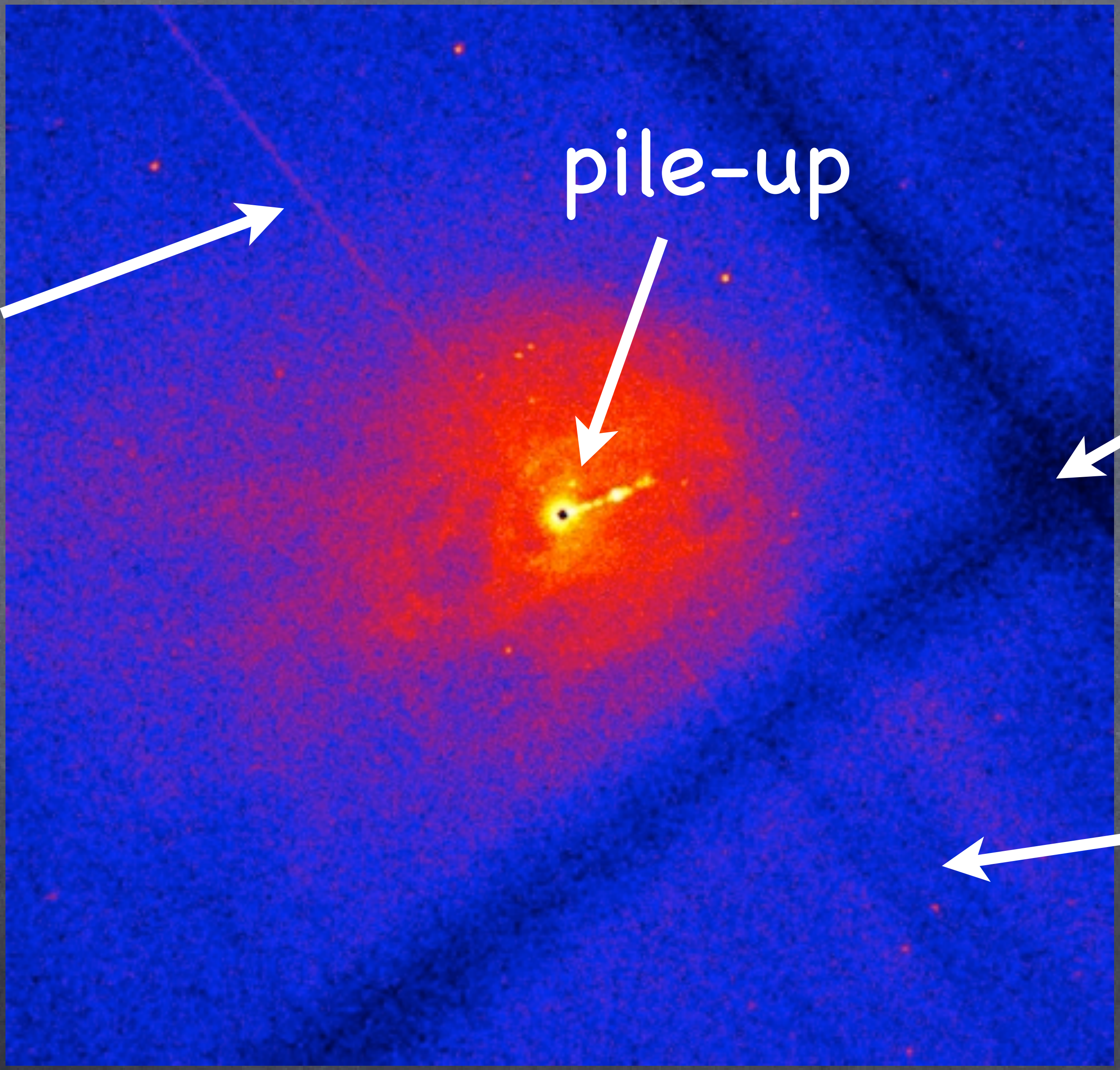
M87/Virgo Cluster in X-ray



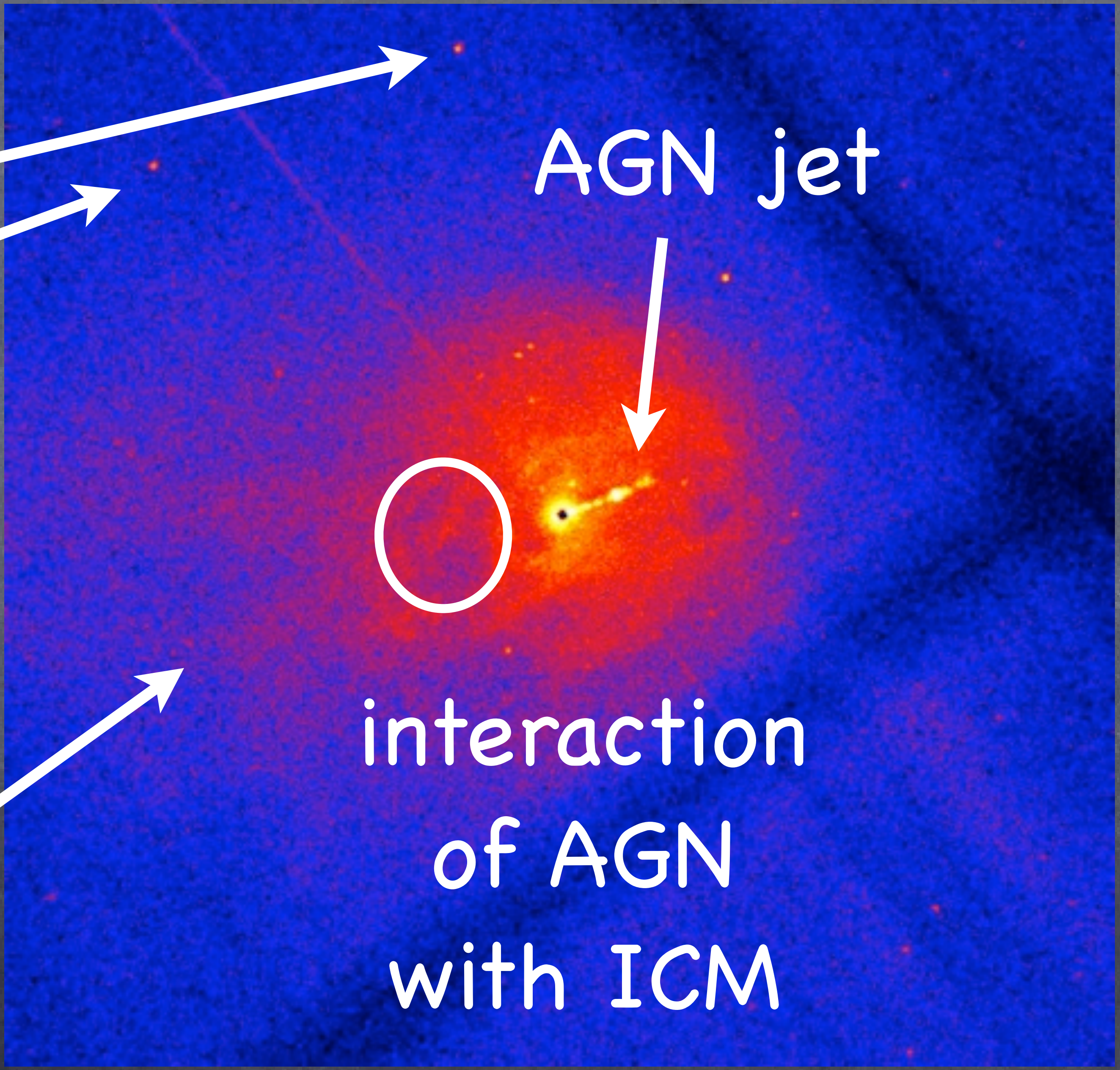
pile-up

readout streak

chip gaps

dithered bad columns

M87/Virgo Cluster in X-ray



background sources

AGN jet

interaction of AGN with ICM

cluster hot gas

Virgo Cluster Galaxies in X-ray

Cut on mr < 17 and half light radius > 5 pixels. Of these, 8 sources are within the Chandra field.

- 3 galaxies and 1 star undetected in X-ray. These are the fainter galaxies.
- M87 and 3 brighter Virgo cluster galaxies detected in the soft band. M87 and at least one are extended, the other two may be mildly extended.
- M87 and 2 (of 3) galaxies are detected in hard band. M87 is extended but the other sources are point-like.

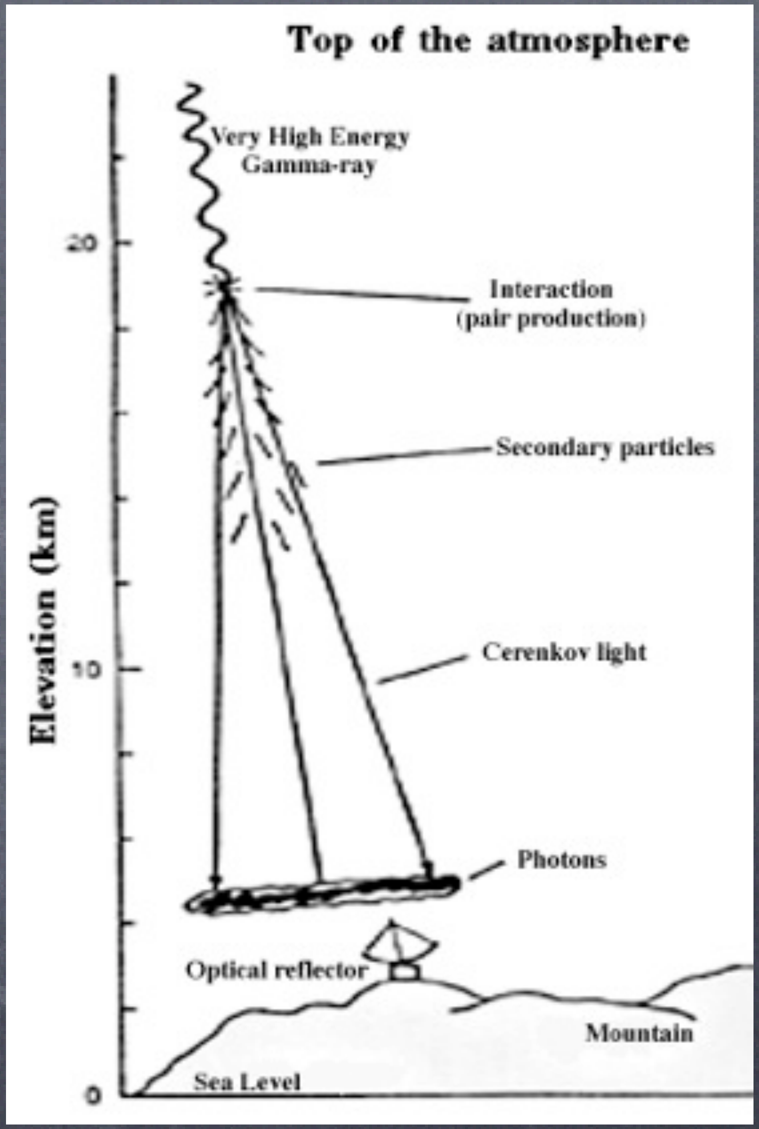
Contribution to the X-ray emission may include hot gas (soft, extended), AGN (hard, point), unresolved binaries (hard, extended), individual binaries (one of the galaxies actually has 2 detected X-ray sources).

Gamma-Ray Telescopes - Ground

Very high energy gamma-rays can be detected from the ground.

The original gamma-ray photon undergoes pair production in the upper atmosphere to produce an energetic e^-e^+ pair which then interacts with the atmosphere leading to a cascade of energetic secondary particles.

These very fast moving charged particles temporarily polarize atoms in the atmosphere leading to Cherenkov radiation, faint bluish light.



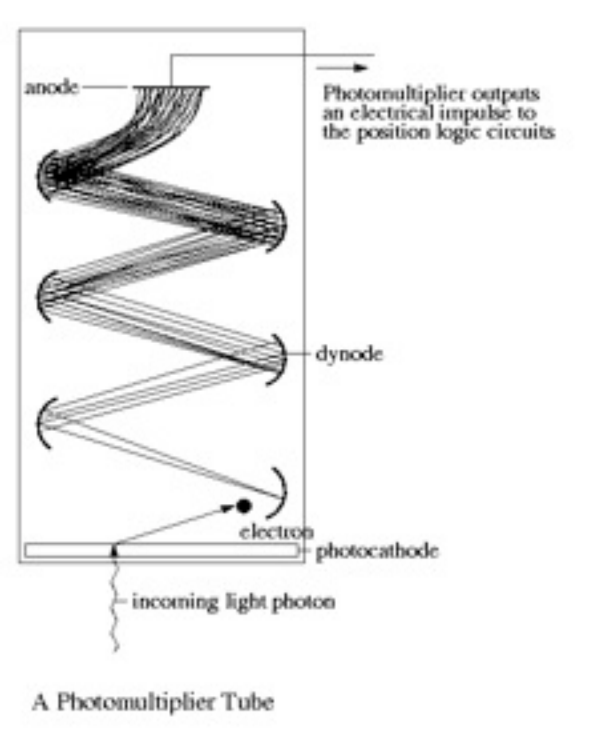
NASA Imagine the Universe: http://imagine.gsfc.nasa.gov/docs/science/how_l2/cerenkov.html

IACTs

Atmospheric (or air) Cherenkov Telescopes detect the pool of Cherenkov radiation created.

The telescopes themselves are large optical reflectors at high, dry sites. The mirrors can be lower quality than optical telescopes, but need to be big.

The detectors are composed of an array of photomultiplier tubes (vacuum tube with a series of electrodes) coupled to fast electronics, which amplify and readout the signal and provide some imaging of the Cherenkov light pool.



A Photomultiplier Tube

Extensive Air Shower Arrays

Secondary particles in the air shower produced when very high energy gamma-rays (> TeV) hit the atmosphere can survive to reach the ground.

Water Cherenkov detectors detect the Cherenkov light produced in water from these air showers.

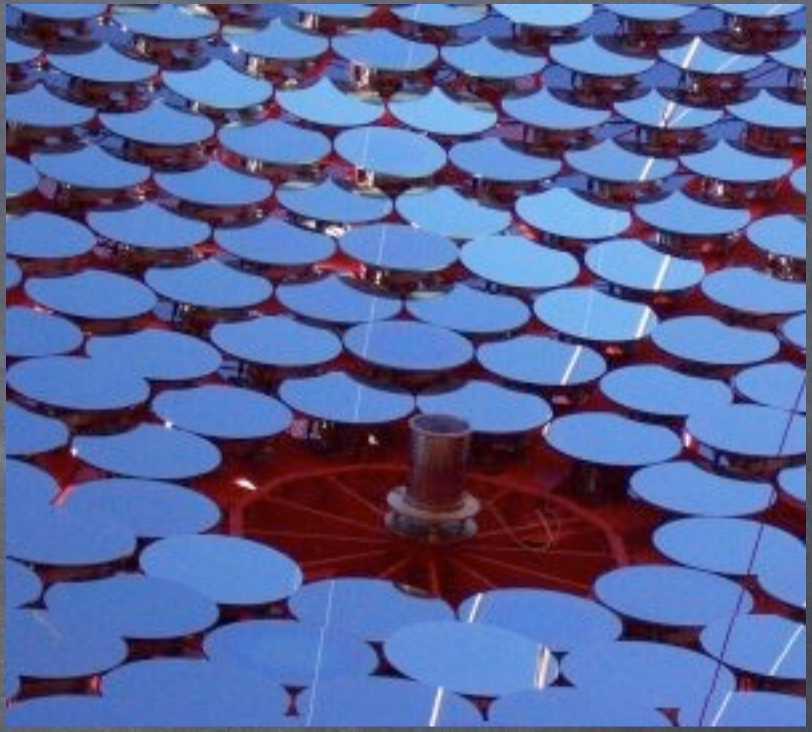
Milagro (1998-2008) used a football sized pool of water filled with 723 photomultiplier tubes.

