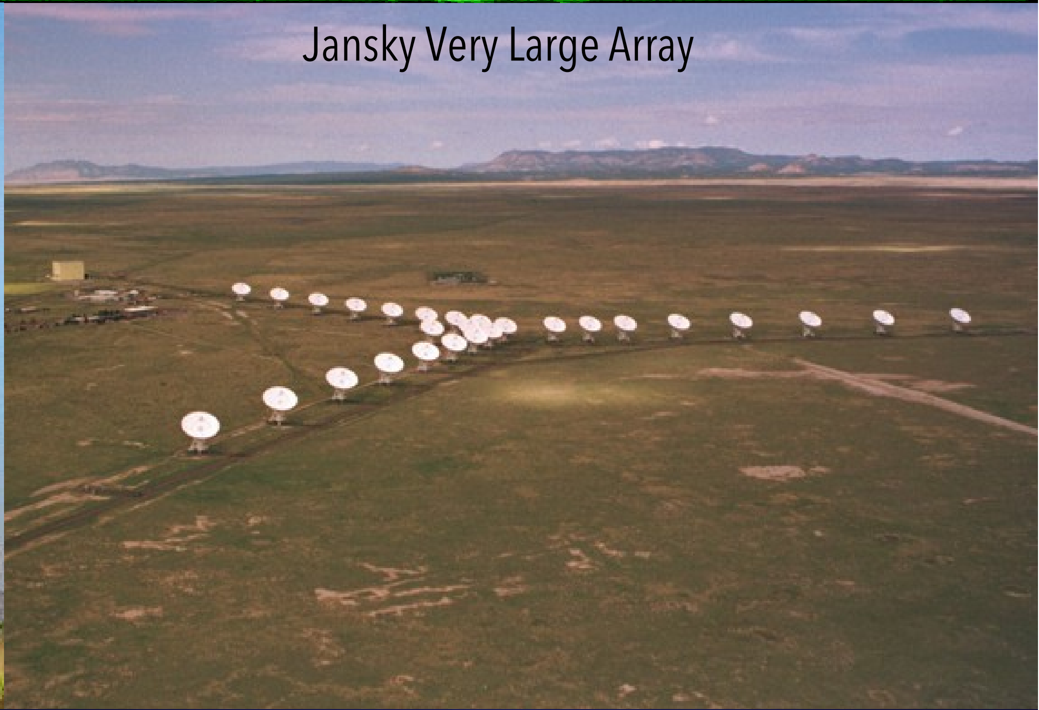
Sardinia Radio Telescope

Fast

Parkes (Australia) 64m

Interferometers


Giant Metrewave Radio Telescope

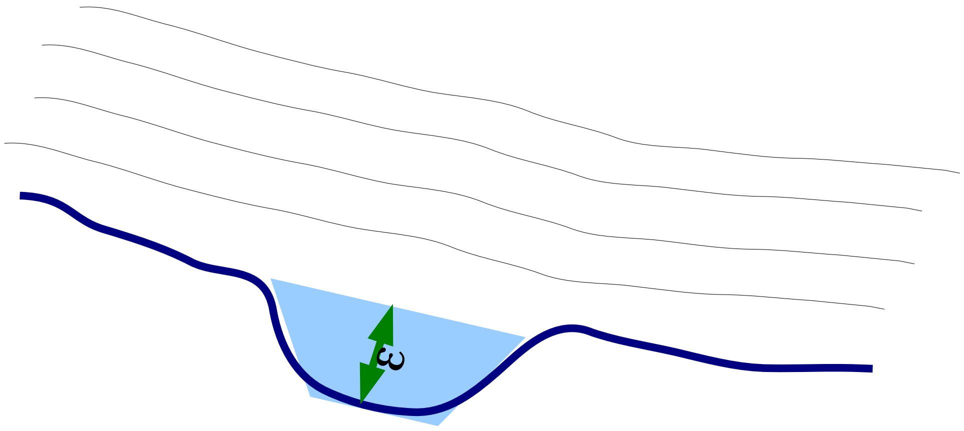

Jansky Very Large Array


Westerbork Synthesis Radio Telescope

Why the mirrors of telescopes may look that different each other?

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, $2\varepsilon/\lambda$) leading to a reduction of the coherence.

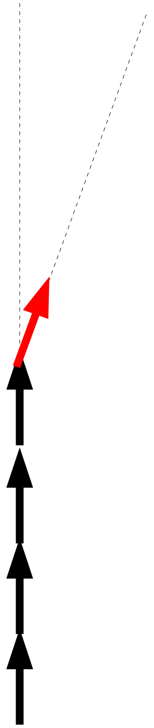
$$\delta = 2\times 2\pi\left(\frac{\epsilon}{\lambda}\right)$$



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

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

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



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

surface accuracy -2-

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

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

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

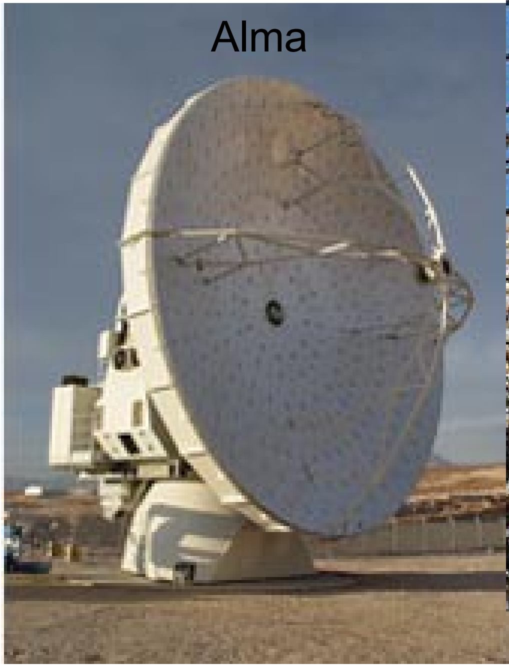
therefore , conservatively, one can chose $\lambda_{min} = 20\varepsilon$.

Reflecting surface:

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

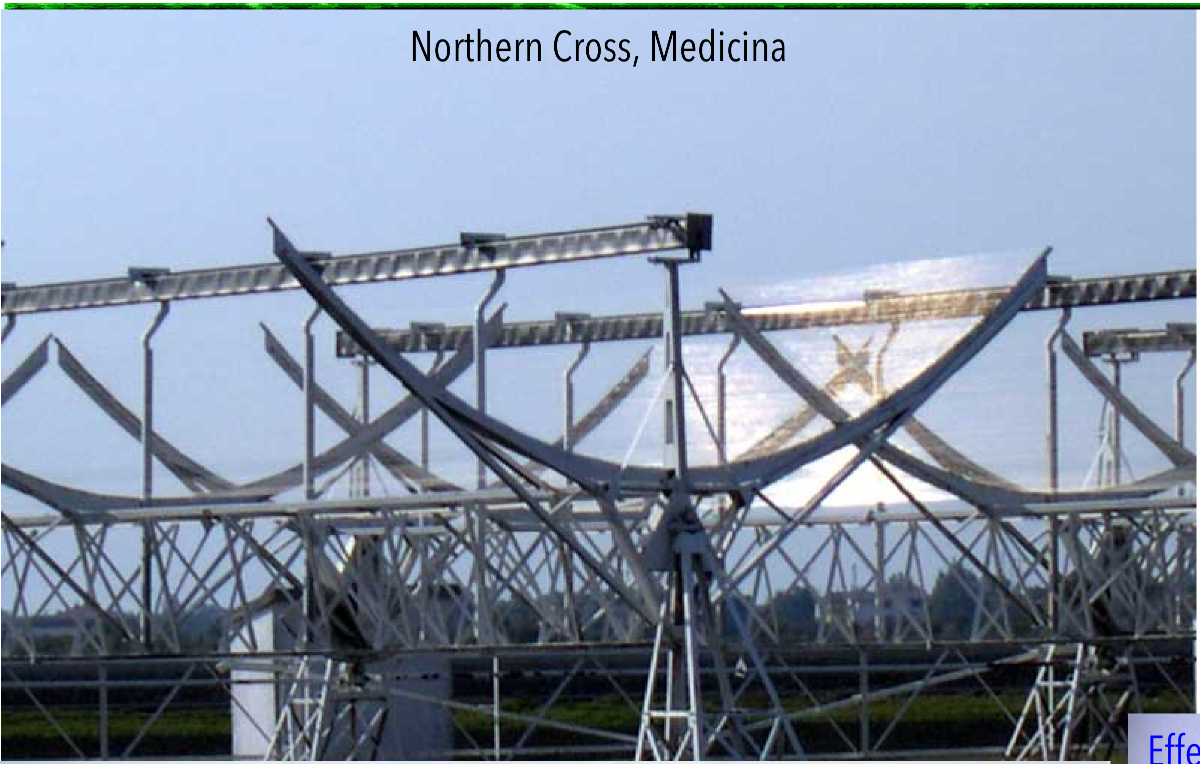
Accuracy: solid panels, mesh, wires.

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



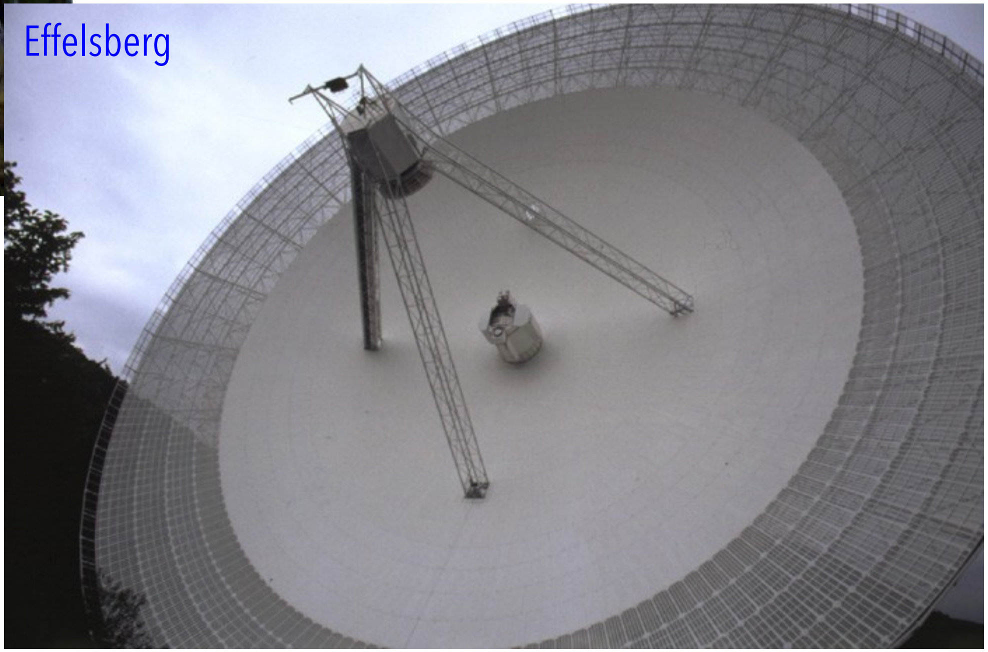

Caltech Sub-millimeter Observatory

surface accuracy -3- Mesh/wires OK at low frequencies



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:

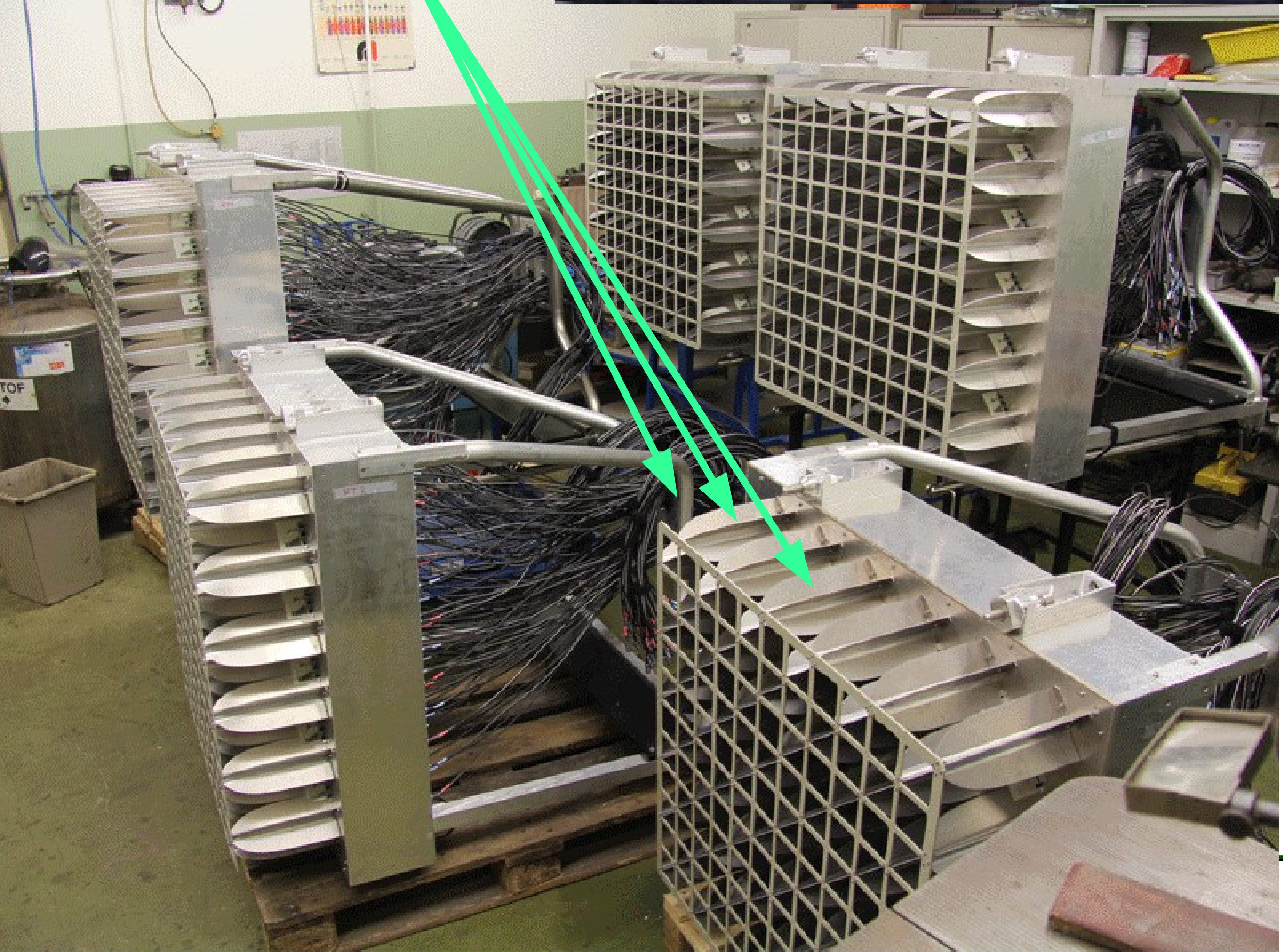
- Made of low-cost mirrors/collectors, high-cost electronics & infrastructures
- Huge amount of data throughput (storage and data transfer)

(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

Instead of a single feed, many of them are placed about the focus exploring a larger FoV



The field of view of a single dish is relatively small.
Small dish means large FoV
Otherwise FPAs!