Milagro Gamma-Ray Observatory

Current Telescopes

Atmospheric Cherenkov Telescopes (50 GeV-100 TeV):

- HESS (2002-, Namibia)
  - 4, 108 m^2 telescopes
  - Phase 2 has add one 600 m^2 mirror
- MAGIC (2004-, Canary Islands)
  - 2, 17-m telescopes
- VERITAS (2007-, Arizona)
  - 4, 12-m telescopes
- CANGAROO III (2004, Australia)
  - 4, 10-m telescopes

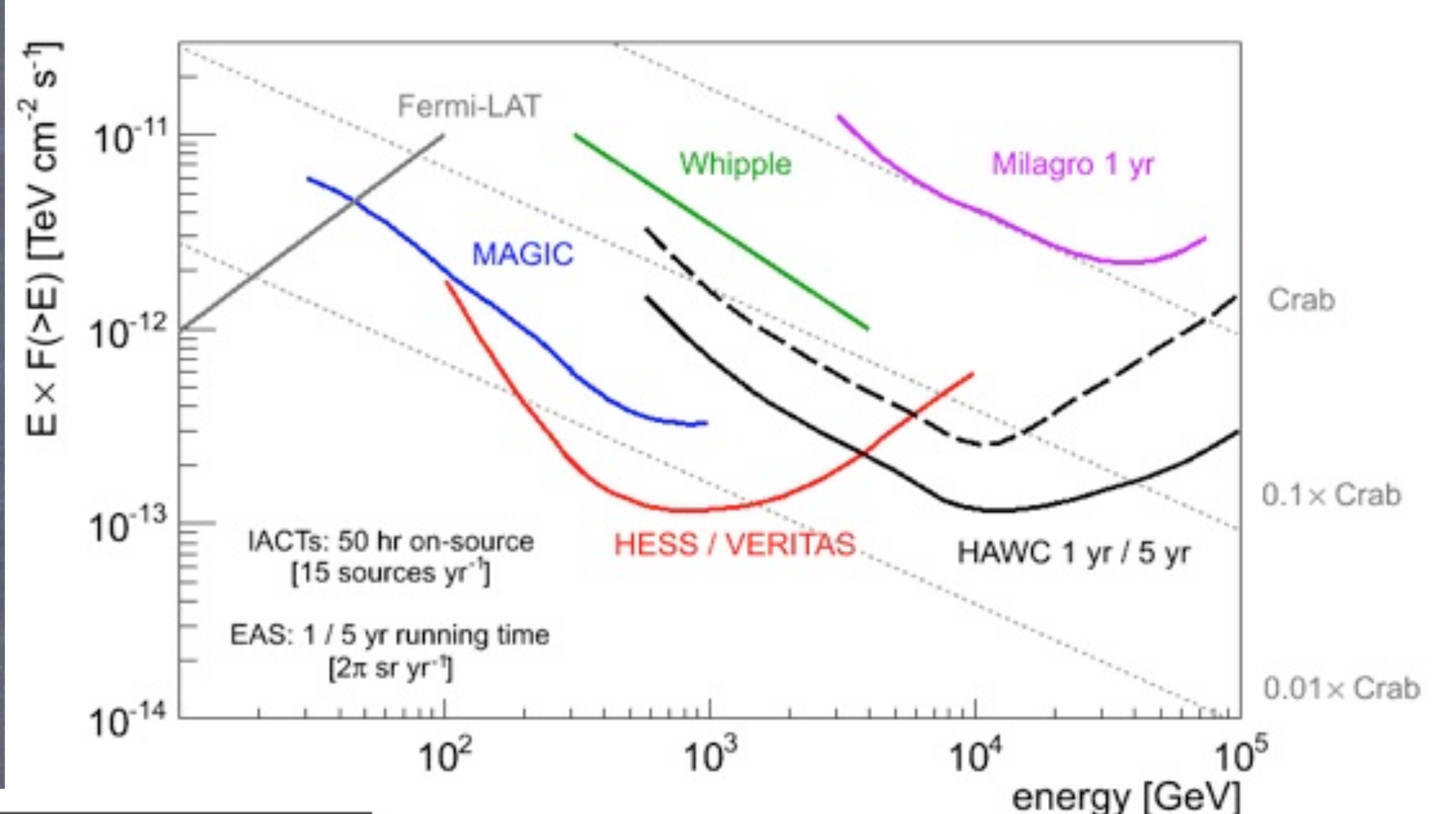


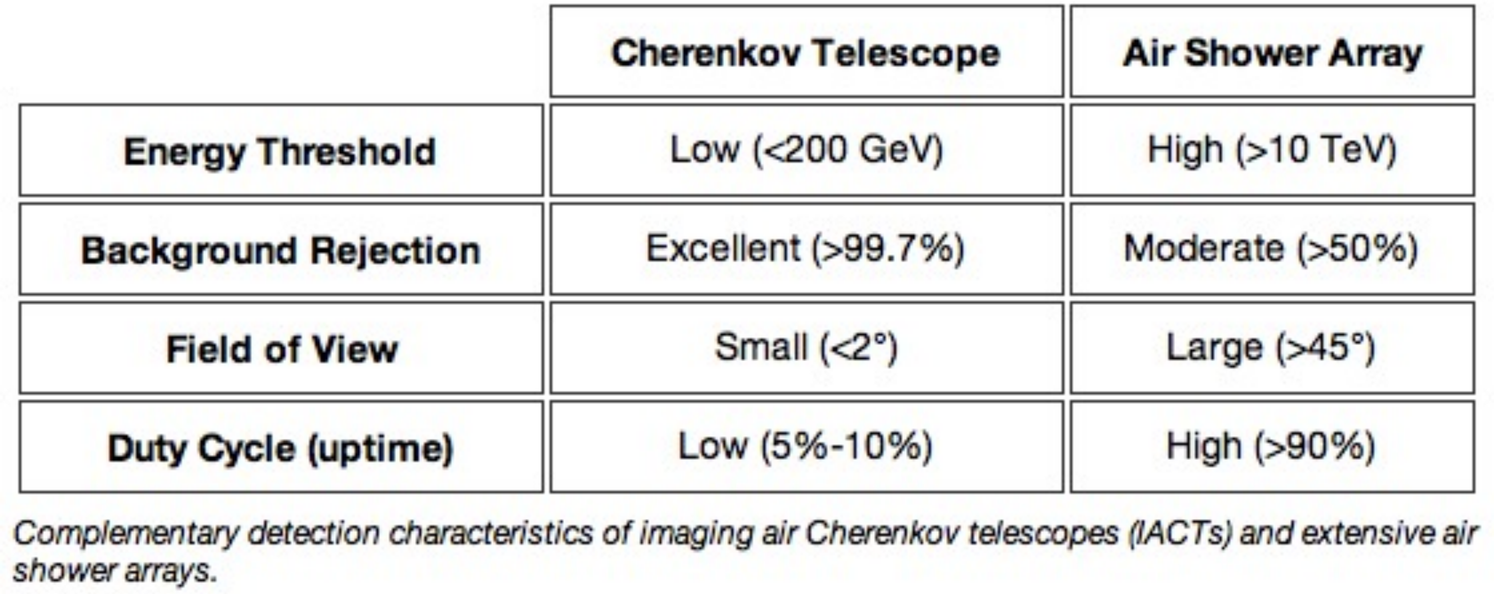
one of the HESS telescopes

Extensive Air Shower Array (> few TeV):

- Milagro (1998-2008, near Los Alamos)
  - 4800 m^2 of water

Instrument Comparisons





	Cherenkov Telescope	Air Shower Array
Energy Threshold	Low (<200 GeV)	High (>10 TeV)
Background Rejection	Excellent (>99.7%)	Moderate (>50%)
Field of View	Small (<2°)	Large (>45°)
Duty Cycle (uptime)	Low (5%-10%)	High (>90%)

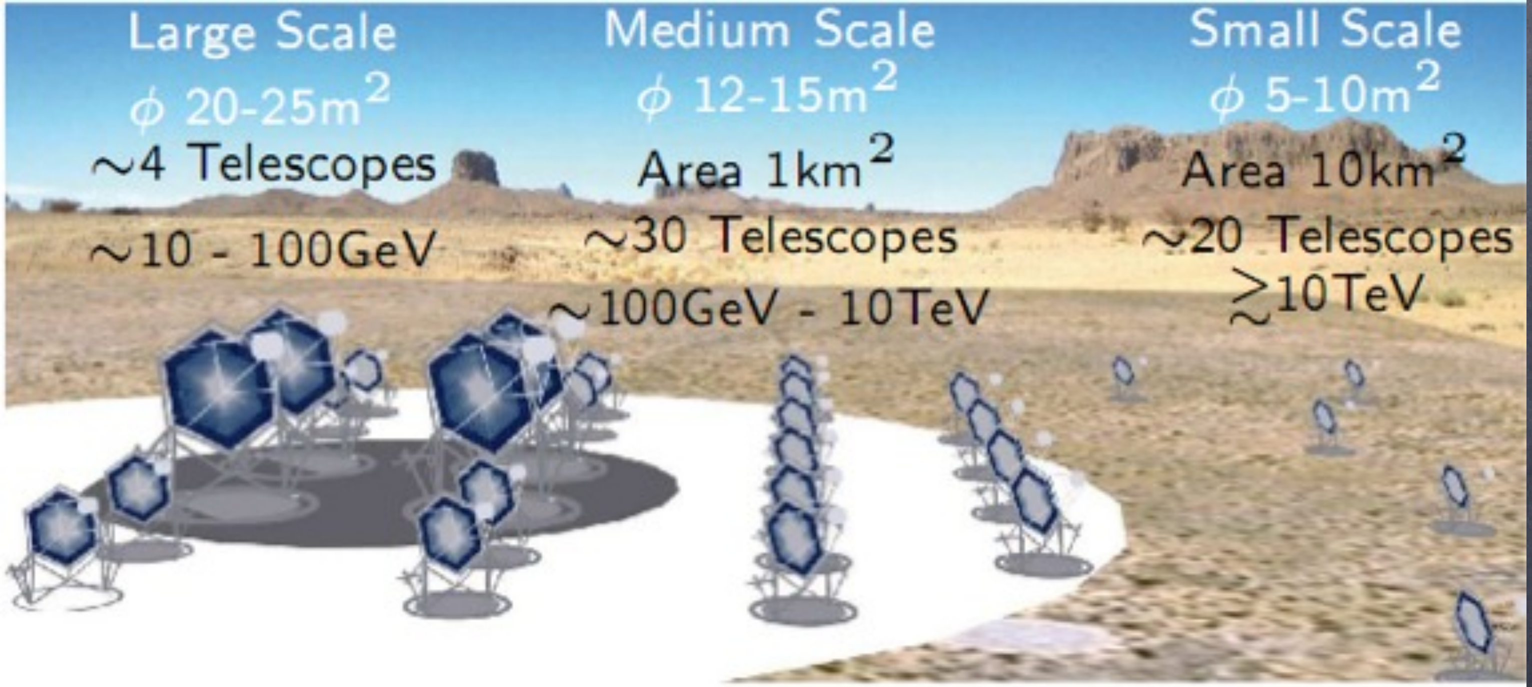
Complementary detection characteristics of imaging air Cherenkov telescopes (IACTs) and extensive air shower arrays.

Future Telescopes - IACT

The Cherenkov Telescope Array (CTA): design is still under consideration. Both a northern and southern array are planned.

Will consist of tens of telescopes of varying size (24m, 10-12m, 4-6m) to get sensitivity to both low and high energy gamma-rays.

Potentially the northern array will concentrate on extragalactic science and the lowest energies with the southern array concentrating on galactic sources and full energy range.



sensitivity from tens of GeV to > 10 TeV

Future Telescopes - EAS

HAWC: will be a water Cherenkov detector composed of 300 closely packed steel water tanks each with 4 photomultipliers. Located at 4100m in Mexico.

The aperture covers 15% of the sky and will sample half the sky in 24 hours.

Designed to probe TeV gamma-rays and cosmic rays

Radio Astronomy

Picture by Michael Bietenholz using data from the NRAO and Rick Perley (prize-winner in the NRAO/AUI Radio Astronomy Image Awards)

References

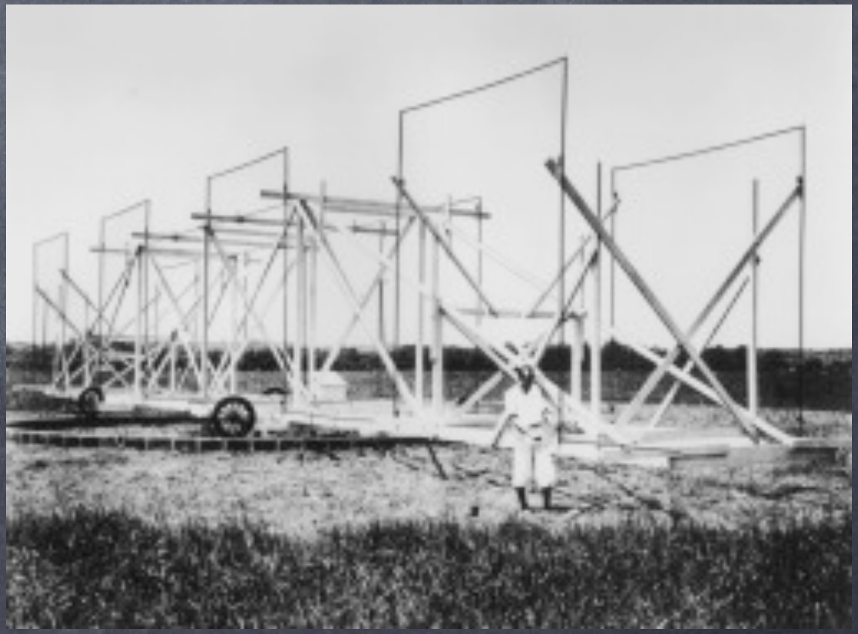
“Measuring the Universe” - Rieke, Chapt. 8 and 9

“Tools of radio astronomy” - Wilson, Rohlfs, Hüttemeister

“Techniques of Radio Astronomy” - Wilson, arXiv:1111.1183

“ESSENTIAL RADIO ASTRONOMY” - Condon and Ransom, NRAO: http://www.cv.nrao.edu/course/astr534/ERA.shtml

Beginning of Radio Astronomy



The first cosmic radio source was discovered by Karl Jansky in the early 1930's. Jansky was working for Bell Labs investigating sources of static which might interfere with radio communications.

He built an antenna (20.5 MHz) mounted on a turntable with Model-T tires (Jansky's merry-go-round). He detected both thunderstorms and a faint steady hiss which after months of monitoring he discovered was coming from the center of the Milky Way.

Beginning of Radio Astronomy

Fascinated by Jansky's discovery, Grote Reber built his own radio telescope in his backyard in Illinois in 1937. His telescope was a 9-m reflector composed of sheet metal.

Reber conducted the first survey of the radio sky. He also studied the spectrum of cosmic radio sources, showing it was inconsistent with black-body radiation (discovery of synchrotron emission).

Sources of Emission

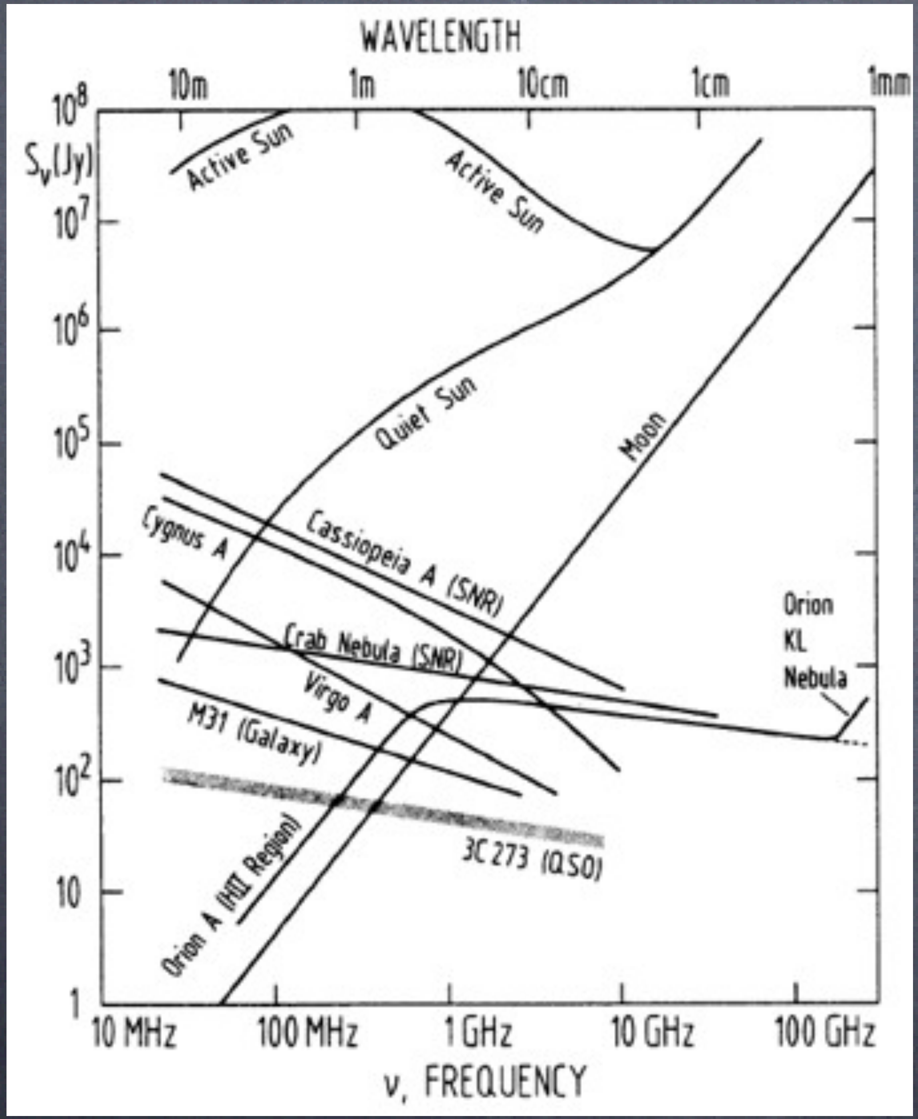
Processes producing radio emission include:

- bremsstrahlung (HII regions)
- synchrotron (SNR, pulsars, AGN)
- line emission from low energy transitions (hyperfine splitting - 21cm for hydrogen, rotational transitions - CO)
- black-body (CMB, Moon)
- masars (stimulated emission from molecular lines like OH)

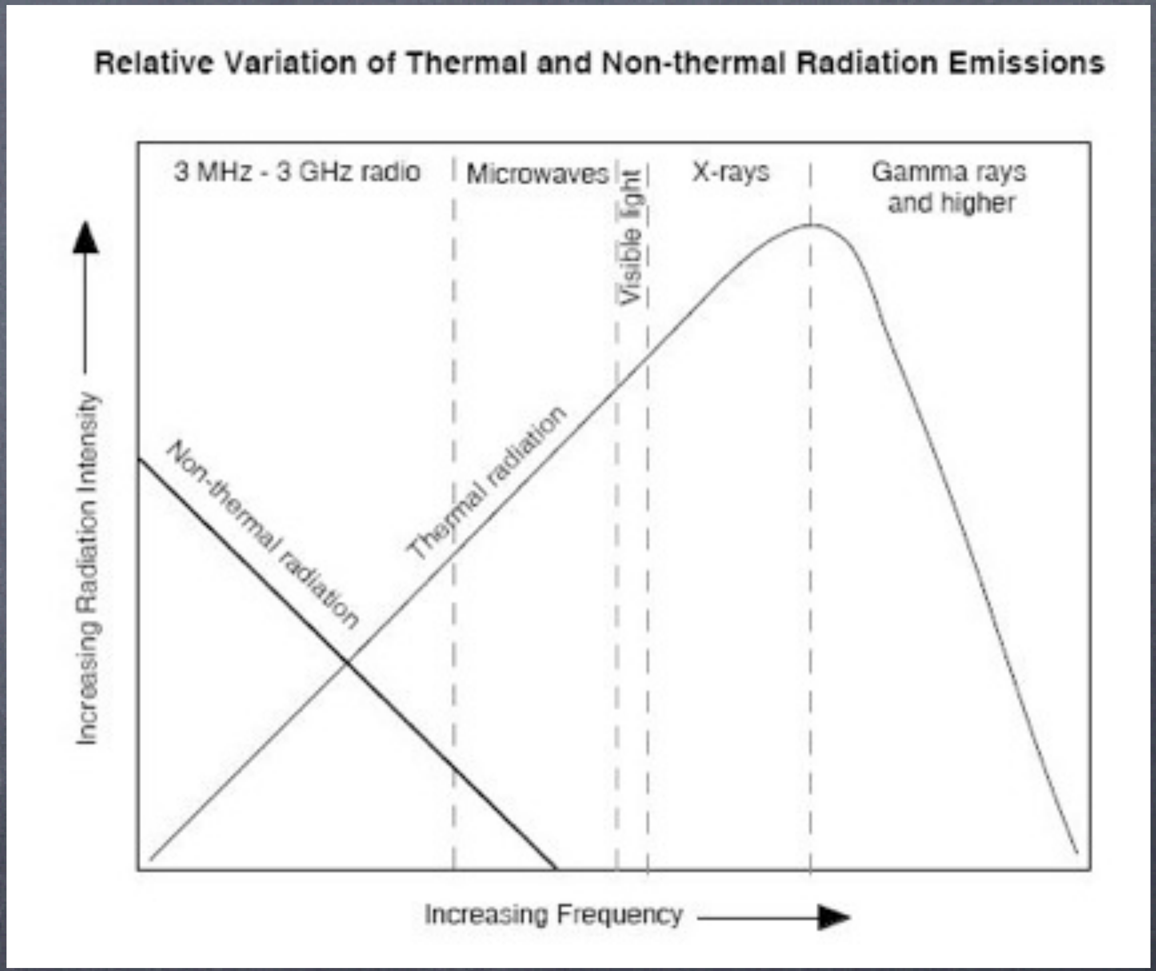
Radio sources:

- the Sun
- AGN, jets, the Galactic Center
- pulsars (discovered by Bell and Hewish in 1967)
- supernova remnants
- star formation: molecular lines from cold gas (HI, CO), bremsstrahlung from HII regions
- clusters of galaxies

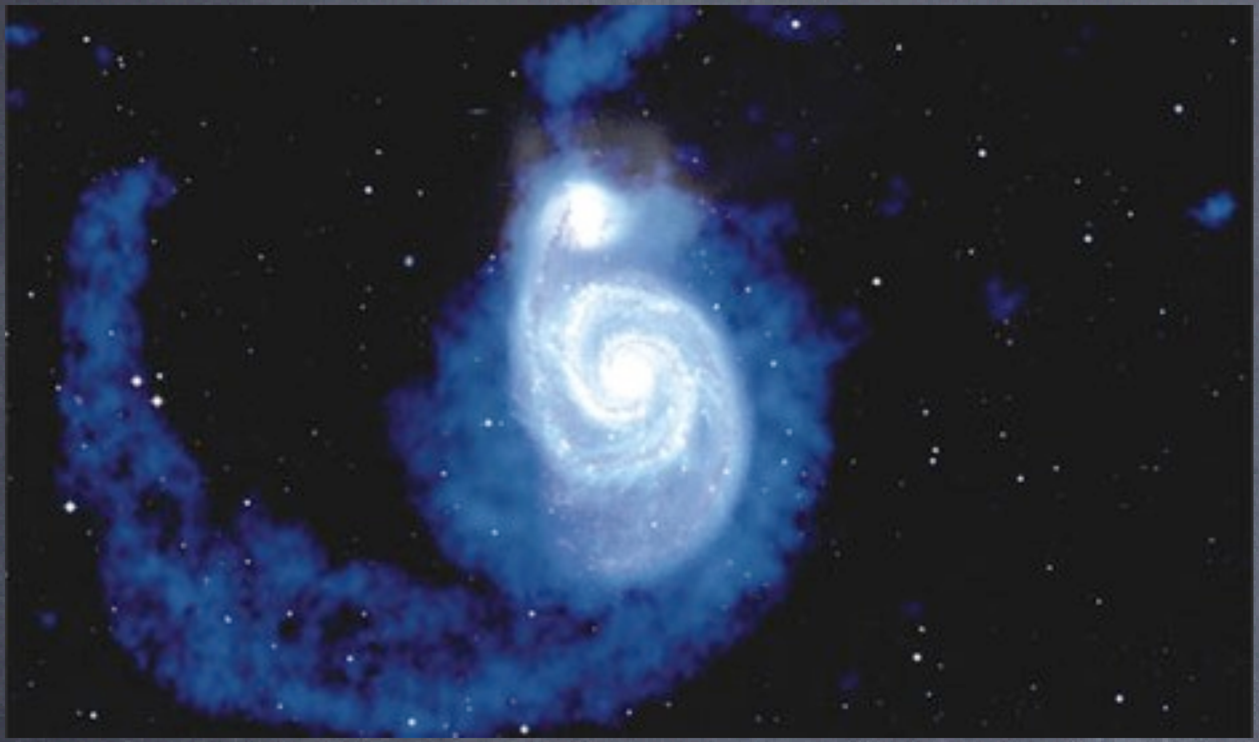
Sources of Emission - thermal vs. non-thermal



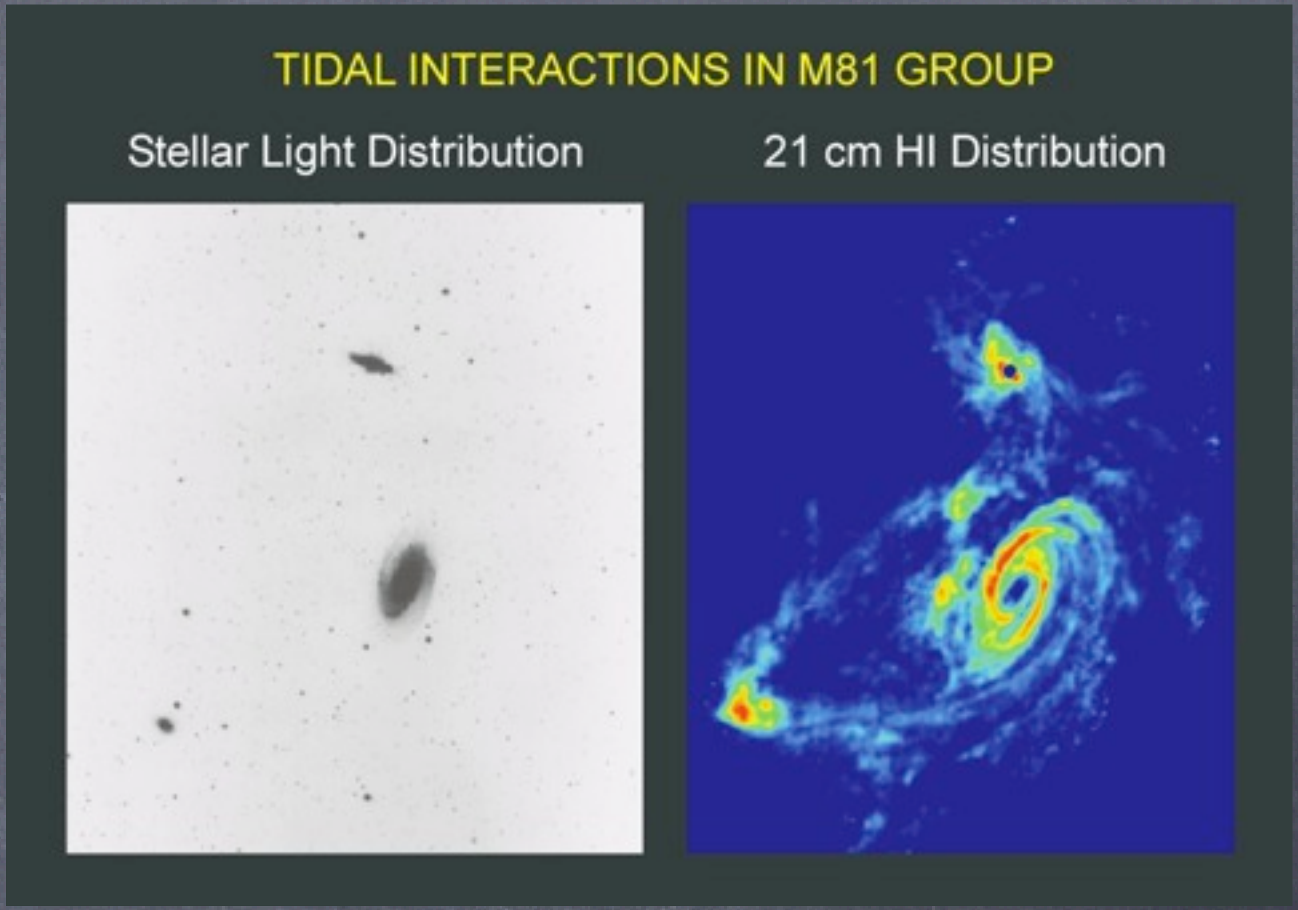
"Tools of radio astronomy" - Wilson, Rohlfs, Hüttemeister