Real Instruments -1- single dishes (Just for your information, never asked @ exams)

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 (FRB) surveys (where large collecting areas are necessary)

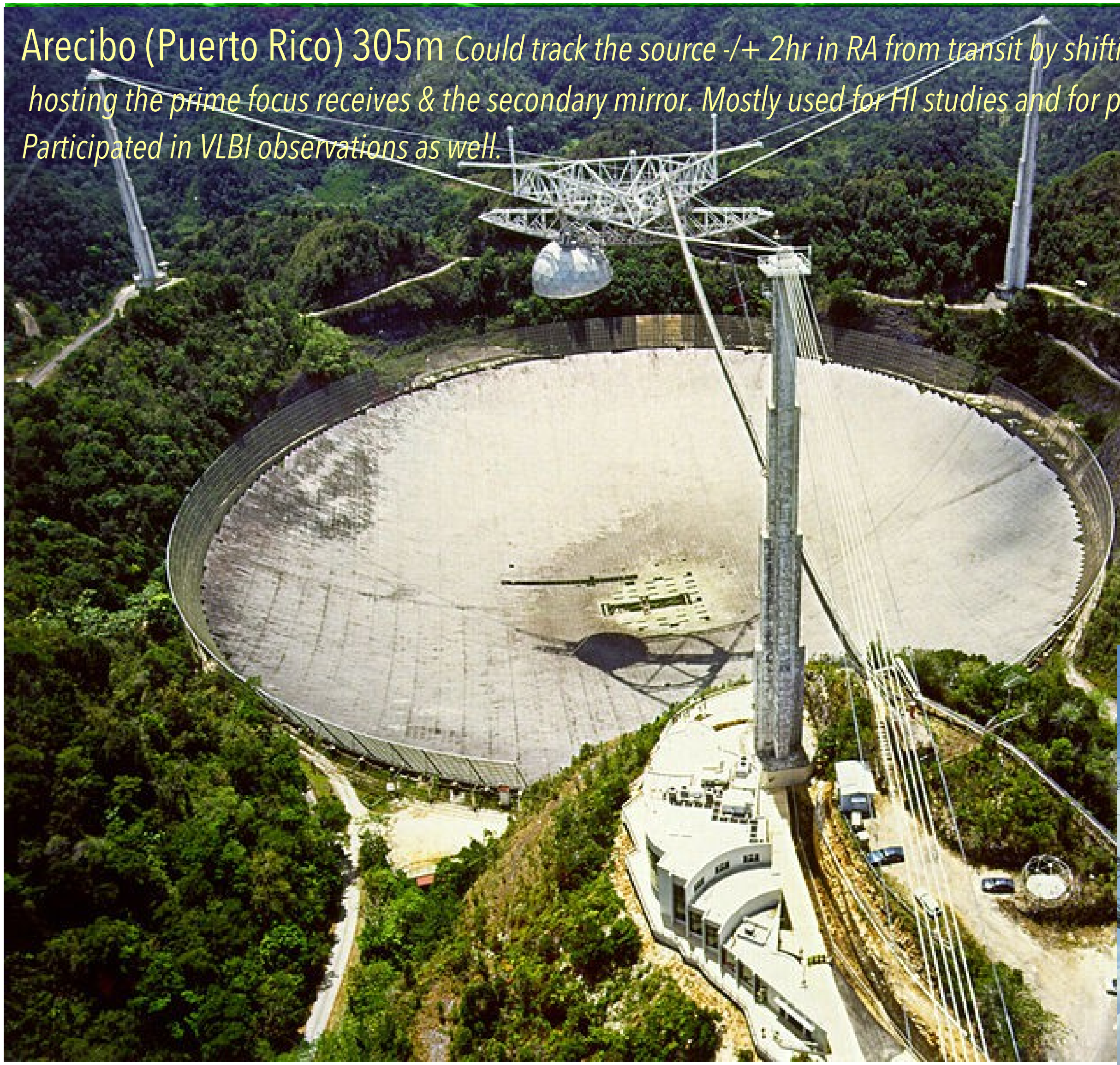
Real Instruments -2- Single dishes

Large mirrors mean good sensitivity.

- ~~Arecibo 300 m, partially stearable (secondary mirror)~~ Can't go to high frequencies
- Green Bank Telescope (GBT) 105 m fully stearable 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 -/+ 2hr 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

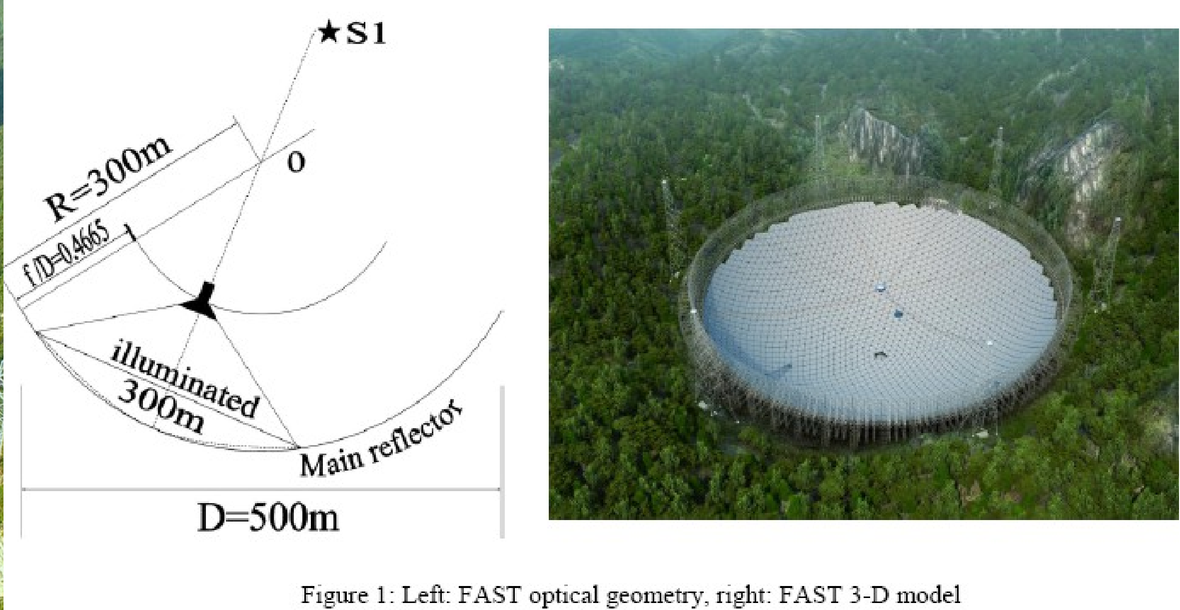


Figure 1: Left: FAST optical geometry, right: FAST 3-D model

Real Instruments -5- single dishes

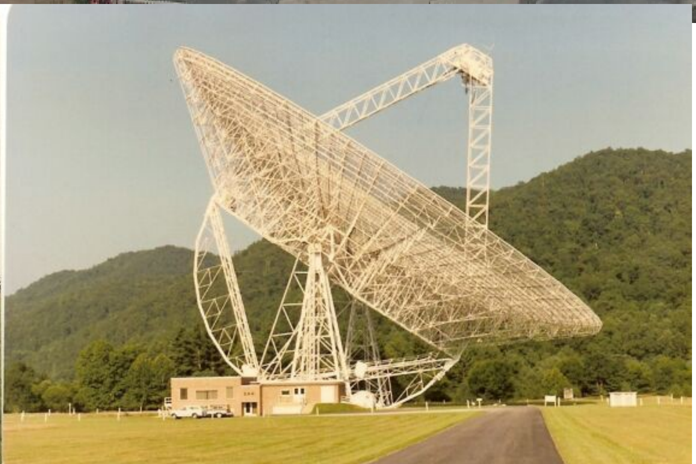
Effelsberg (Germany) 100m

Can track a source for the whole time it is above the horizon (only limitations are hills preventing low elevation [~10°] 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.

Real Instruments - 6 - single dishes

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.



Summary of concepts on (Modern) radio instrumentation

A radio telescope may have a **MIRROR**

Accuracy of surface of the mirror sets the **minimum wavelength** at which reflection is effective

The radio wave is conveyed to the (primay, secondary, …) focus where the **FEED** is the detector

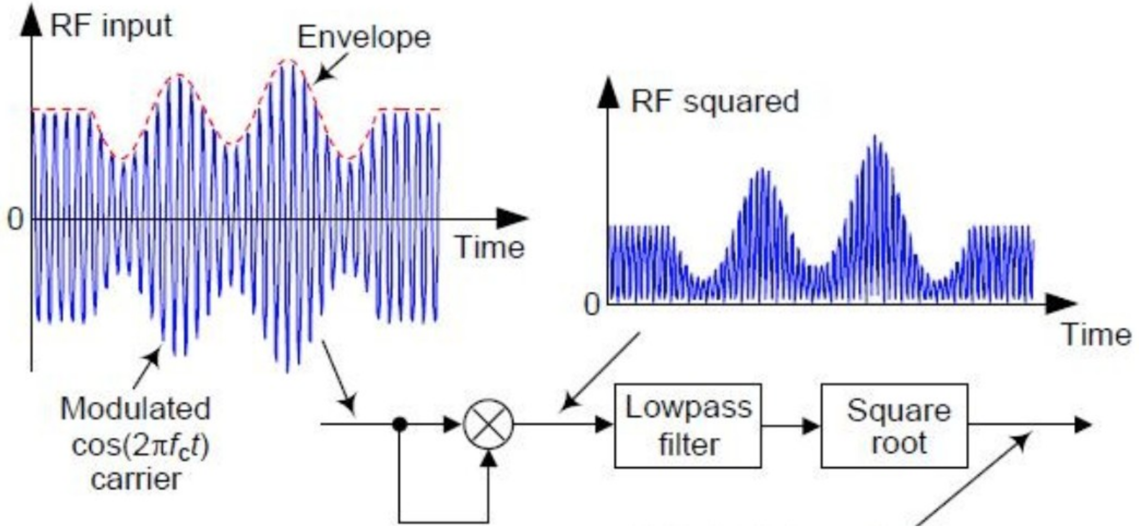
The incoming astronomical signal is very weak and must be amplified (@ the FEED/RECEIVER)

The detector (dipoles or circular feeds) transforms the incoming signal into an **oscillating voltage**

Signal is sampled at the Nyquist frequency: amplitude and phase

At this stage, detection may take place

(SQuare Law Detector) →



(Modern) Single Dishes & Interferometers

Radiotelescopes sample $V(u,v)$, the FT of the sky brightness $B(\theta,\phi)$

The HPBW of the PSF of a radio telescope is $\Delta\theta \sim \frac{\lambda}{D}$ (rad) [D = telescope diameter]

The HPBW of an interferometer is $\Delta\theta \sim \frac{\lambda}{B}$ (rad) [B = baseline length]

Field of view of an interferometer: it is the PSF of the telescopes in the interferometer

Single dishes may have large collecting areas → **sensitivity**

Interferometers may have elements at large distances → **resolution**

Each "antenna" samples 2 orthogonal polarizations (X,Y or RCP,LCP)

$$V(t)^i_R = E^o_R \sin(\omega t + \phi_R)$$

$$V(t)^i_L = E^o_L \sin(\omega t + \phi_L)$$

(Modern) Interferometers

$$V(t)^i_R = E^o_R \sin(\omega t + \phi_R)$$

$$V(t)^i_L = E^o_L \sin(\omega t + \phi_L)$$ For each i-th antenna

They are sent to the computer which performs the correlation of the signals of the **i** and **j** telescopes

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

This happens

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

For an interferometer made of N elements, the number of independent pairs is $\frac{N(N-1)}{2}$

The Earth rotation changes the length and orientation of each baseline

The amount of data is generally large → BIG DATA

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 $\lambda \sim$ cm

The JVLA (2)


Traffico
Altro...
Mappa
Satellite
Terreno
60
52
1 km
1 mi
Very Large Array
Old Highway 60
200 m
1000 ft
Cibola National Forest
Magdalena
Socorro
La Borcita
169
107
12
85
25
380
10 km
Glen Canyon National Recreation Area
Rio Grande National Forest
Cedar City
Hurricane
St George
Mesquite
Las Vegas
Bullhead City
Flagstaff
Winslow
Sedona
Prescott
Arizona
Lake Havasu City
New River
Phoenix
Apache Junction
Goodyear
Gilbert
Casa Grande
Tucson
Green Valley
Sierra Vista
Yuma
El Cajon
Mexicali
Tecate
San Luis Rio Colorado
Puerto Peñasco
Heroica Nogales
Cananea
Agua Prieta
Caborca
Imuris
Magdalena
Cortez
Durango
Shiprock
Farmington
Bloomfield
Gallup
Espanola
Santa Fe
Las Vegas
Albuquerque
Los Lunas
Cibola National Forest
Socorro
New Mexico
Roswell
Ruidoso
Alamogordo
Artesia
Carlsbad
Silver City
Deming
Las Cruces
Juárez
Nuevo Casas Grandes
Miguel Ahumada
Lovington
Hobbs
Andrews
Big Spring
Midland
Odessa
Monahans
Clovis
Portales
Hereford
Amarillo
Pampa
Canyon
Plainview
Lubbock
Levelland
Brownfield
Lamesa
Snyder
Dalhart
Dumas
Borger
Perryton
Guymon
Liberal
Dodge City
Comanche National Grassland
Woodward
Enid
Oklahoma City
Lawton
Wichita Falls
Abilene
Fort Worth
San Angelo
Texas
Killeen
Round
Stockton
Fort
Ensenada
Lazaro Cardenas
Sonoita
Palm Desert
Mojave National Preserve
200 km
100 mi
100 m
200 ft
Segnala un problema
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Real Instruments -3- http://science.nrao.edu/evla/

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 available with narrower bandwidths

Surveys (carried out in the '90ies):
NVSS (the whole sky north of Dec= – 40° (~ 75% of the sky), D-Array ⇒ HPBW = 45″, L band
rms~ 0.45 mJy/beam, about 2 M sources)

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

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

VLA & E-VLA specs

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	[illegible]	35	55	5+20	0.061
4.5 - 5.0	[illegible]	C	45	69	5+20	0.058
8.1 - 8.8	[illegible]	X	35	63	5+20	0.049
14.6 - 15.3	[illegible]	U	120	58	5+0	1.0
22.0 - 24.0	[illegible]	K	50 - 80	40	5+20	0.11
40.0 - 50.0	[illegible]	Q	80	35	5+20	0.27

Obsolete!