Cold Gas

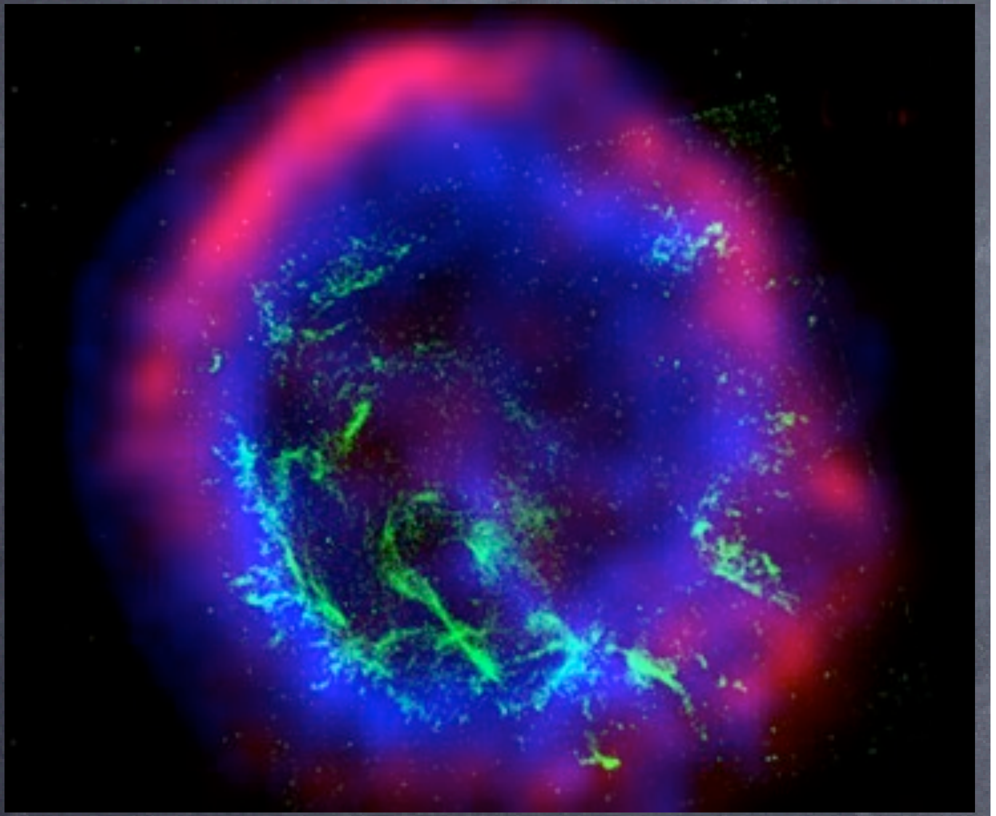


Whirlpool Galaxy, HI emission from the galaxy's cold hydrogen gas in blue (Credit: NRAO/AUI, J. Uson)

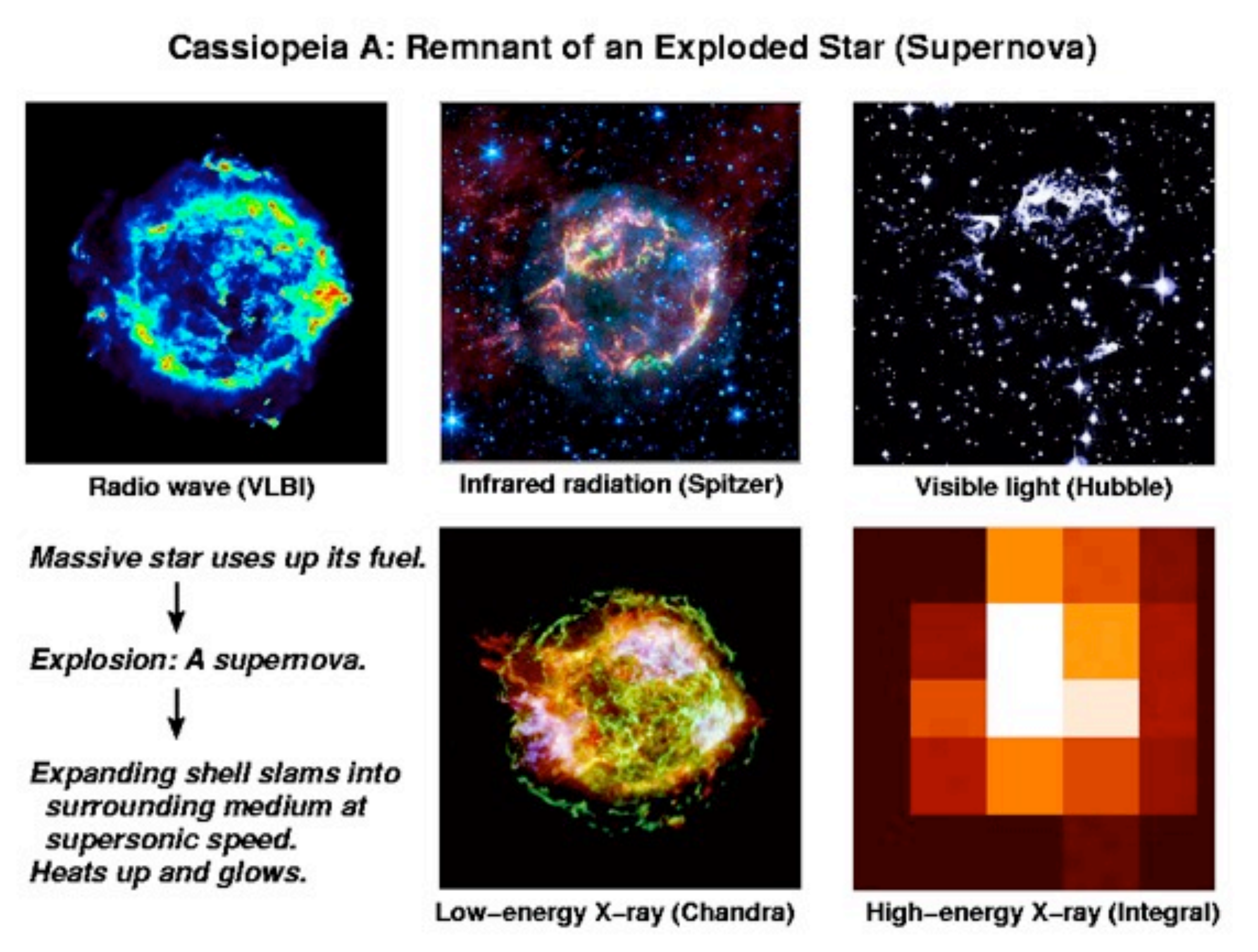


HI observations allowed observation of the spiral structure of the Milky Way, rotation curves of galaxies.

Supernova Remnants



red: radio
green: optical
blue: X-ray



Cassiopeia A: Remnant of an Exploded Star (Supernova)

Radio wave (VLBI)

Infrared radiation (Spitzer)

Visible light (Hubble)

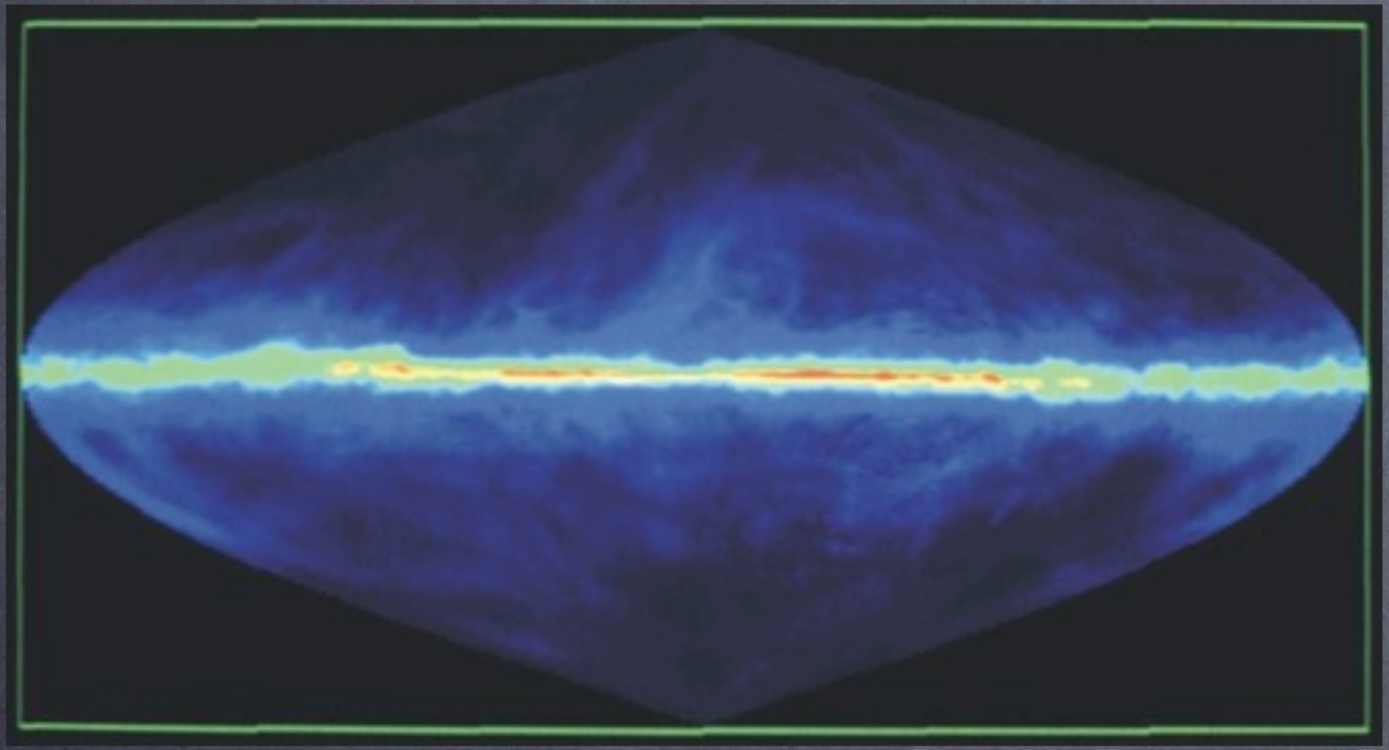
Massive star uses up its fuel.
↓
Explosion: A supernova.
↓
Expanding shell slams into surrounding medium at supersonic speed.
Heats up and glows.

Low–energy X–ray (Chandra)

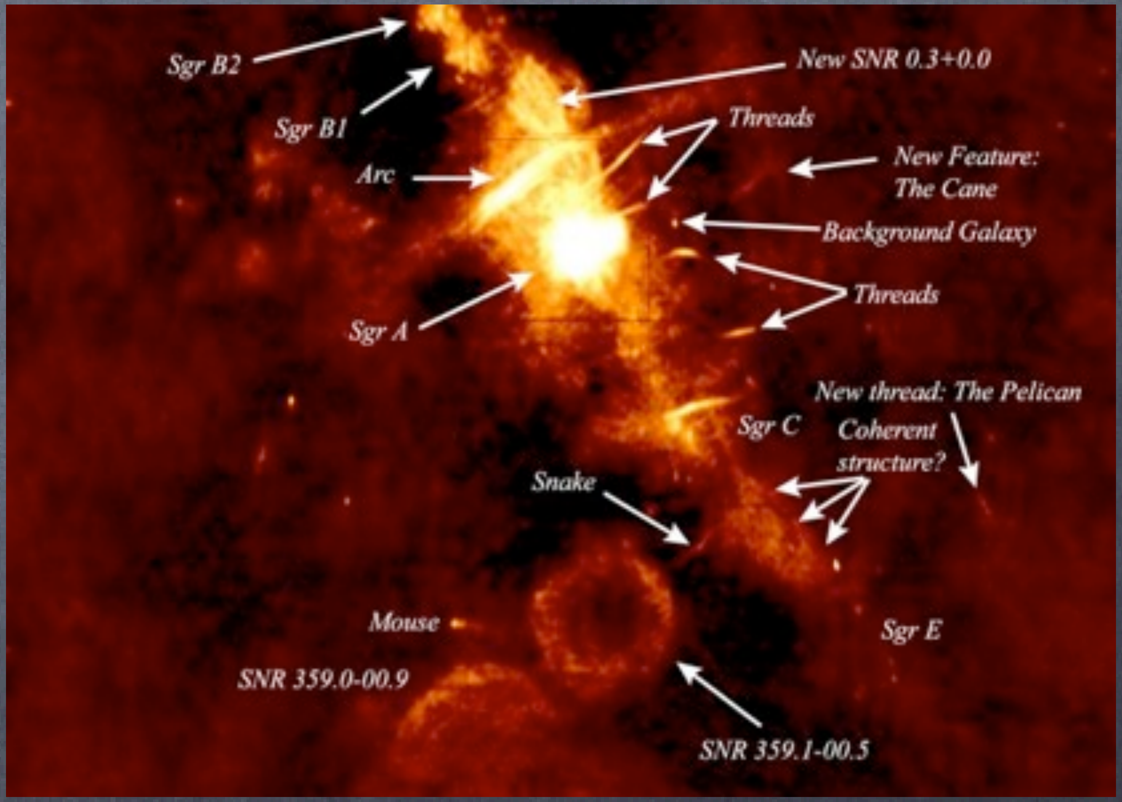
High–energy X–ray (Integral)

The Milky Way

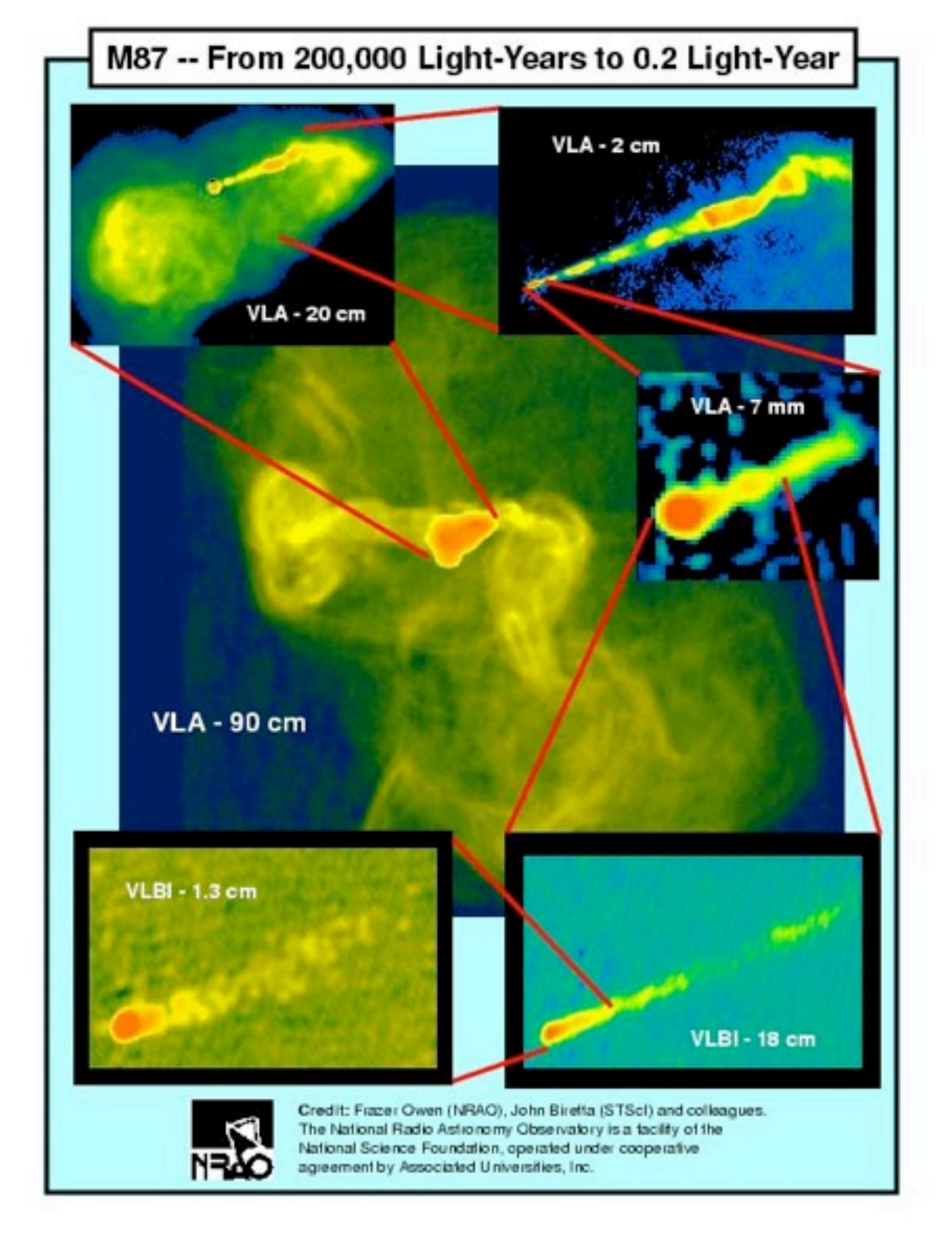
The Milky Way in HI



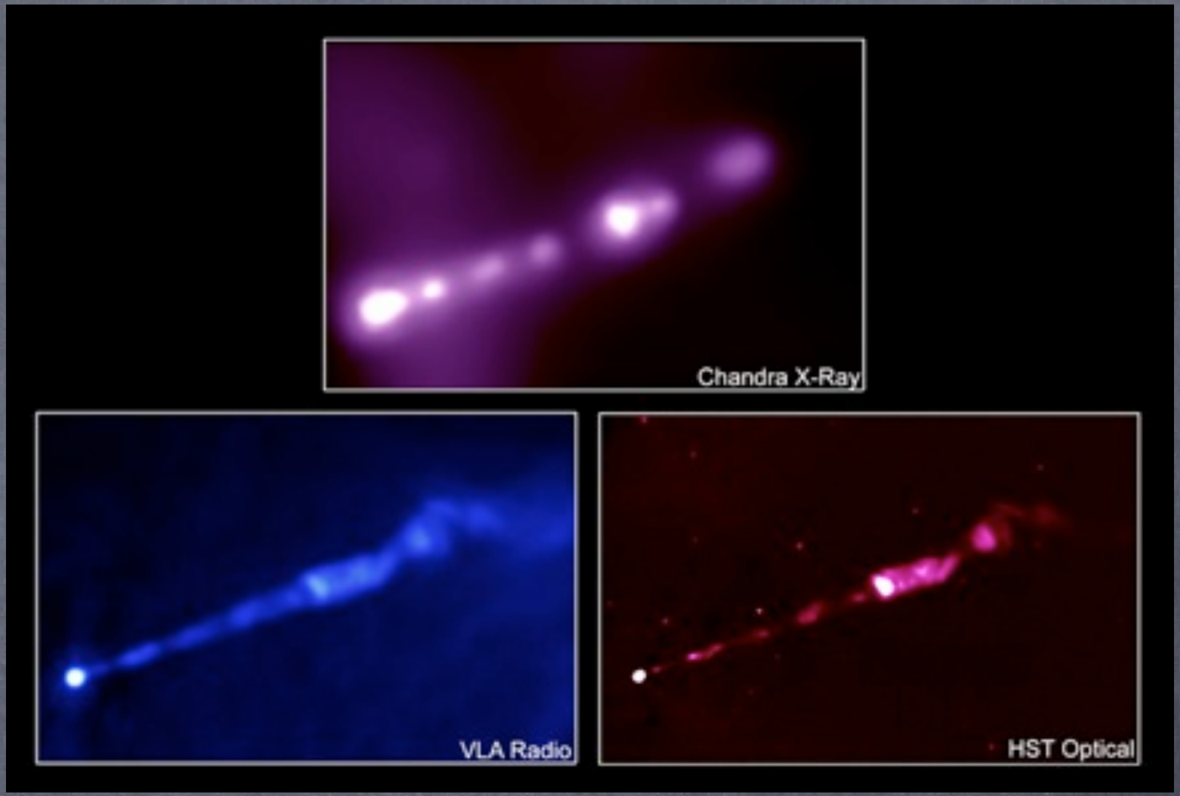
Galactic Center



M87


M87 -- From 200,000 Light-Years to 0.2 Light-Year

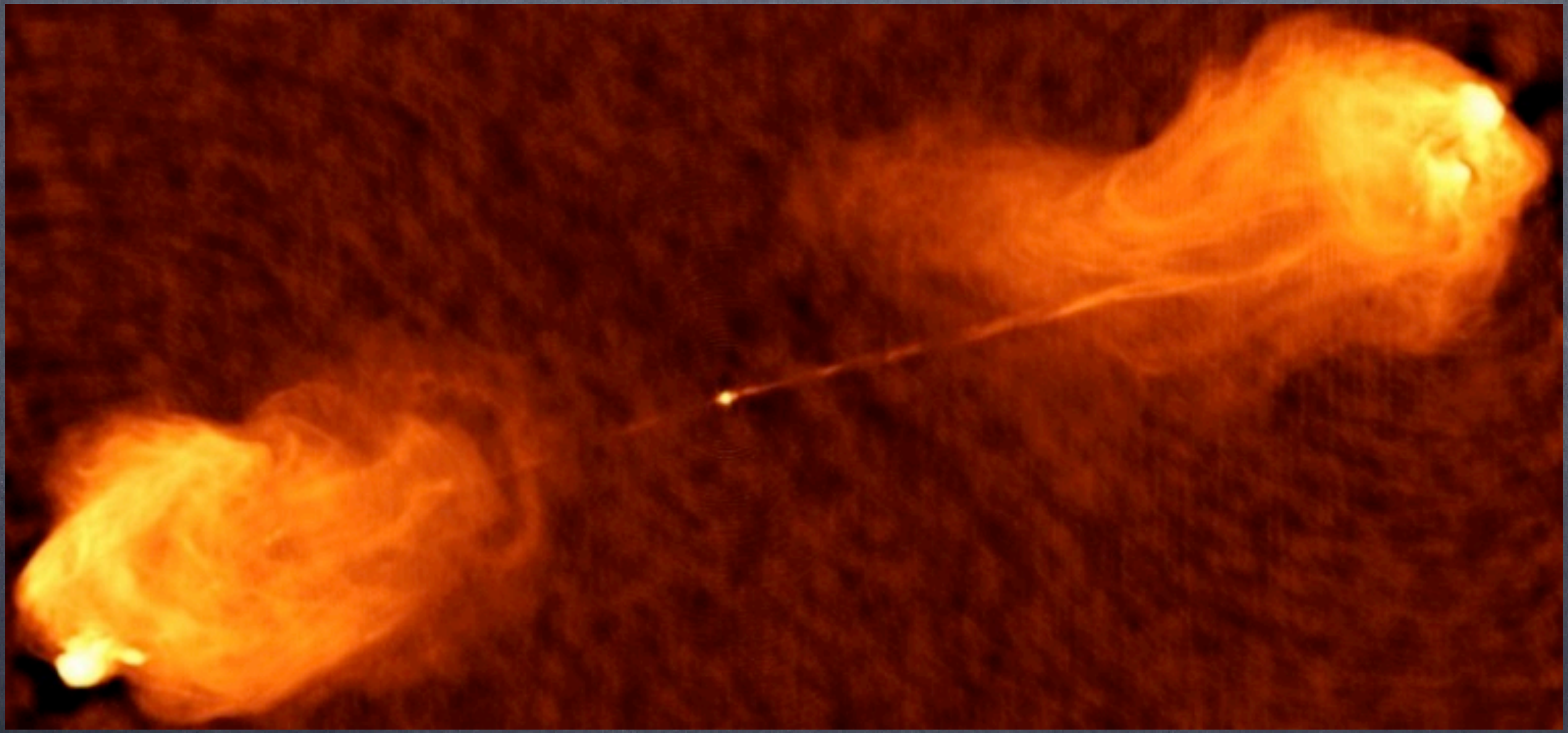
Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.



Note: resolution better at shorter λ and for longer baselines

Cygnus A

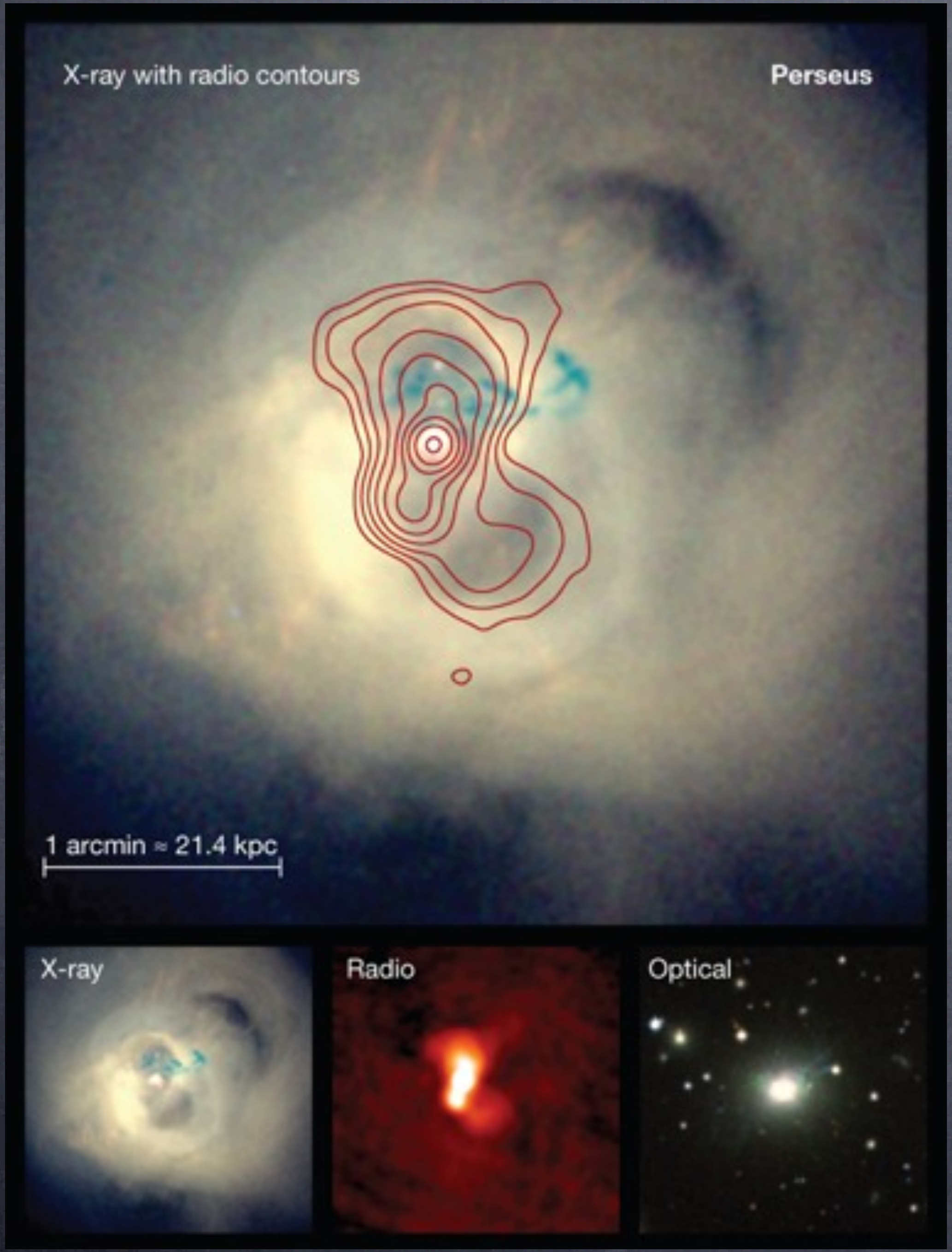
The brightest extragalactic radio source in the sky with an extent of 100 kpc, much longer than the extent of the stars in the galaxy.



A high-resolution VLA image of the radio source Cygnus A.