FYI
Not commented
Never asked @ exam

Modern Interferometers – 4 – WSRT

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 uniformely 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"x54"/sin(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

www.astron.nl/radio-observatory/astronomers/wsrt-astronomers

Modern Interferometers -5- ATCA

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

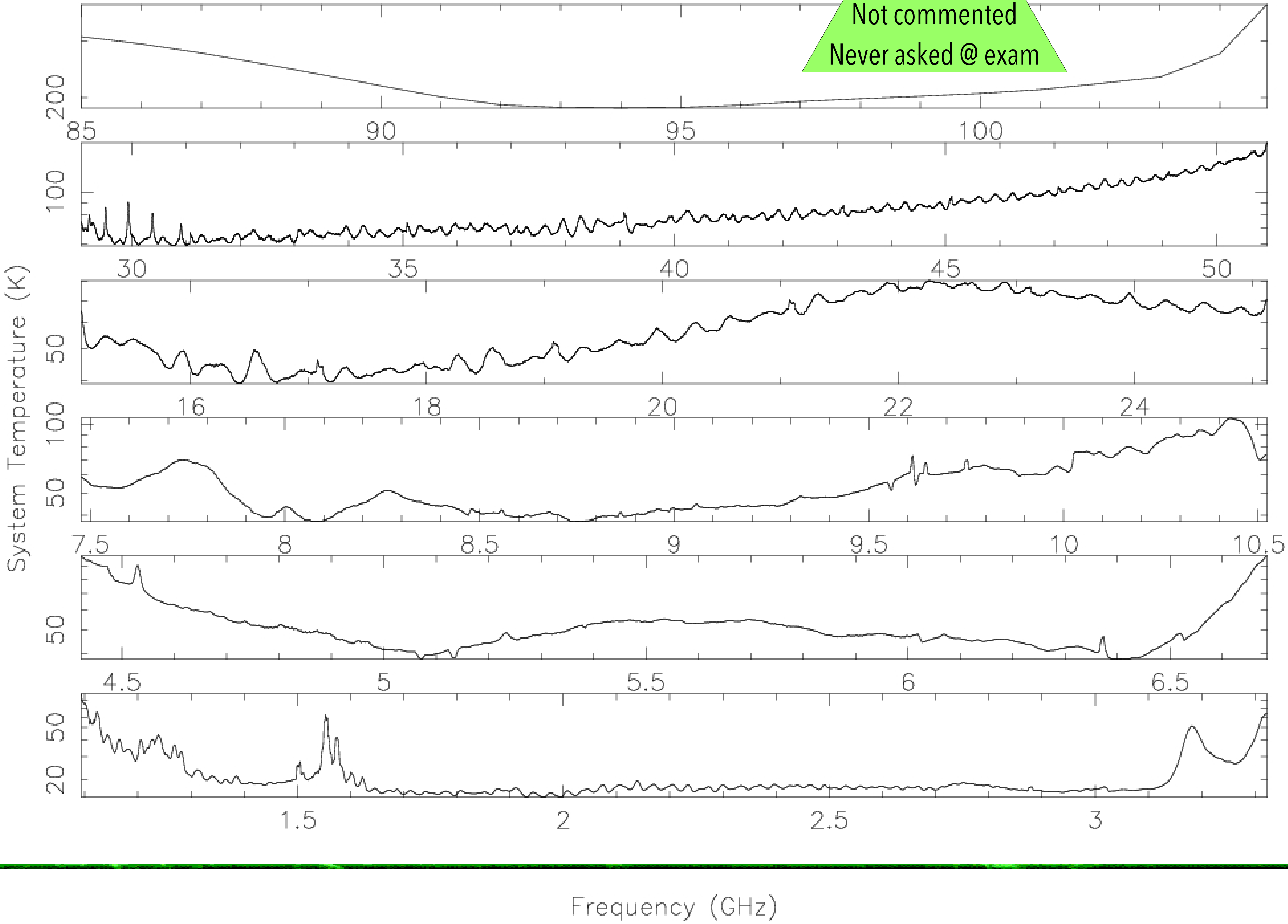
Real Instruments -5-

ATCA: T_{SYS} .vs.frequency coverage

FYI

Not commented

Never asked @ exam



Modern Interferometers -6- uGMRT

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

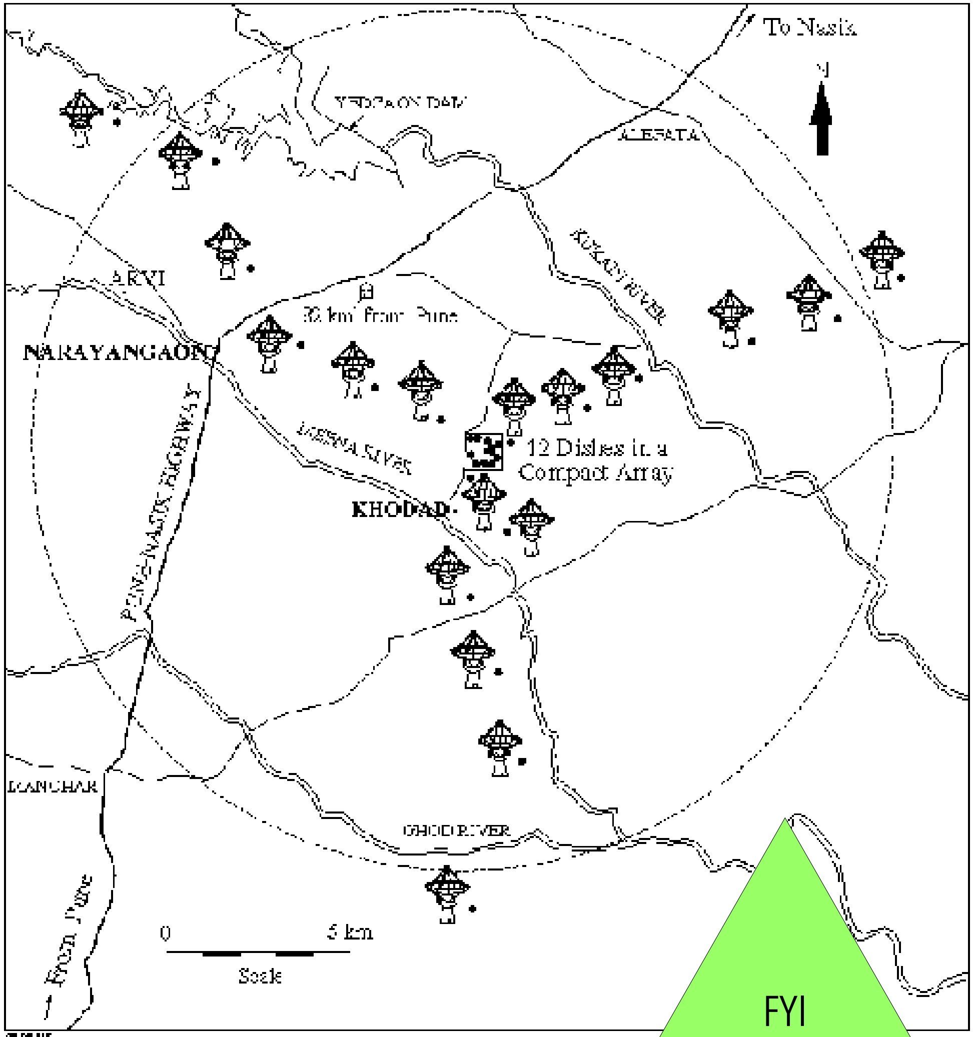
120-250 250-500 500-900 1000-1400 MHz

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

Present/Future Instruments -1- LOFAR (http://www.lofar.org/)

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.

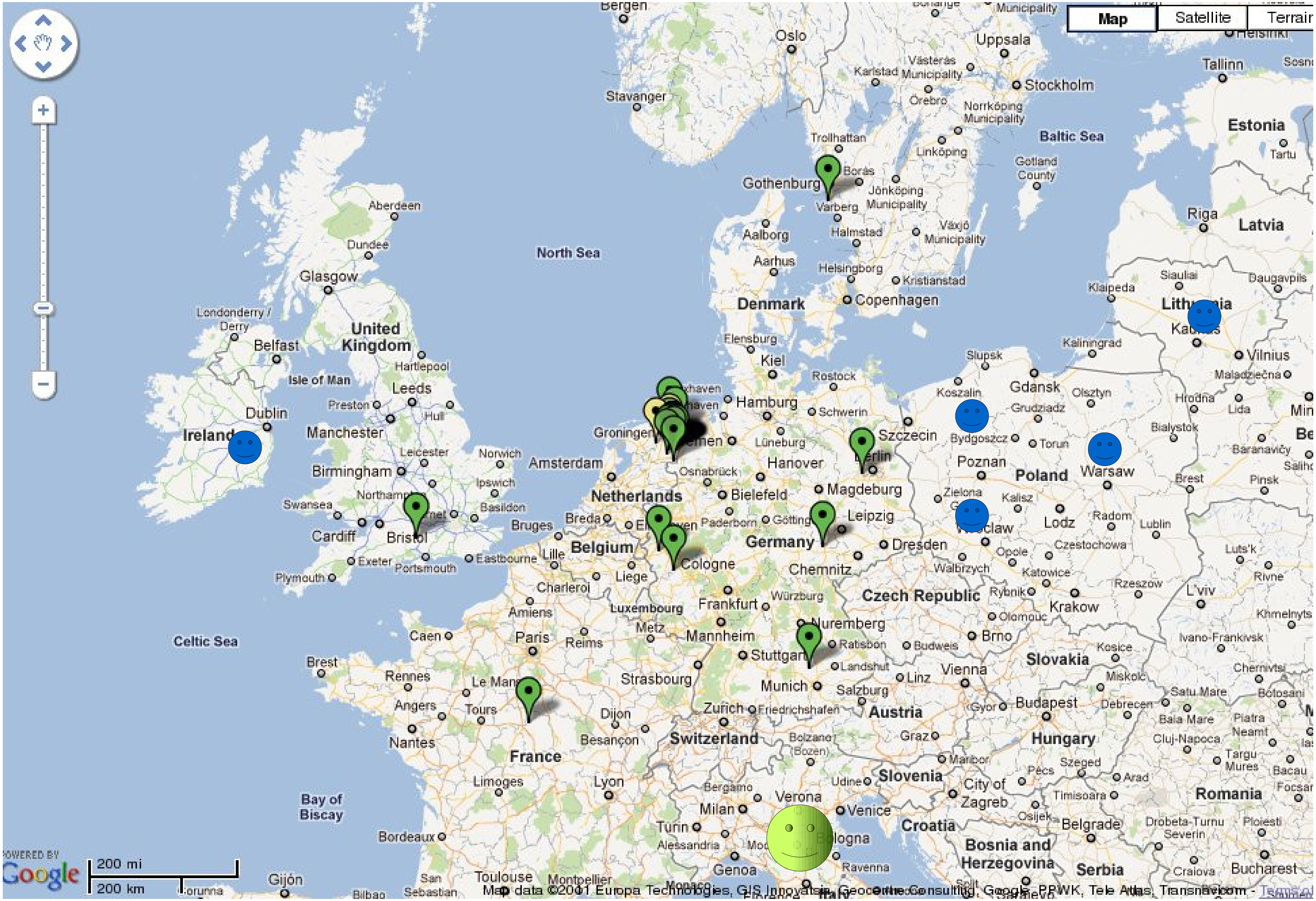
LOFAR was intended as a precursor/demonstrator of SKA (but now the frequency range is different).

Survey images are already available.