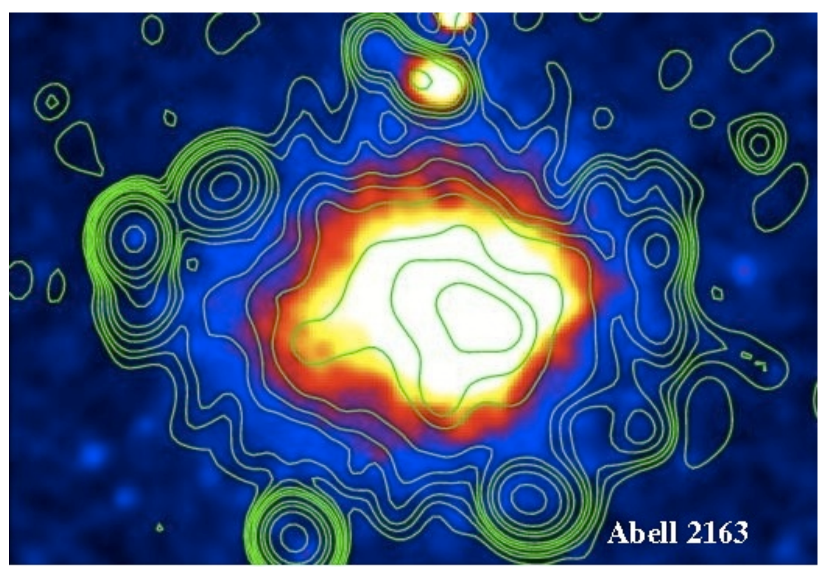
Clusters of Galaxies

Perseus - AGN feedback

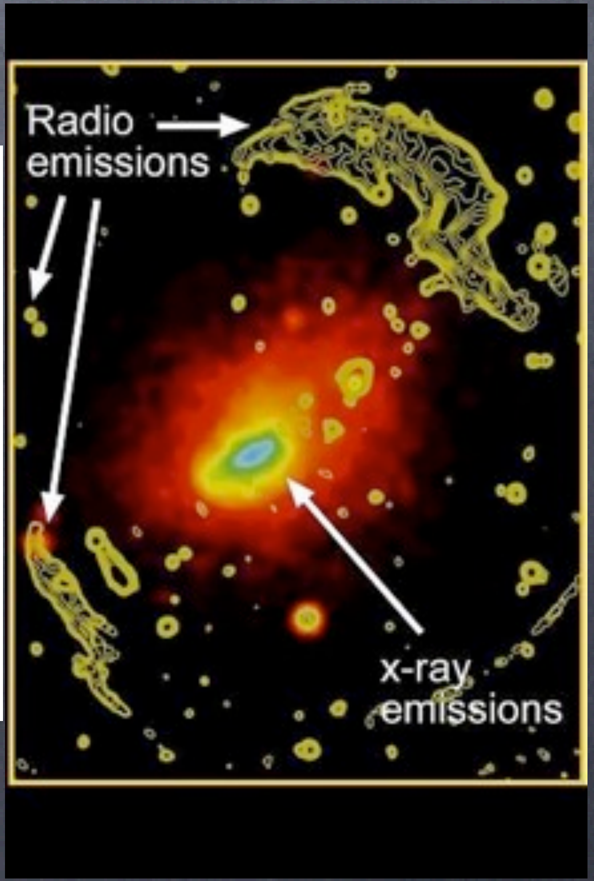


Cattaneo et al. 2009, Nature 460, 213

Particle acceleration - Radio Halos and Relics

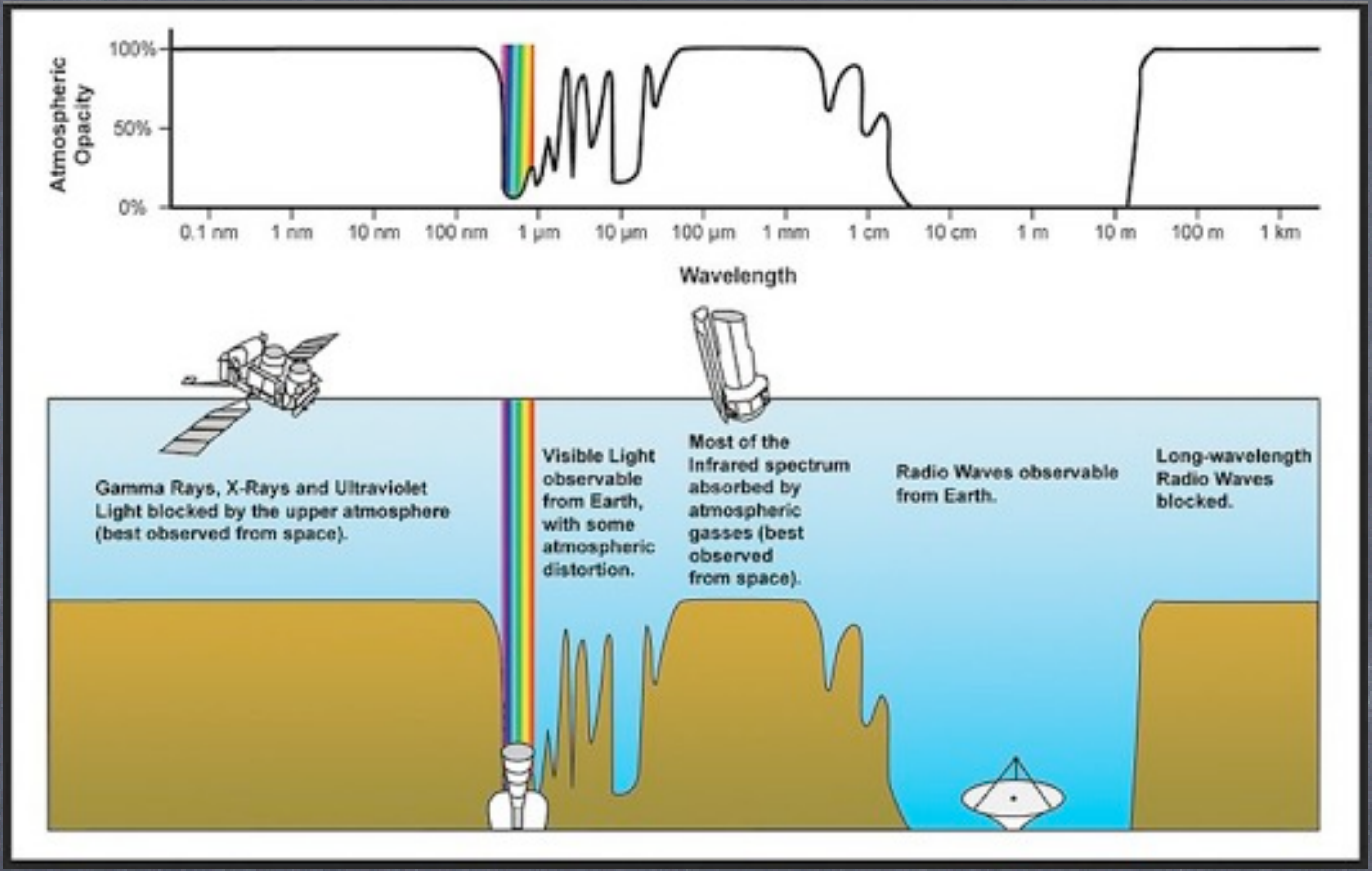


Abell 2163



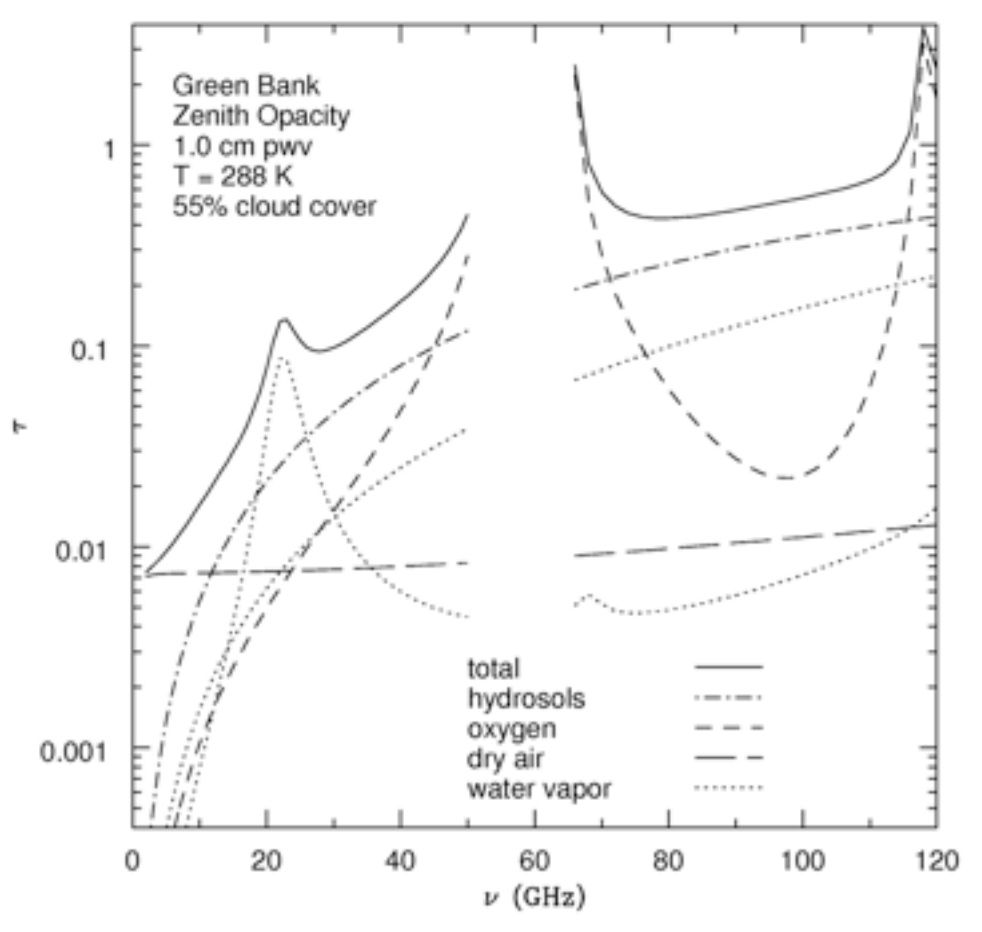
Abell 3667

Atmospheric Window



The radio window stretches over several decades in frequency from 5 MHz and 300 GHz, limited at the low end by reflection by the ionosphere and at the high end by absorption by water and CO_2.

Atmospheric Attenuation



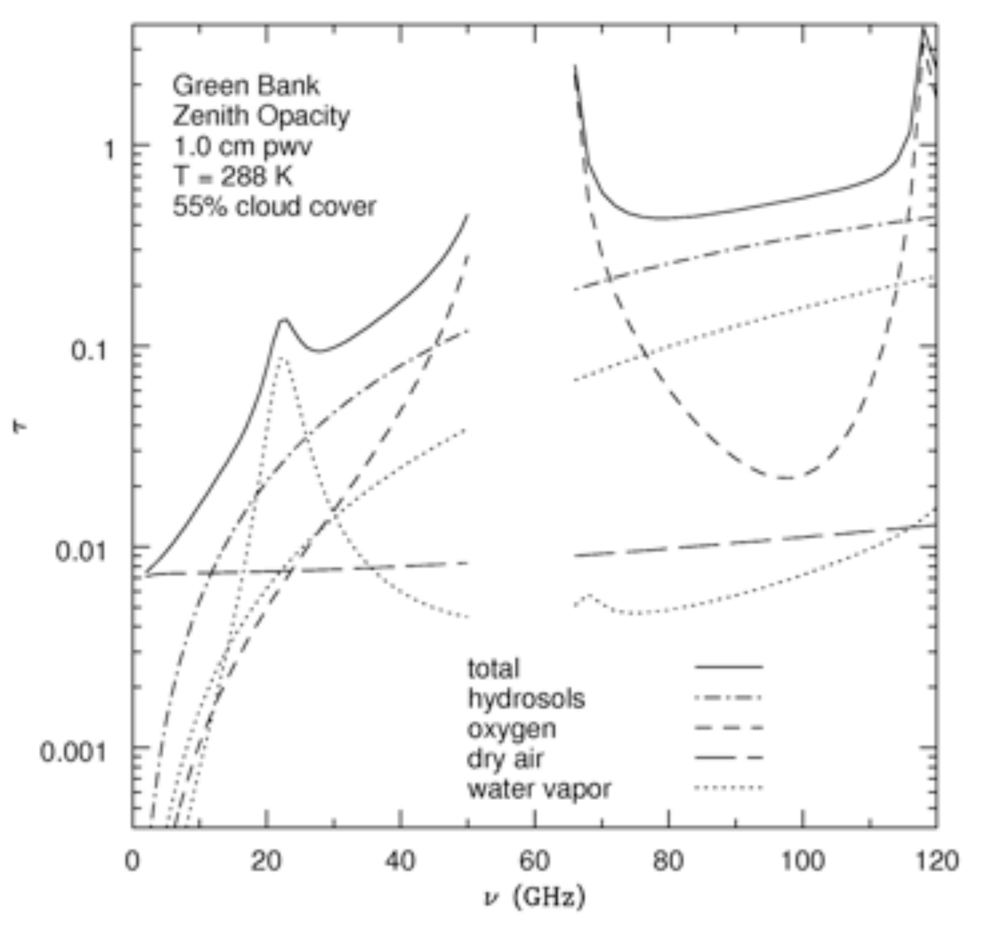
Leibe, H. J. 1985, Radio Science, 20, 1069

The atmosphere is not perfectly transparent in radio and has an absorption that is weather dependent. In particular, water vapor and water droplets can attenuate radio, and O_2 has rotational transitions that make the sky quite opaque around 60 GHz.

The source signal is reduced as

$$S \propto e^{-\tau}$$

Atmospheric Noise



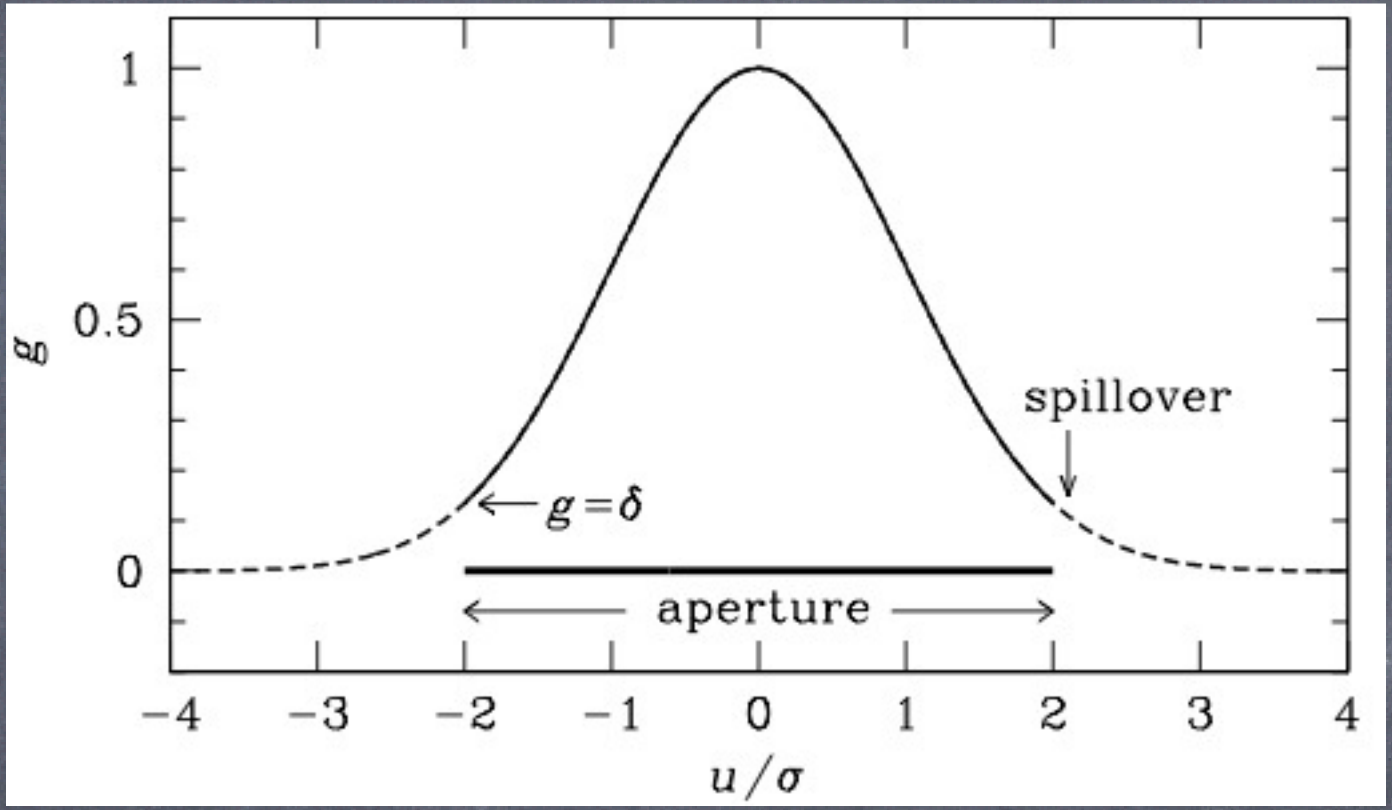
Leibe, H. J. 1985, Radio Science, 20, 1069

The atmosphere also emits radio noise dependent on the atmosphere kinetic temperature and opacity. The noise added by the atmosphere is

$$T_{atmosphere} (1-e^{-\tau})$$

The ground is another source of radio noise, both from the ground temperature and from reflected radiation.