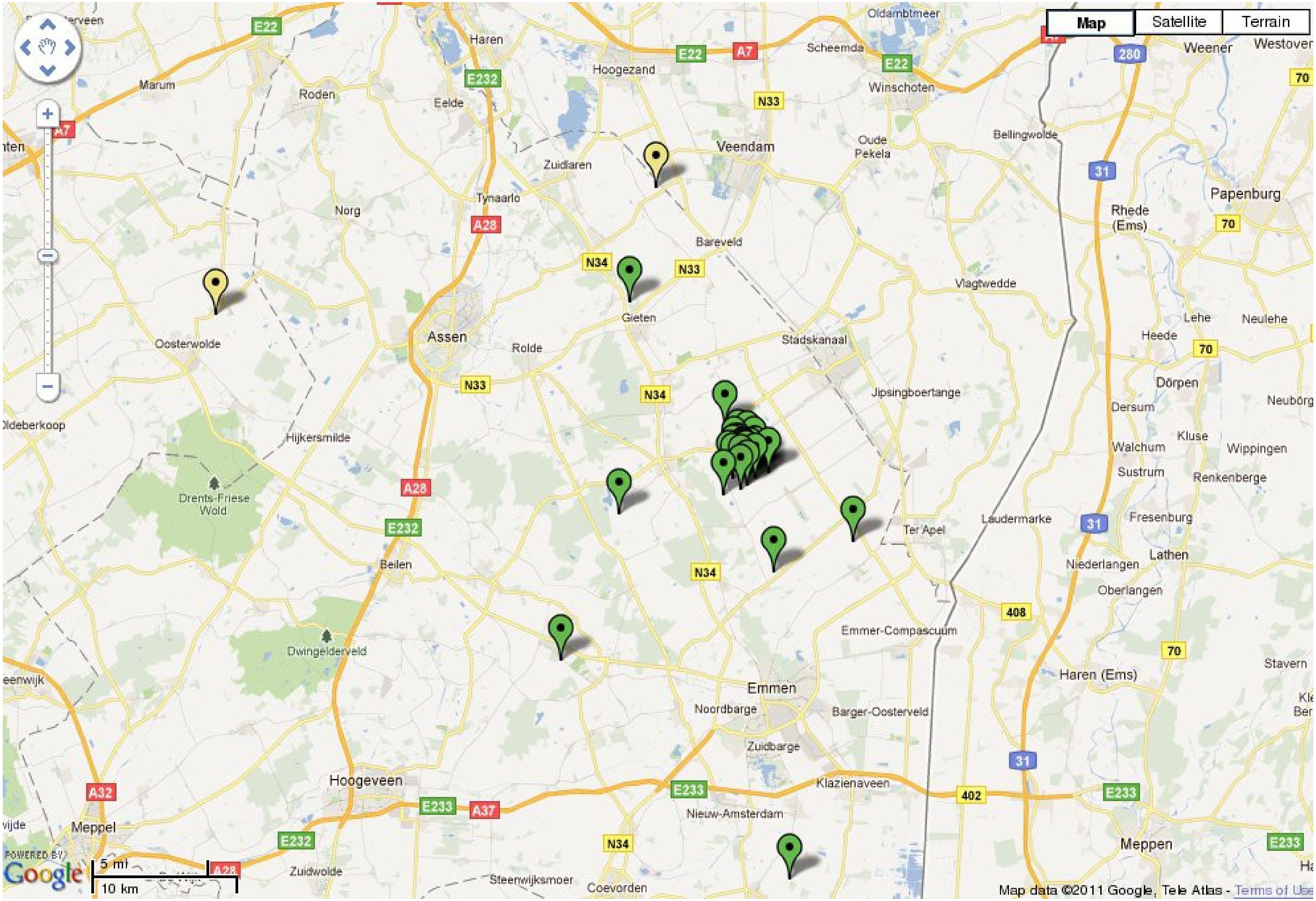
Huge data throughput,

https://www.media.inaf.it/2019/02/19/lofar-nuova-survey/

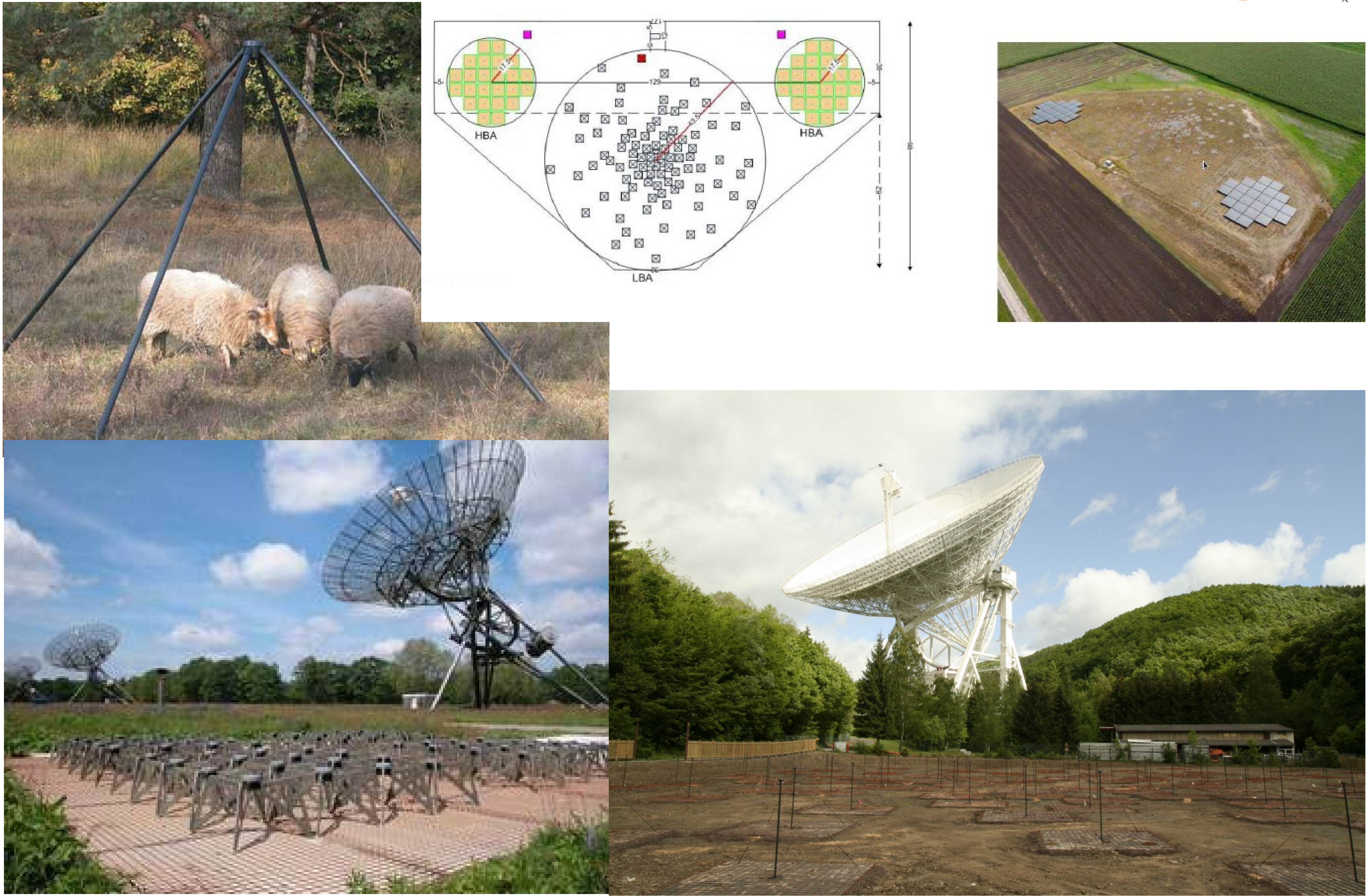
Present/Future Instruments -1- LOFAR (http://www.lofar.org/)



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



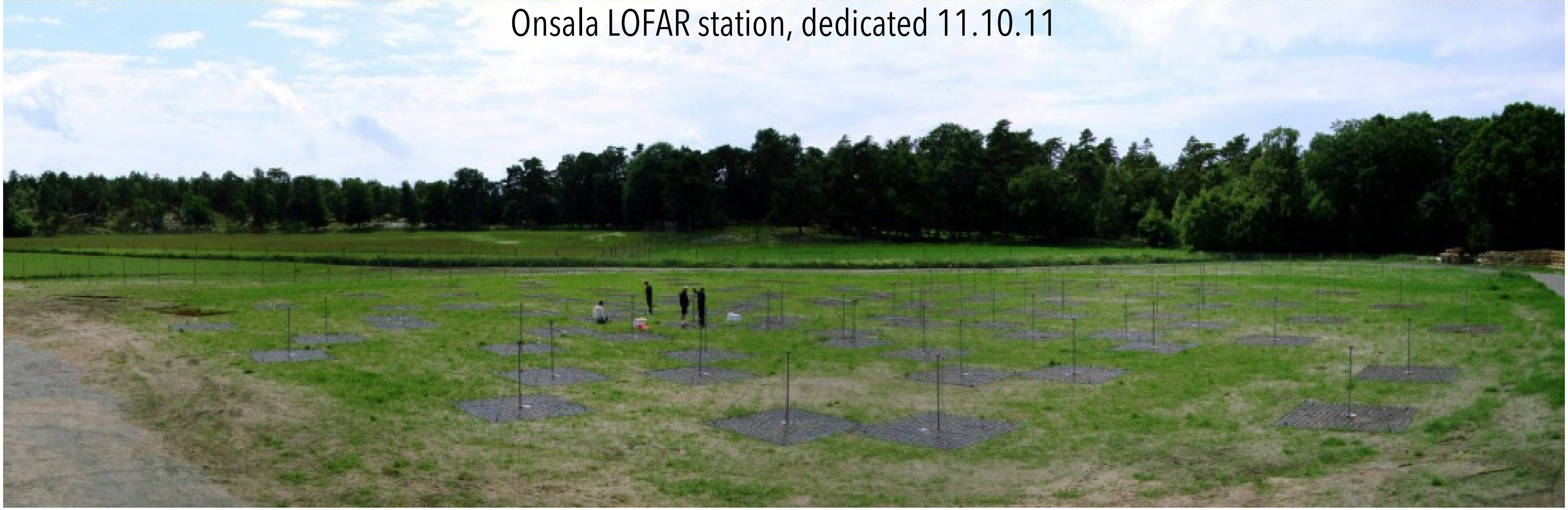
Present/Future Instruments -1- LOFAR: details of the station(s)



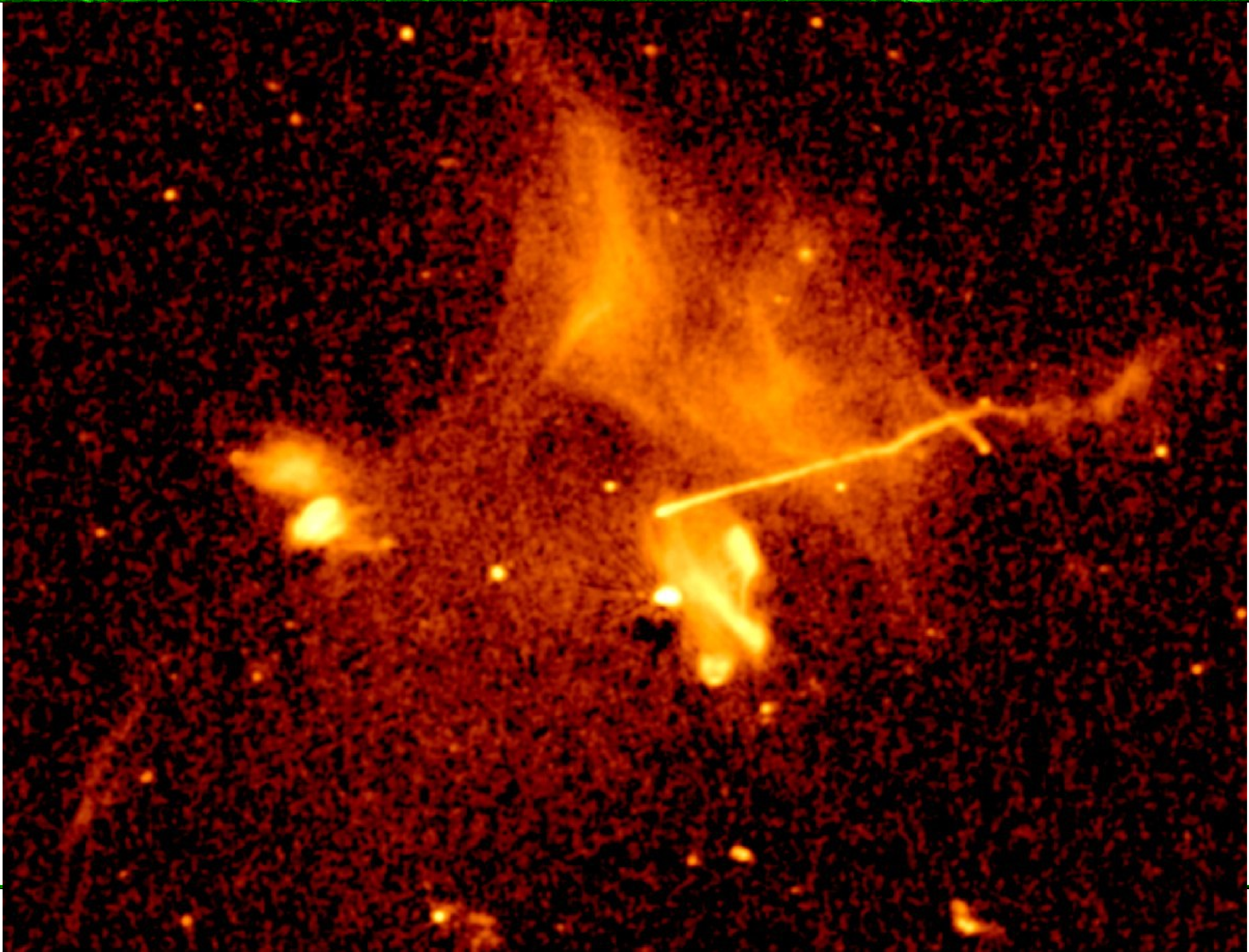
Present/Future Instruments -1- LOFAR: the Superterp

Present/Future Instruments -1- LOFAR: the international stations (Onsala, Sweden)

Onsala LOFAR station, dedicated 11.10.11



Present/Future Instruments -1- LOFAR: early science results, Abell 2256, HBA image



Present/Future Instruments -2- High frequencies (microwaves!) ALMA

ALMA

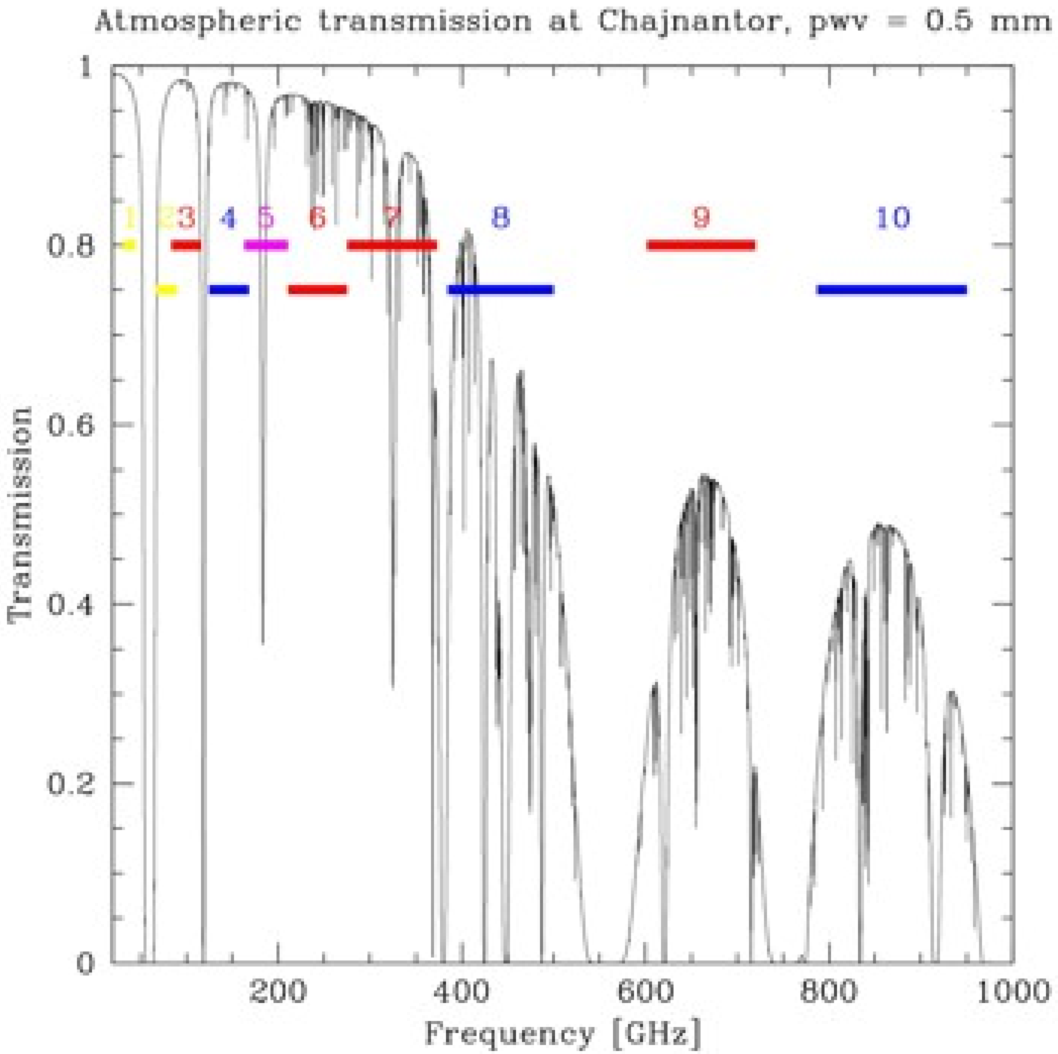
(Atacama Large Millimeter Array). Joint instrument of ESO, NRAO, Japan and Chile. ALMA is a single telescope of revolutionary design, composed of 66 high (50 +4 are 12m dishes, with the addition of 12 antennas 7m in diameter) precision antennas located on the Chajnantor plateau, 5000 meters altitude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

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”



Present/Future Instruments -2- ALMA

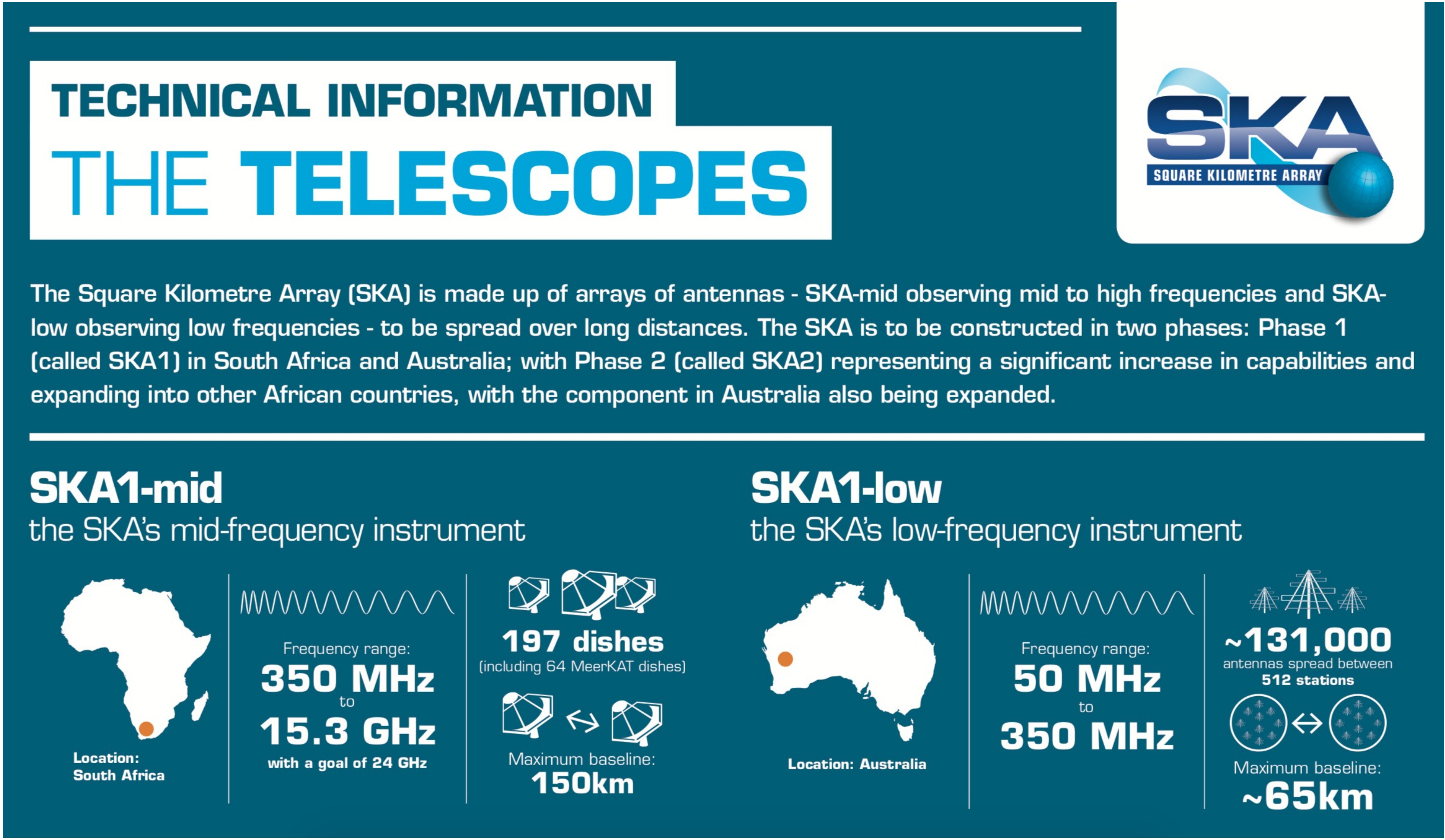
Overview of ALMA's Scientific Potential

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.