Spillover



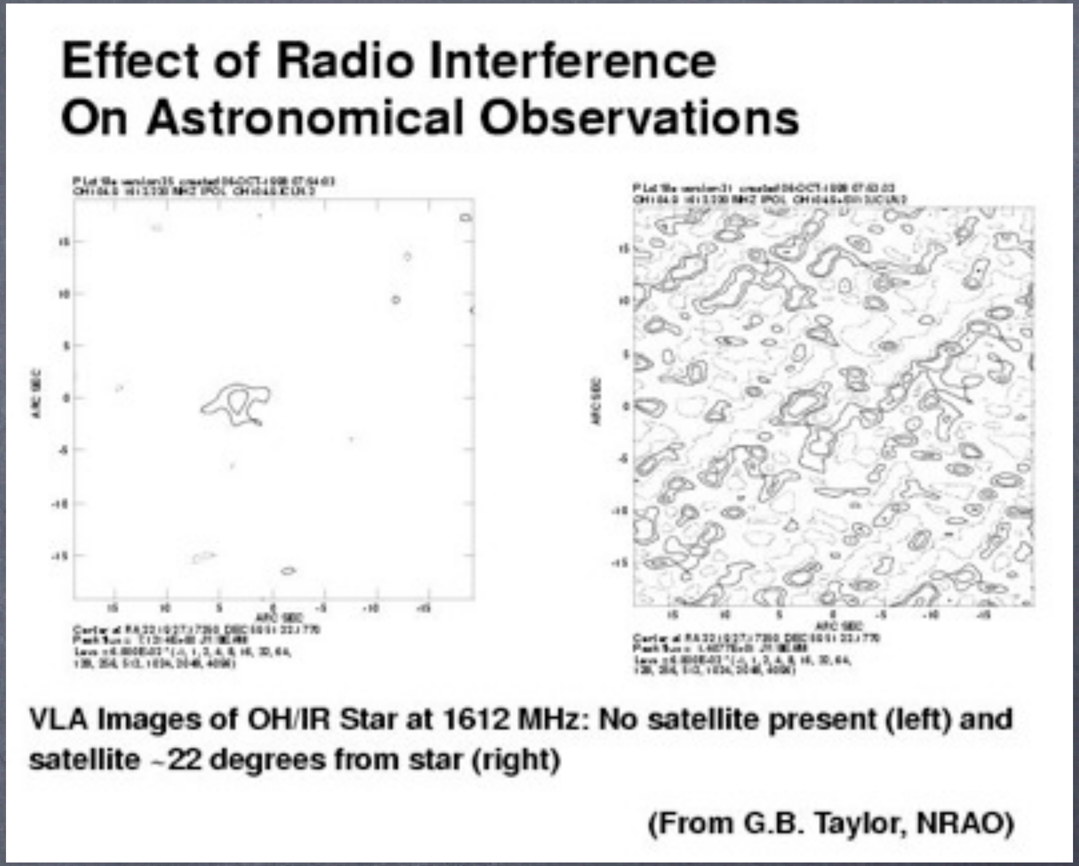
“ESSENTIAL RADIO ASTRONOMY” - Condon and Ransom

Spillover is the fraction of the radiation not intercepted by the telescope. Reflection of spillover from the ground adds noise.

Backgrounds - Human

Man-made interference is a big problem. A cell phone on the Moon would be a strong radio source!

Certain narrow bands are reserved for radio astronomy, and radio telescopes are located in radio quiet areas (sometimes in valleys), but this is an increasing problem.



Effect of Radio Interference On Astronomical Observations

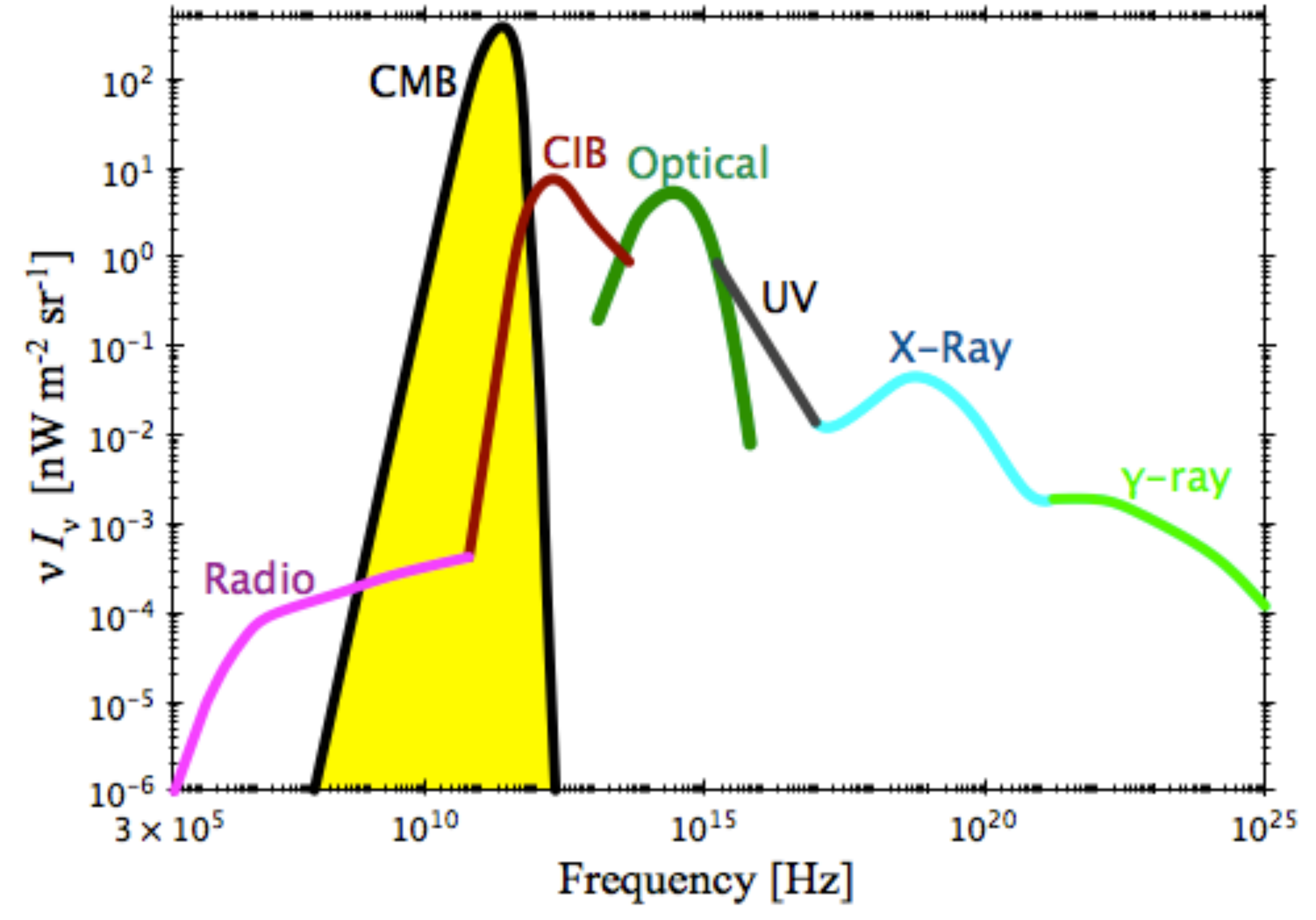
VLA Images of OH/IR Star at 1612 MHz: No satellite present (left) and satellite ~22 degrees from star (right)

(From G.B. Taylor, NRAO)

NRAO website

Poor engineering can cause transmitters to emit outside their proscribed range. Satellites particularly a problem, but also cell phones, microprocessors in everything, ...

Backgrounds - Cosmic



The CMB obviously gives a very large background, but outside this range the cosmic radio background is quite low.

Radio Units and Terms

Units:

frequency: Hz

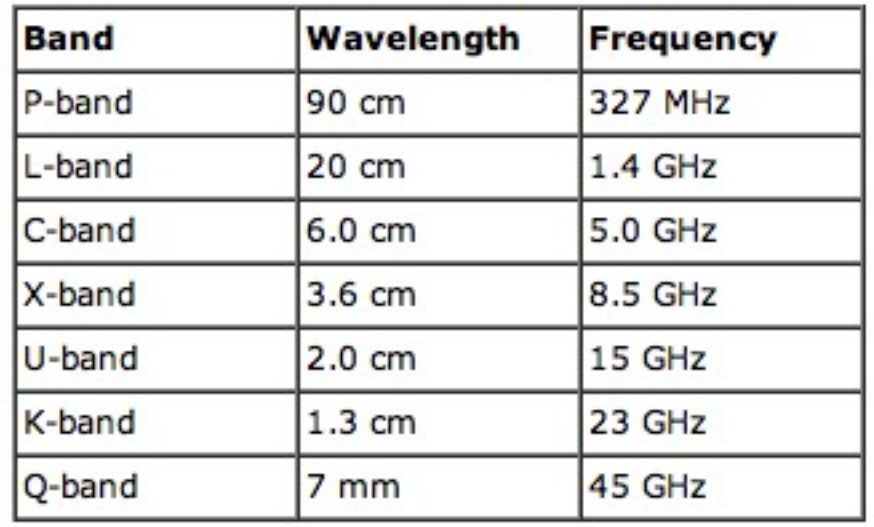
source brightness: Jy (1 Jy = 10^{-26} W m^{-2} Hz^{-1} = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}), this is a flux density

surface brightness: expressed in terms of brightness temperature, the temperature of a blackbody that would have the same intensity per unit solid angle

(and you thought magnitudes were annoying)

Radio bands:

certain narrow frequency bands are reserved for radio astronomy, and observations are made near particular frequencies

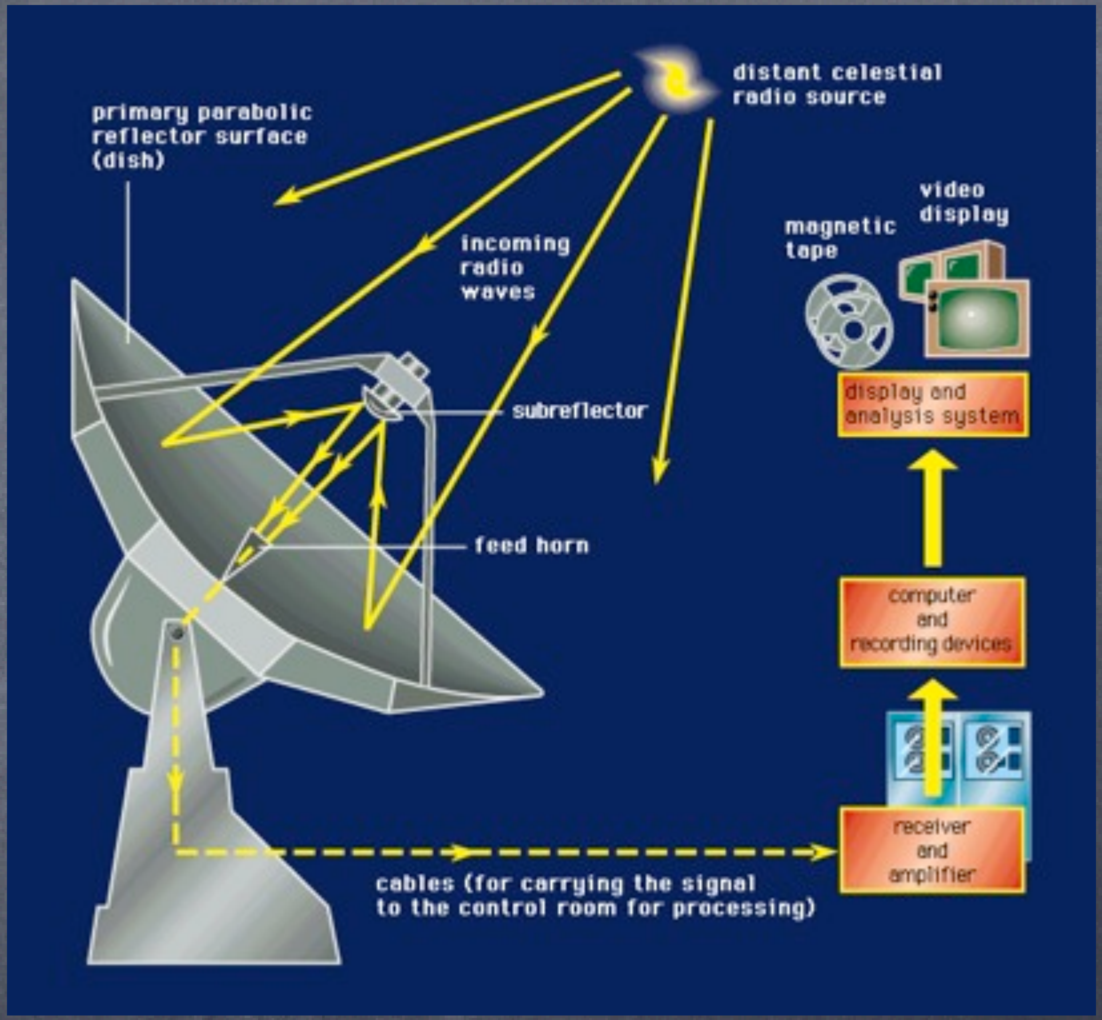


Band	**Wavelength**	**Frequency**
P-band	90 cm	327 MHz
L-band	20 cm	1.4 GHz
C-band	6.0 cm	5.0 GHz
X-band	3.6 cm	8.5 GHz
U-band	2.0 cm	15 GHz
K-band	1.3 cm	23 GHz
Q-band	7 mm	45 GHz

Radio Telescopes

Most radio telescopes are large parabolic dish antennas (filled aperture). They are reflectors with similar designs to optical telescopes (e.g. Cassegrain, Gregorian).

In radio, telescopes don't need to be perfect parabolic reflectors; the tolerance for irregularities depends on the highest frequency probed (~1/16 of shortest wavelength).



At long enough wavelengths the reflector surface can be simple wire mesh (wavelengths much longer than the mesh size).

Radio Telescopes

Gravitational deformation can effect the short λ performance of very large movable dishes.

Homologous telescope designs are used to improve the short wavelength sensitivity. Here the telescope is allowed to deform under gravity, but structural elements are designed such that the reflecting surface deforms to a new paraboloid with a slightly different focus. The feed of secondary reflector is then moved.

The 100-m Effelsberg Telescope in Germany was the first large telescope with this type of design, and it works down to 7mm wavelengths.