The Square Kilometre Array (**SKA**)

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



TECHNICAL INFORMATION

THE **TELESCOPES**

SKA
SQUARE KILOMETRE ARRAY

The Square Kilometre Array (SKA) is made up of arrays of antennas - SKA-mid observing mid to high frequencies and SKA-low observing low frequencies - to be spread over long distances. The SKA is to be constructed in two phases: Phase 1 (called SKA1) in South Africa and Australia; with Phase 2 (called SKA2) representing a significant increase in capabilities and expanding into other African countries, with the component in Australia also being expanded.

SKA1-mid

the SKA's mid-frequency instrument

Location: South Africa

Frequency range:
350 MHz
to
15.3 GHz
with a goal of 24 GHz

197 dishes
(including 64 MeerKAT dishes)

Maximum baseline:
150km

SKA1-low

the SKA's low-frequency instrument

Location: Australia

Frequency range:
50 MHz
to
350 MHz

~131,000
antennas spread between
512 stations

Maximum baseline:
~65km

The Square Kilometre Array (SKA)

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

SKA stands for Square Kilometre Array. It is expected to start operations around 2024.

It consists of TWO independent radio telescopes (interferometers) split into

- **SKA-LOW** (in Western Australia)
- **SKA-MID** (in South Africa and neighboring countries)

SKA specifications

FREQUENCY RANGE ~100 MHz TO 15 GHz

SENSITIVITY 400 μJy IN 1 MINUTE) between 70 AND 300 MHz

FIELD-OF-VIEW 200 SQUARE DEGREES BETWEEN 100 AND 300 MHz
1-200 SQUARE DEGREES BETWEEN 0.3 AND 1 GHz
1 SQUARE DEGREE MAXIMUM BETWEEN 1 AND 10 GHz

Target ANGULAR RESOLUTION <0.1 ARCSECOND

INSTANTANEOUS BANDWIDTH BAND CENTRE ± 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 (big DATA!)

The Square Kilometre Array (SKA)

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 an incoplete 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

The Square Kilometre Array (SKA)

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.

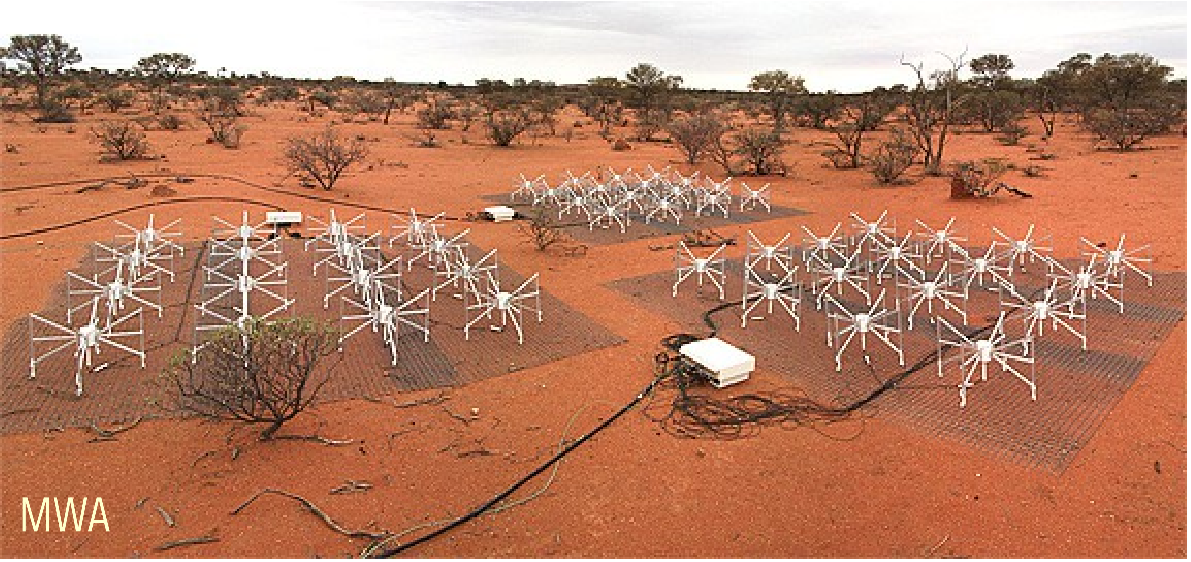
The Square Kilometre Array (SKA)

Low-frequency detectors (1 Million when completed!)

High-frequency dishes. They will be small to have a larger field of view.

End of section

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)



Summary and take home message(s)

- ➔A radio telescope has (~) the same basic structure of an optical telescope (mirror(s), detectors, recorders)

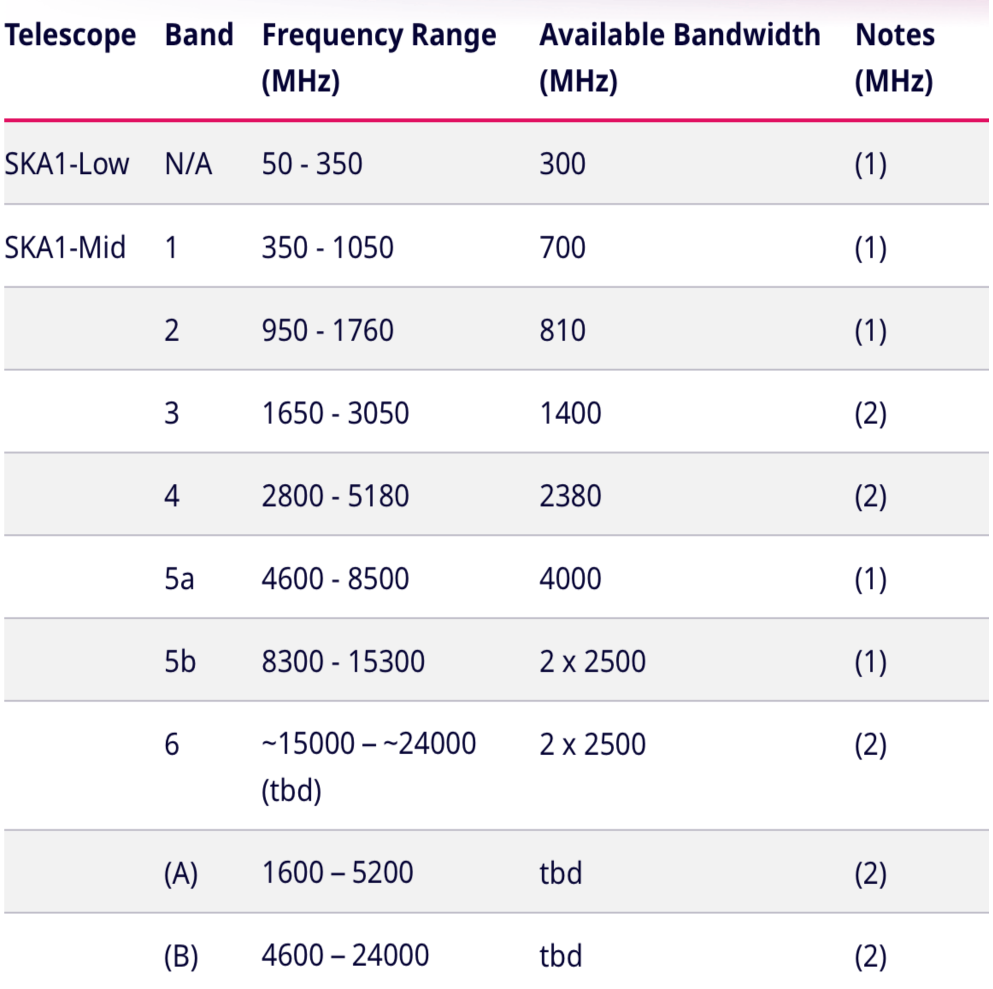
- ➔It works at the diffraction limit of the aperture (D=diameter), but its resolution is disfavored by λ/D
  It samples the FT of the sky brightness.

- ➔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 & expensive electronics & 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 – **2?**0 GHz]

SKA1(i.e. Phase 1) – as of Feb 2023



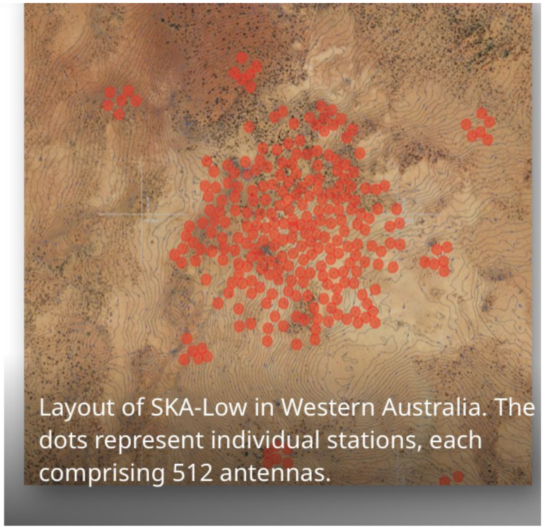
Telescope	Band	Frequency Range (MHz)	Available Bandwidth (MHz)	Notes (MHz)
SKA1-Low	N/A	50 - 350	300	(1)
SKA1-Mid	1	350 - 1050	700	(1)
	2	950 - 1760	810	(1)
	3	1650 - 3050	1400	(2)
	4	2800 - 5180	2380	(2)
	5a	4600 - 8500	4000	(1)
	5b	8300 - 15300	2 x 2500	(1)
	6	~15000 – ~24000 (tbd)	2 x 2500	(2)
	(A)	1600 – 5200	tbd	(2)
	(B)	4600 – 24000	tbd	(2)

(1) = planned

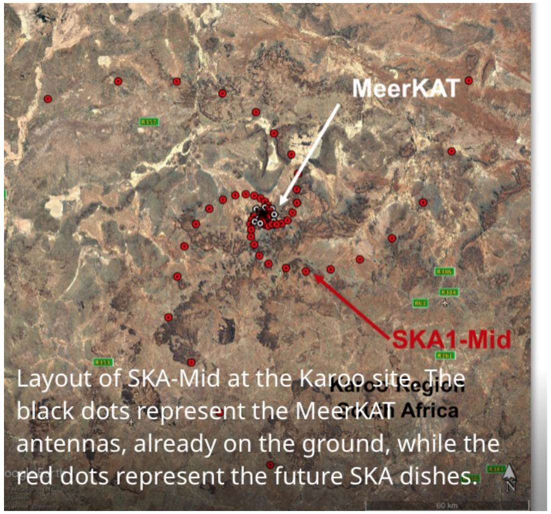
(2) = under consideration

SKA1 Layout

SKA1-Low (also referred to as SKA-Low in public communication) will consist of 131,072 log-periodic dipole antennas distributed across 512 aperture array stations of 256 antennas each. It will be located in the Murchison Radio-astronomy Observatory, Western Australia. Around 50% of the stations will be located within a 1 km diameter core, with the remaining stations organised in clusters of 6 stations on three modified spiral arms. The maximum baseline length will be around 70 km.



Layout of SKA-Low in Western Australia. The dots represent individual stations, each comprising 512 antennas.



Layout of SKA-Mid at the Karoo site. The black dots represent the MeerKAT antennas, already on the ground, while the red dots represent the future SKA dishes.

SKA1-Mid (also referred to as SKA-Mid in public communication) will consist of 133 15m SKA dishes and 64 13.5m Meerkat dishes at the Karoo site in South Africa. The core will be composed of around 50% of the dishes, randomly distributed within 2 km. There are 3 logarithmic spiral arms with a maximum baseline extending out to 150 km.

SKA1 – as of Feb 2023

The full SKA vision

While the focus is to deliver the SKA project as per the baseline design, with SKA-Mid in South Africa and SKA-Low in Australia, the SKAO keeps the vision of a much larger SKA alive. Such vision is sometimes referred to as SKA2 (i.e. the second phase of the SKA project), consisting in increasing both the number of elements and the baseline for each telescope (extending to other African countries in the case of SKA-Mid).

While the actual scope of SKA2 will eventually be subject to further discussions, the performance of the extended telescopes may include:

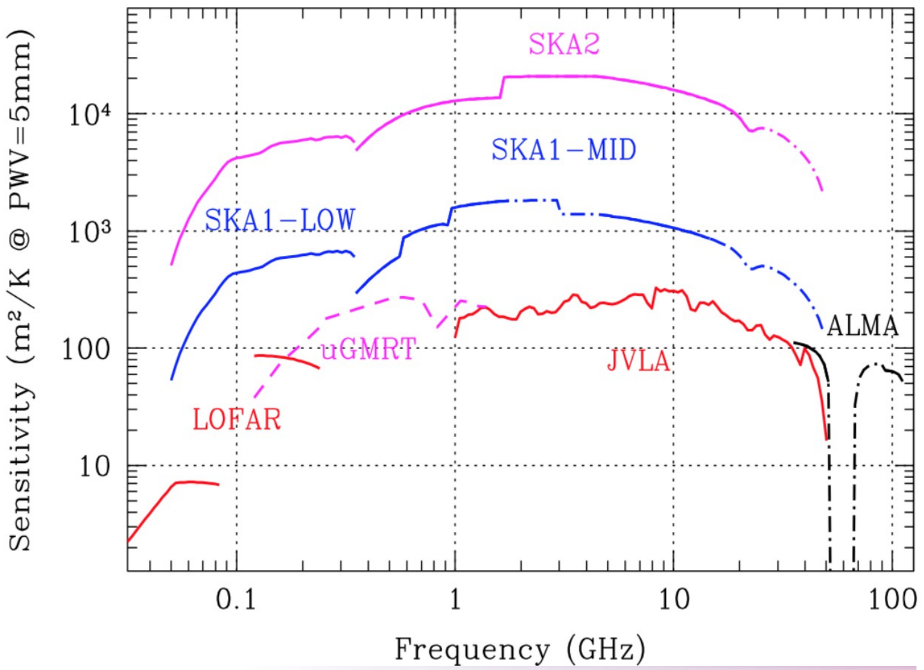
- 4-10 x SKA1 sensitivity in the frequency range of 50 – 350 MHz
- 10 x SKA1 sensitivity in the frequency range of 350 MHz – 24 GHz (including deployment of all five frequency bands)
- 50% of the “natural” sensitivity of the facility over a wide range of beam size
- 20 x SKA1 Field-of-View in the frequency range of 350 MHz – 1.5 GHz
- 20 x SKA1 maximum angular resolution in the frequency range of 50 MHz – 24 GHz

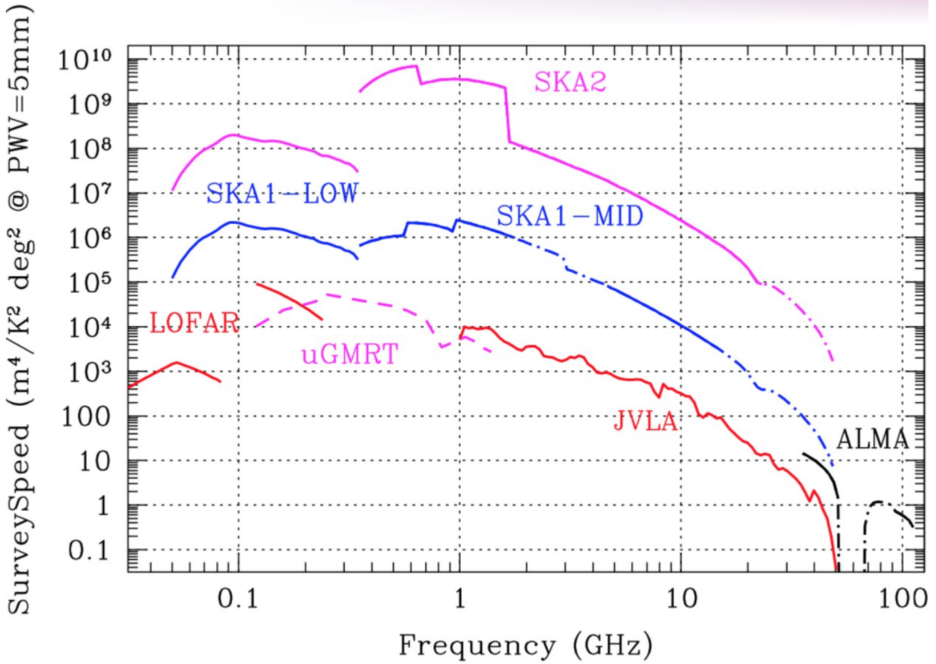
Array Assembly Key Information

Name	Low Stations	Date for Low	Mid Dishes (SKA+MeerKAT)	Date for Mid
AA1	18	C0+35	8+0	C0+34
AA2	64	C0+47	64+0	C0+44
AA3	256	C0+58	120+8	C0+58
AA4	512	C0+70	133+64	C0+67

where the dates are expressed as months after C0, which is the construction start date (1 July 2021).

SKA1 and SKA2 anticipated performance





Appendix:

LOFAR and ALMA science drivers (incomplete list)

FYI
Not commented
Never asked @ exam

Present/Future Instruments -1- LOFAR: science drivers (most common to SKA)

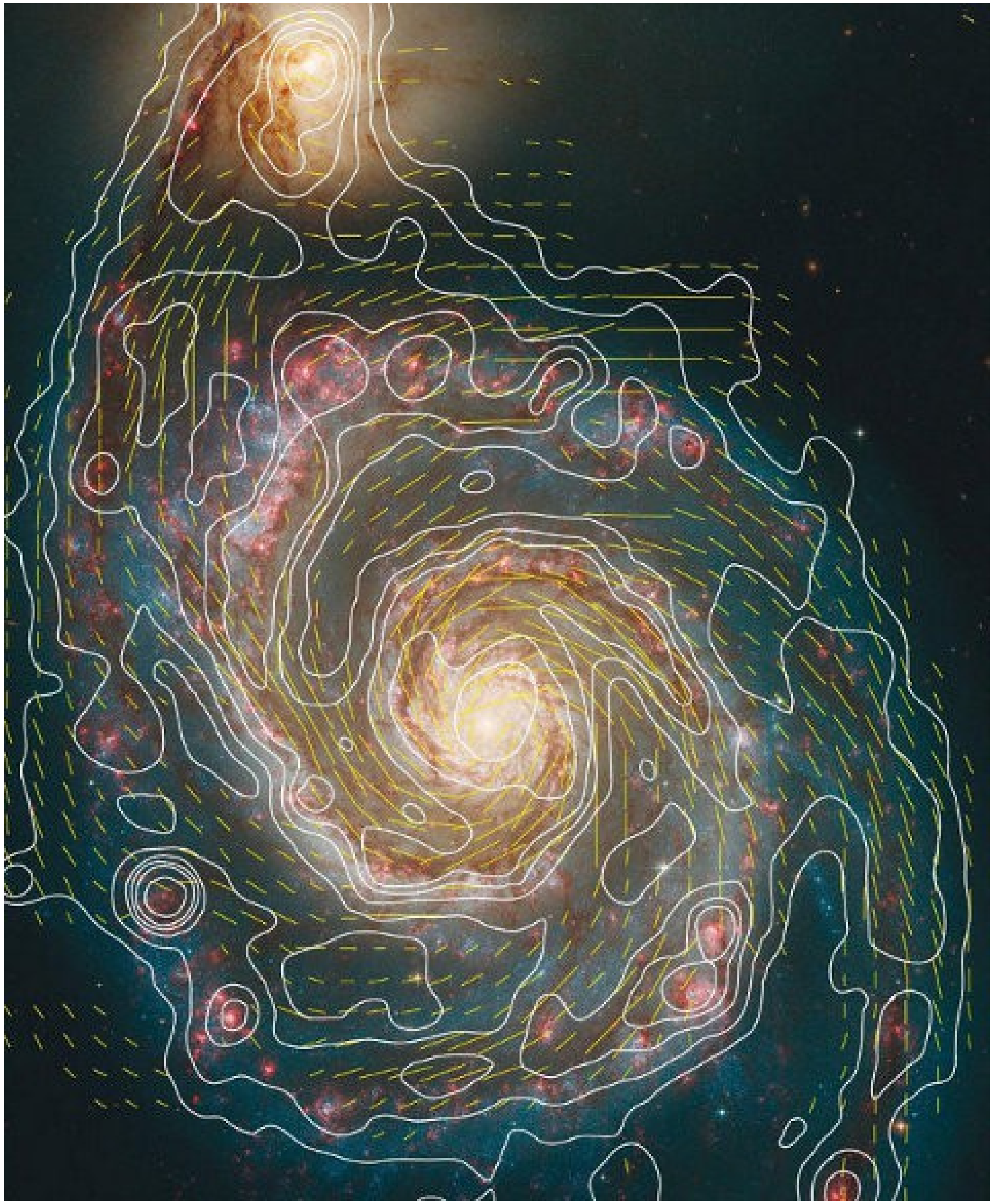
Cosmic Magnetism Key Science Project

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.

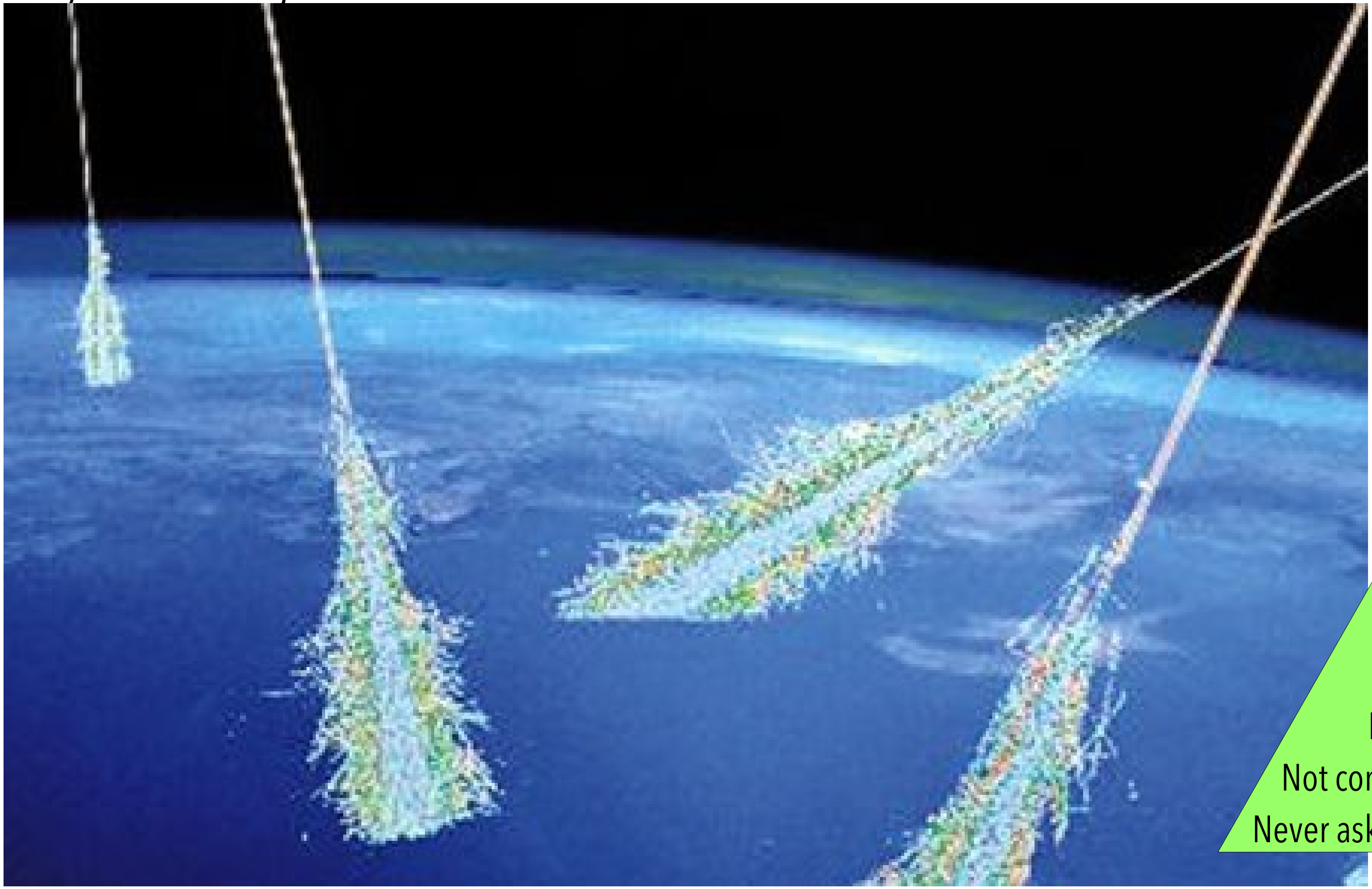


FYI
Not commented
Never asked @ exam

for more information: *http://www.mpifr-bonn.mpg.de/staff/rbeck/MKSP/mksp.html*

Present/Future Instruments -1- LOFAR: science drivers (most common to SKA)

Cosmic Rays Key Science Project



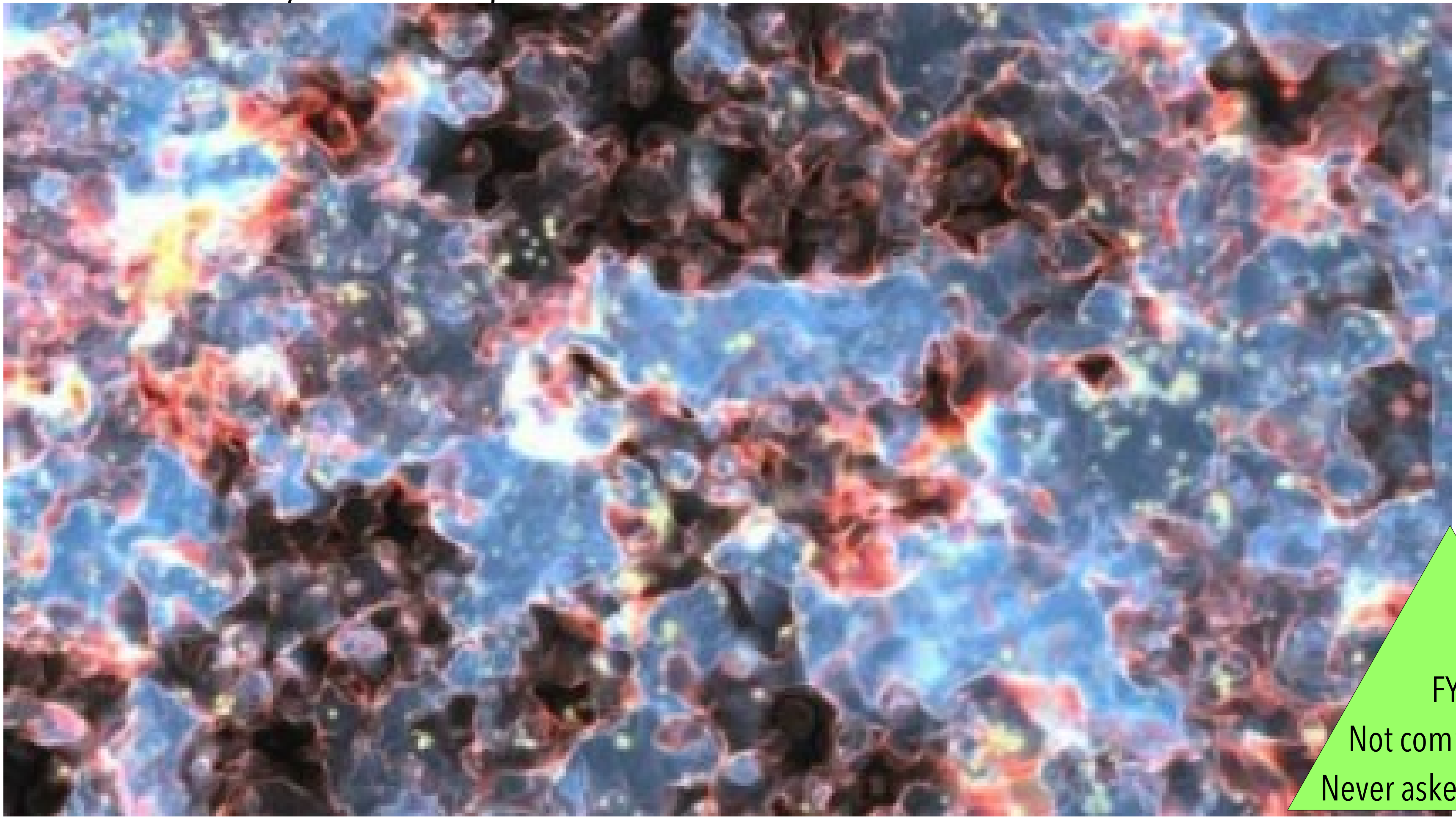
FYI
Not commented
Never asked @ exam

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.

Present/Future Instruments -1- LOFAR: science drivers (most common to SKA)

Epoch of Reionisation Key Science Project



FYI
Not commented
Never asked @ exam

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 $z\sim15$-20 and ending at $z\sim6$. 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

Present/Future Instruments -1- LOFAR: science drivers (most common to SKA)

Solar Physics and Space Weather with LOFAR

FYI
Not commented
Never asked @ exam

The KSP "Solar Physics and Space Weather with LOFAR" is a European LOFAR acitivity. 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/

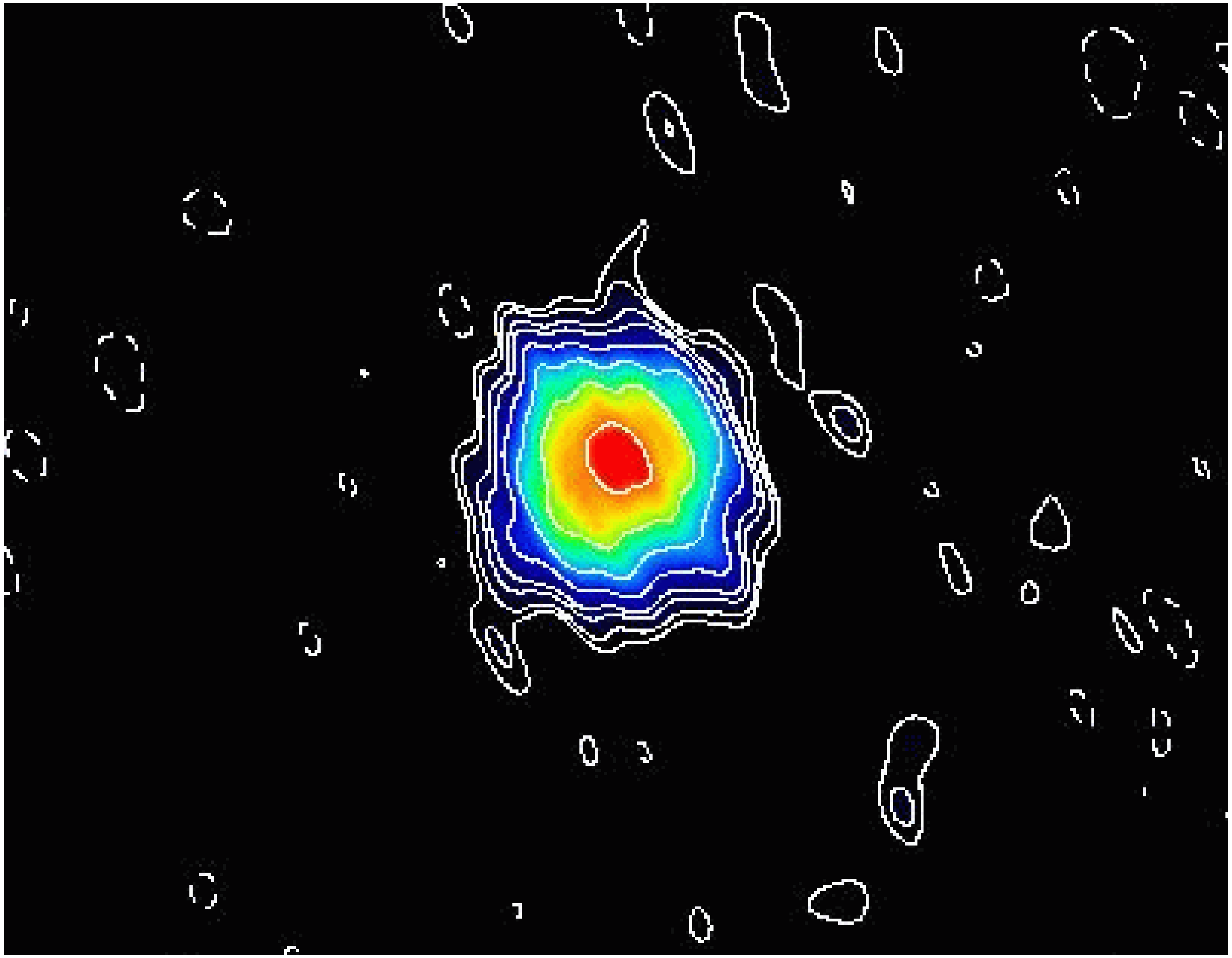
Present/Future Instruments -1- LOFAR: science drivers (most common to SKA)

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/



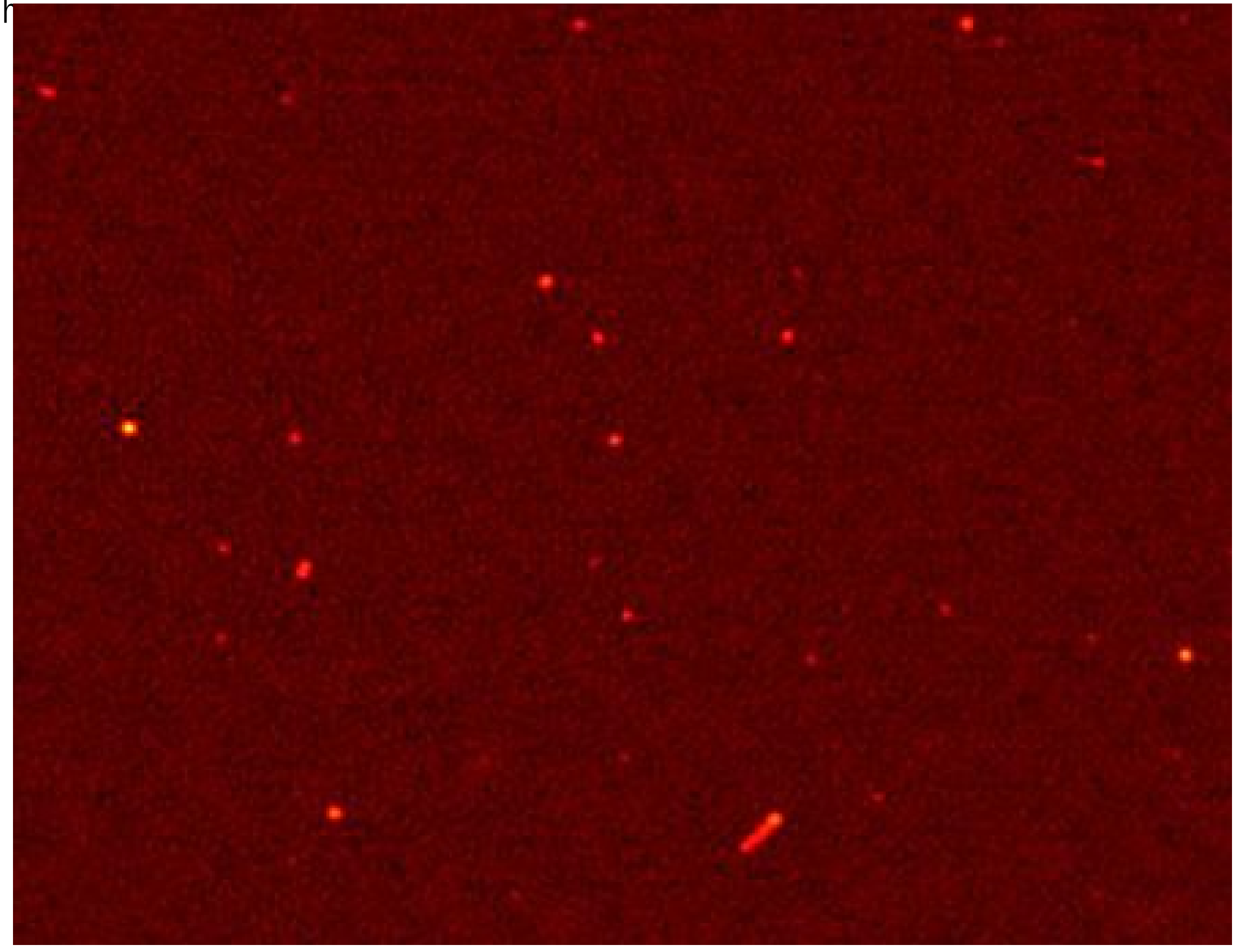
FYI
Not commented
Never asked @ exam

Present/Future Instruments -1- LOFAR: science drivers (most common to SKA)

FYI
Not commented
Never asked @ exam

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. Th



* 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.

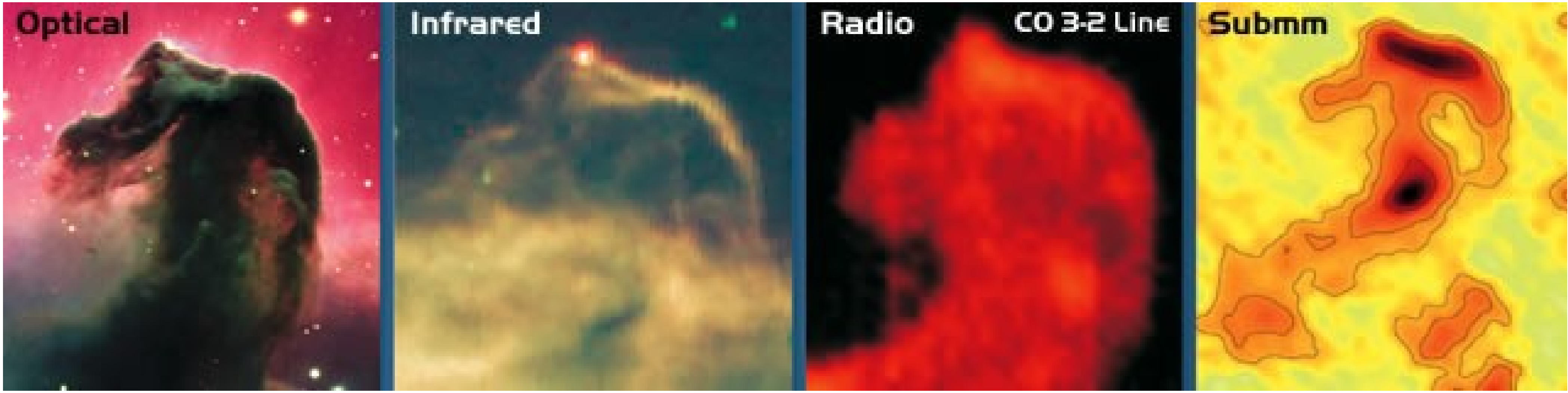
In addition to these, a broad range of topics are expected to be addressed by the surveys team. They span from magnetic fields and the interstellar medium in nearby galaxies, to physics of radio sources (their initial and final stages in the evolution), up to large scale structure of the Universe and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

Present/Future Instruments -2- ALMA

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

FYI
Not commented
Never asked @ exam

- 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.



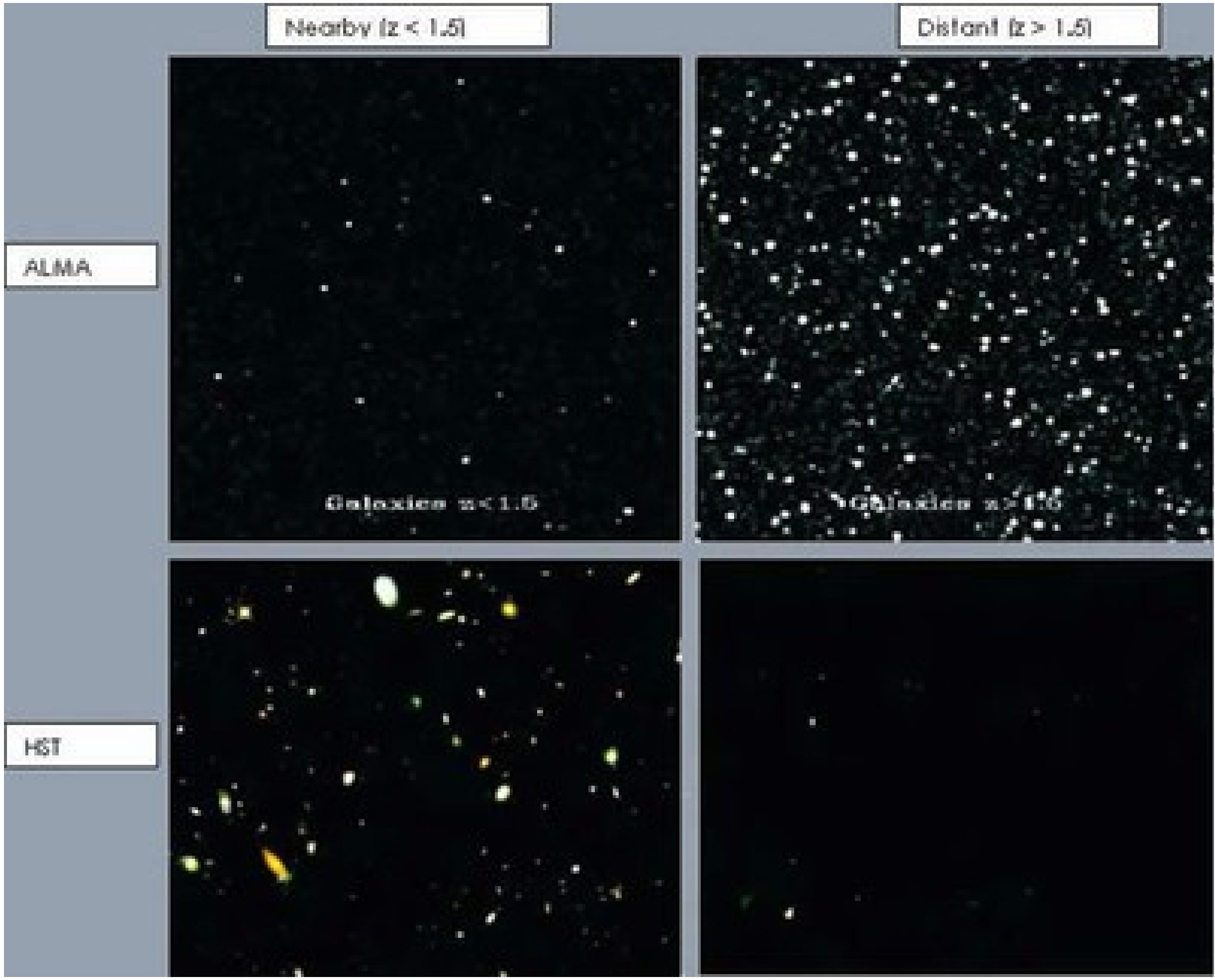
Nebulae

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.

Present/Future Instruments -2- ALMA

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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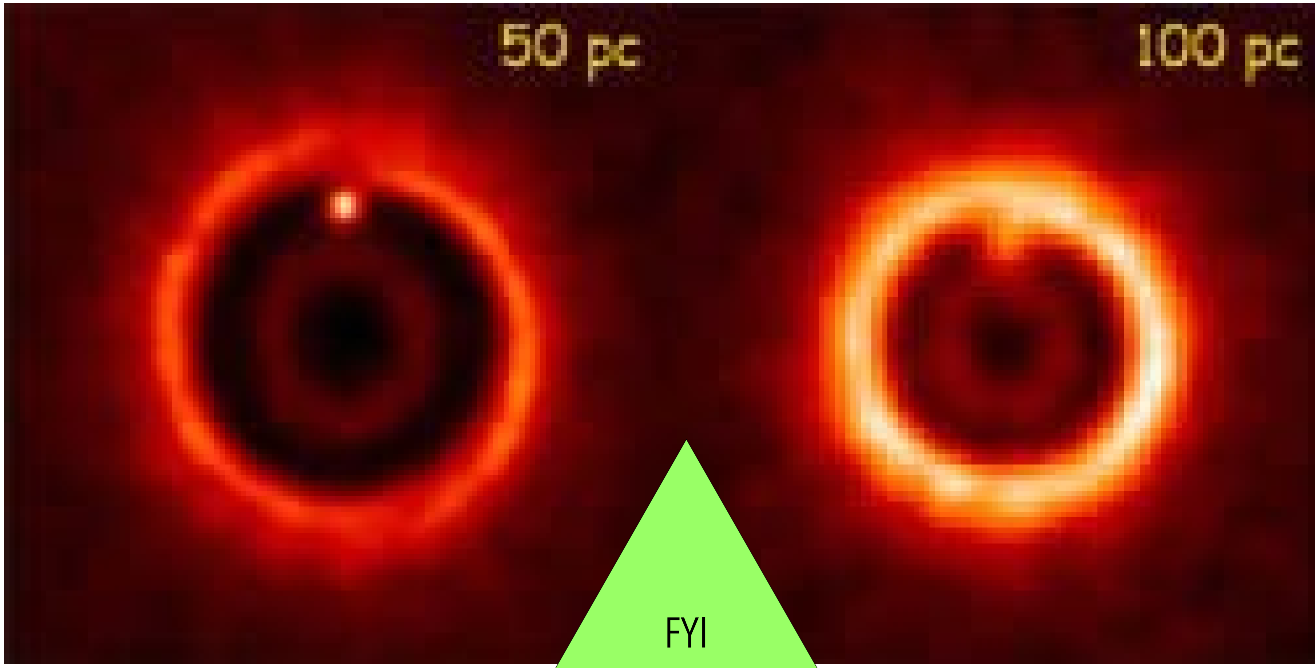
Present/Future Instruments -2- ALMA

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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Present/Future Instruments -2- ALMA

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 wavelenghts 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 wavelenghts 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 wavelenghts, the star's brightness poses less ofa 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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Present/Future Instruments -2- ALMA

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-1. 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 starstuff 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 ν^{21} . Grain growth is expected to be most rapid at distances of a few x 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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Present/Future Instruments -2- ALMA

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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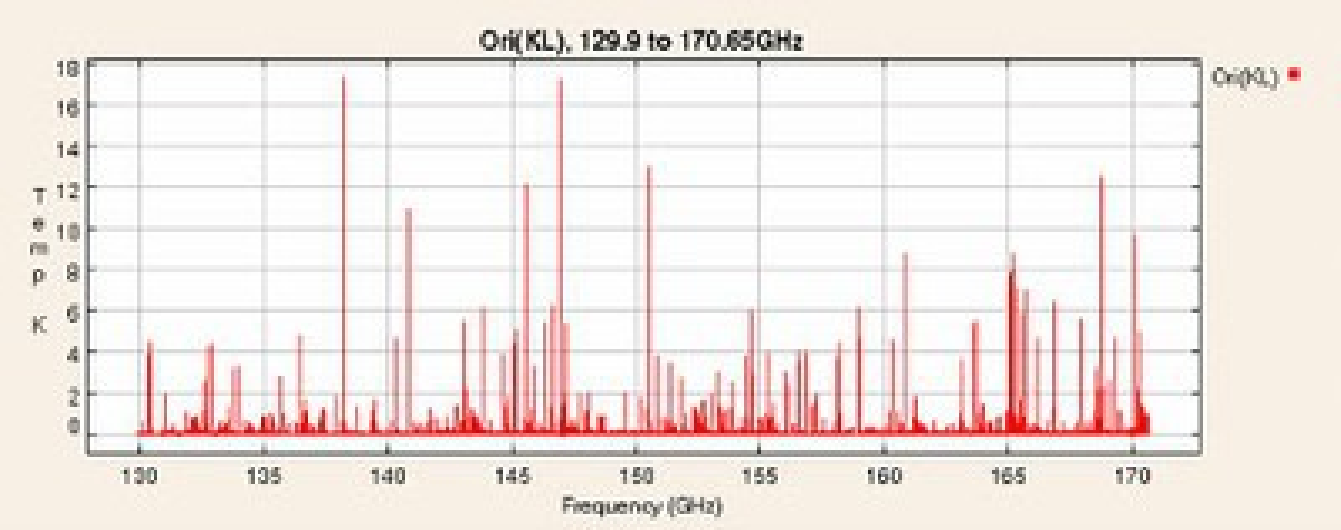
Present/Future Instruments -2- ALMA

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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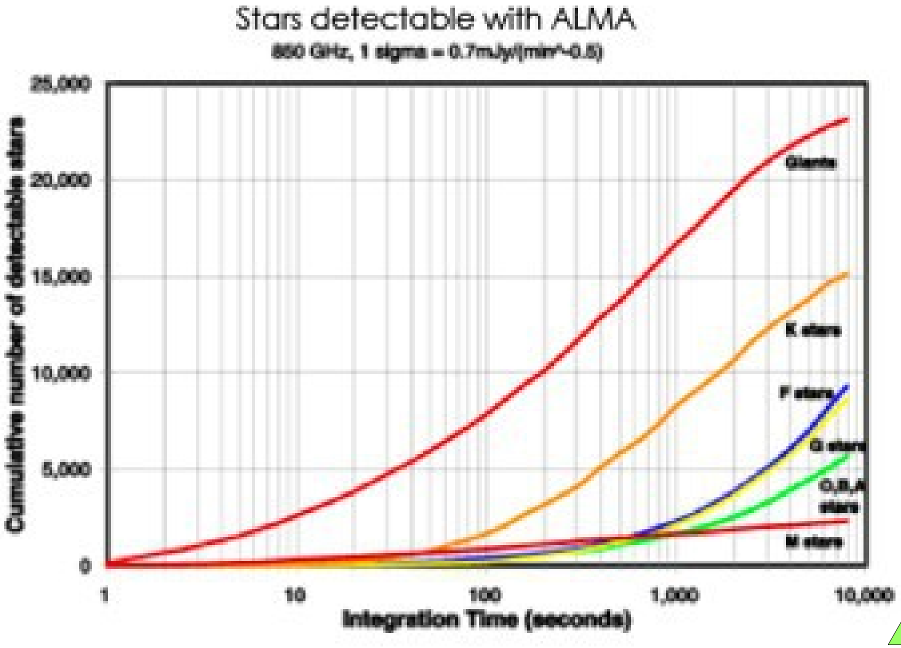
Present/Future Instruments -2- ALMA

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 SG Stars (stars which are 10 to 1000 times the diameter of our Sun, e.g. Betelgeuse).

Stars can be classified by color (or spectra). They 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.



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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
			Mimosa	Ursa Major
A	bluish-white	10,000K	Sirius	Canis Major
			Castor	Gemini
			Vega	Lyra
			Deneb	Cygnus
F	white	7,000K	Polaris	Ursa Minor
			Canopus	Carina
			Procyon	Canis Minor
			Dabih	Capricorn
			Sadr	Cygnus
G	yellowish-white	5,500K	The Sun	
			Capella	Auriga
			Muphrid	Bootes
			Nekkar	Bootes
			Matar	Pegasus
K	orangish	4,000K	Edasich	Draco
			Kochab	Ursa Minor
			Izar	Bootes
			Dubhe	Ursa Major
			Pollux	Gemini
			Aldebaran	Taurus
M	reddish	3,000K	Betelgeuse	Orion
			Mirach	Andromeda
			Menkar	Cetaurus
			Antares	Scorpio
			Scheat	Pegasus

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.

Present/Future Instruments -2- ALMA

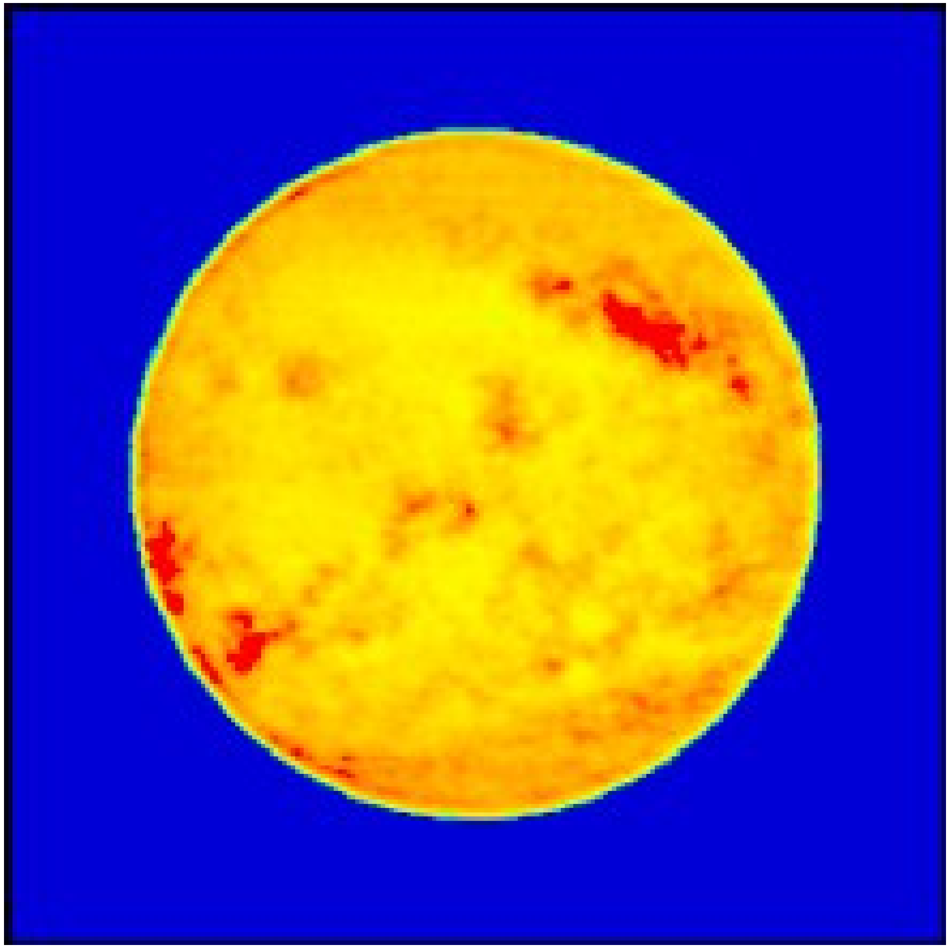
The Sun

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 (~6500K), 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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Present/Future Instruments -2- ALMA

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 ~5880K. 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 problem 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 ~1mm, 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 sub-mm 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.

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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,since the full ALMA array completion, its vision is 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 are used for science observations – and much closer together as well. Both of these factors make the new image just a taster of what is to come.


ALMA Early Science: The Antennae Galaxies

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.

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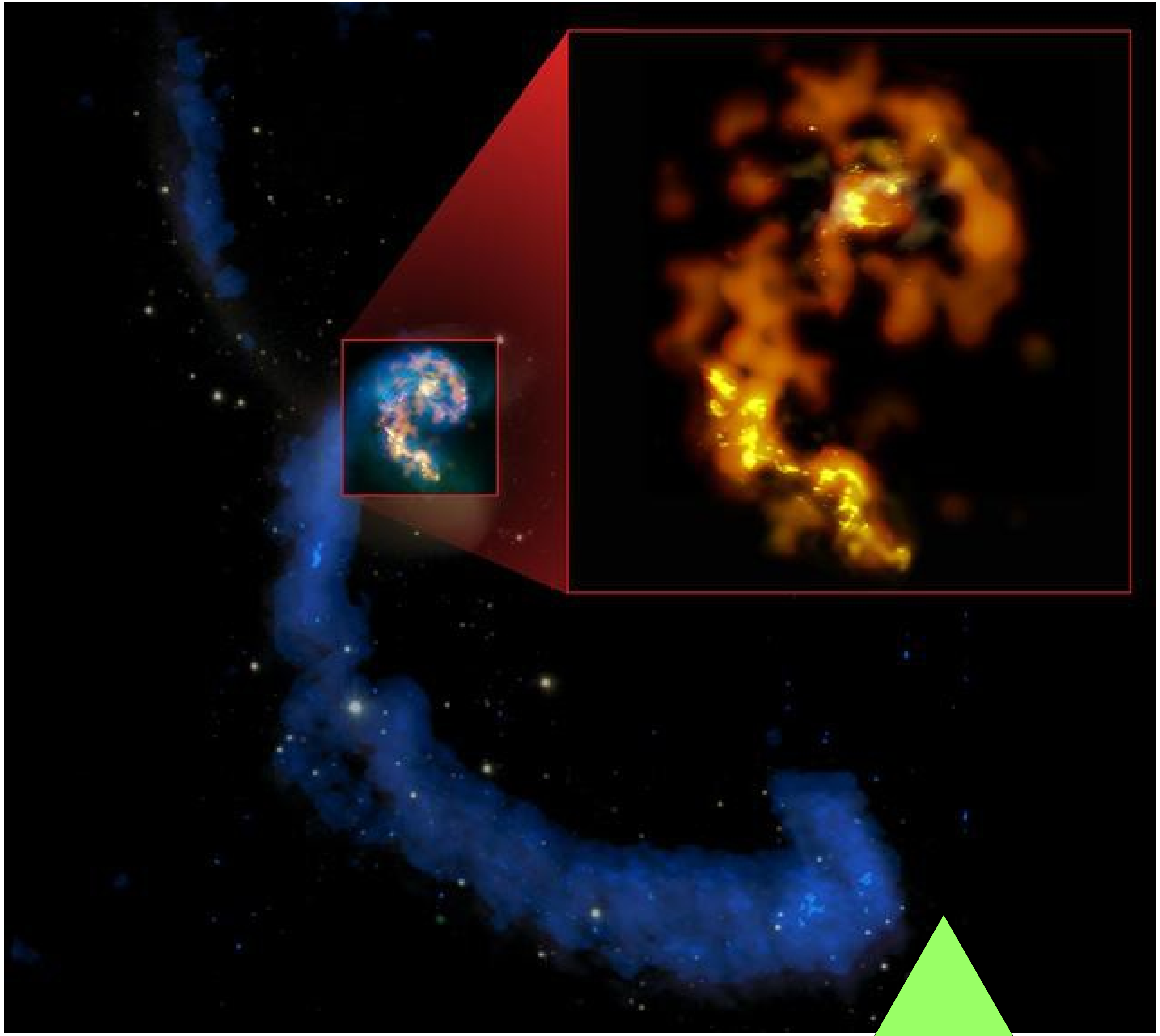
Credit: ALMA (ESO/NAOJ/NRAO). Visible light image: the NASA/ESA Hubble Space Telescope

Present/Future Instruments -2- ALMA



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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