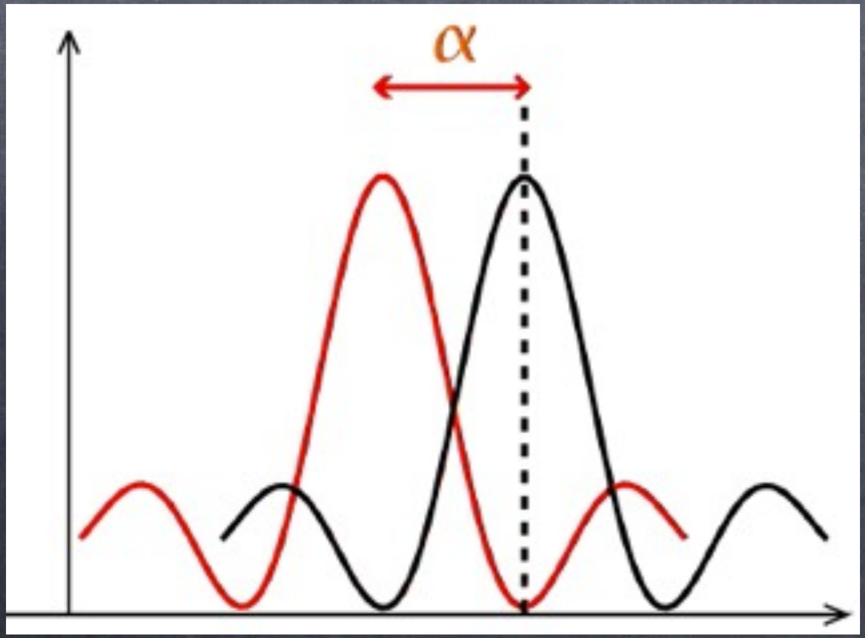
Spatial Resolution - Single Dish

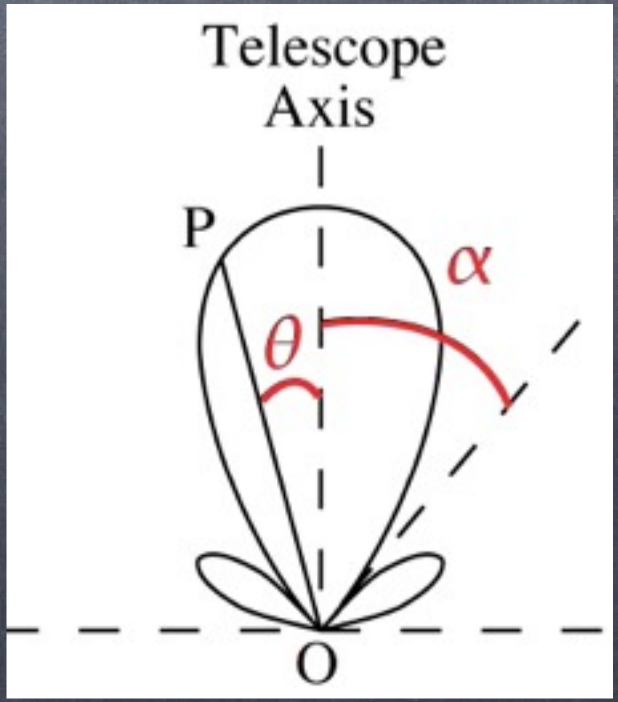
Diffraction limit: $\theta = 1.22\ \lambda/D$

So for a 300-m dish $\lambda = 20$ cm, $\theta = 2.8'$

$\lambda = 1.3$ cm, $\theta = 10.9''$

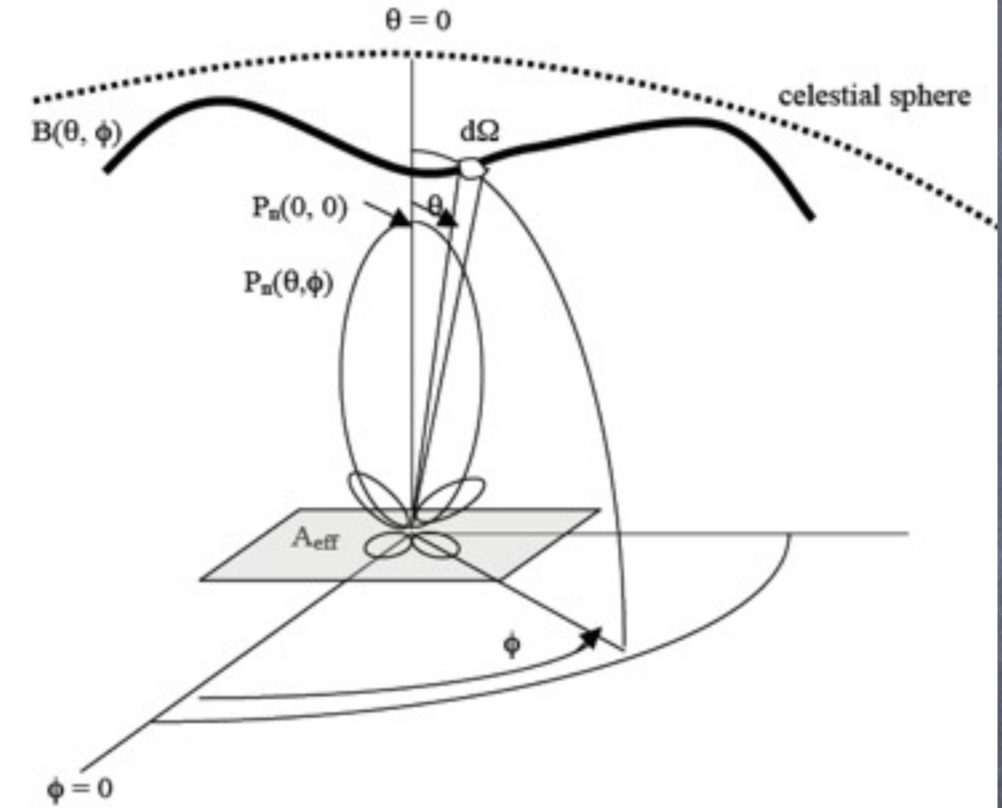
In radio astronomy, resolution typically plotted as a polar diagram (beam pattern) of response versus angle (rather than intensity vs. position). Main/central lobe corresponds to Airy disk and side lobes to the second maximum in the Airy pattern.

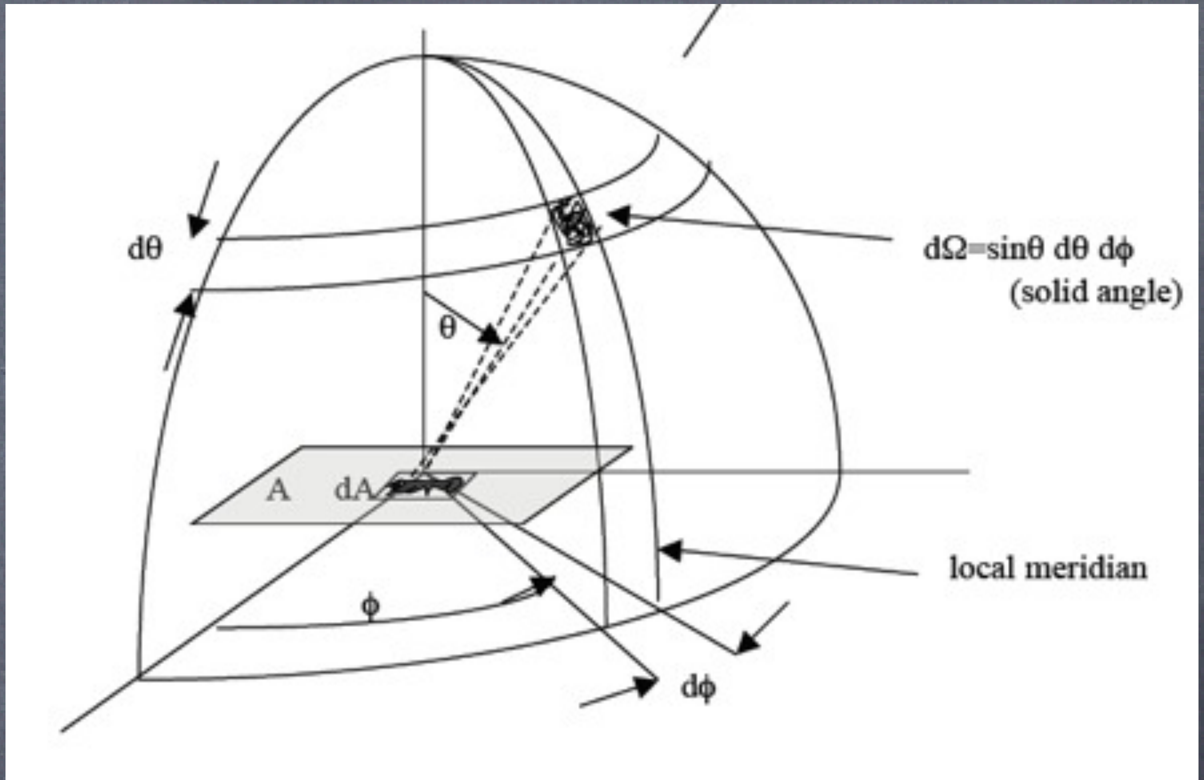




B. Maughan, lecture notes

Radio Observing





Single Dish Telescopes

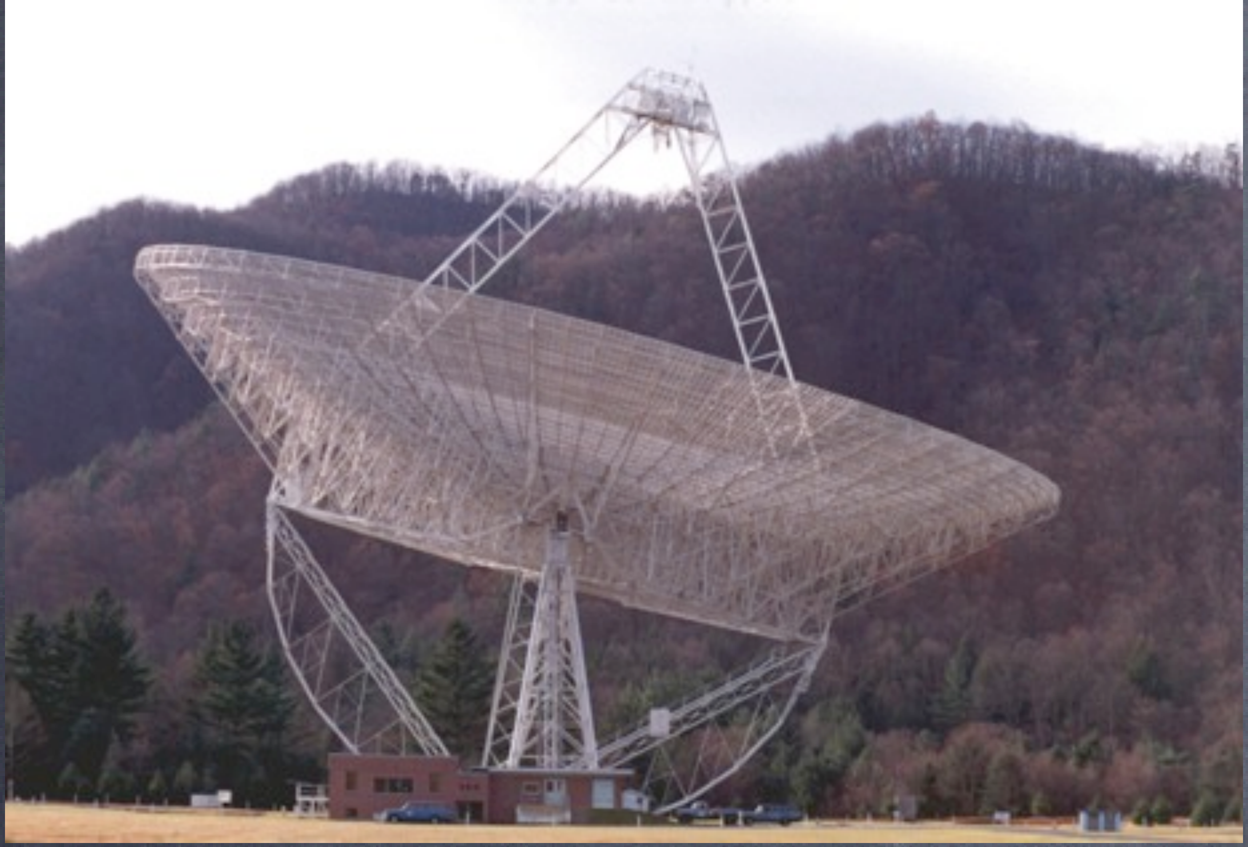
The largest steerable radio dishes are the 100-m Green Bank Telescope in West Virginia and the Effelsberg Telescope in Germany.

These are both Gregorian designs and work from a few mm up to 90 cm.

The GBT is the largest moving structure on land with a total moving weight of 16 million pounds. It is made from over 2000 aluminum panels controlled by actuators.

The GBT, photo by J. Condon

The 300ft Green Bank Telescope



Photos by Richard Porcas

The earlier 300ft telescope at Green Bank collapsed in 1988 due to the failure of a key structural element. This led to the building of the current 100-m telescope.

Single Dish Telescopes - Arecibo

The largest filled aperture dish is the 305-m Arecibo Telescope in Puerto Rico. It operates from 3cm to 6m

It is a spherical reflector made of over 38,000 aluminum panels. It was built inside the depression formed by a sinkhole.

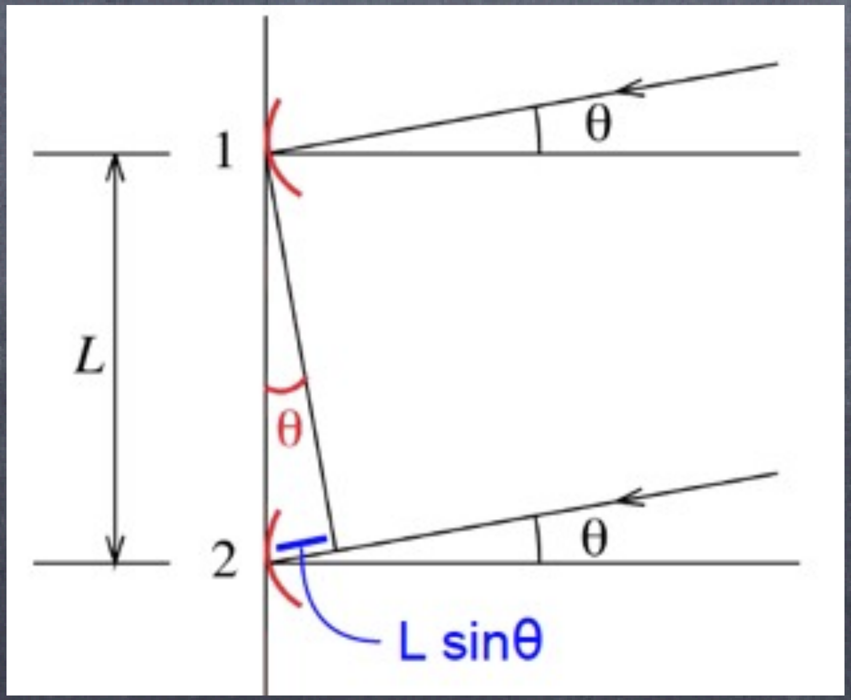
The receiver is located on a 900 ton platform that is suspended 150 m in the air held by cables from three reinforced concrete towers. The beam can be steered by up to 20 degrees.

Interferometry

Consider two identical telescopes separated by a distance L pointing at a source at angle θ. The telescopes are connected by cables and the output is correlated. The path difference for light is:

$$\Delta x = L\sin\theta = n\lambda$$

constructive interference for n=1,2,3,...
destructive interference for n=1/2,3/2,...



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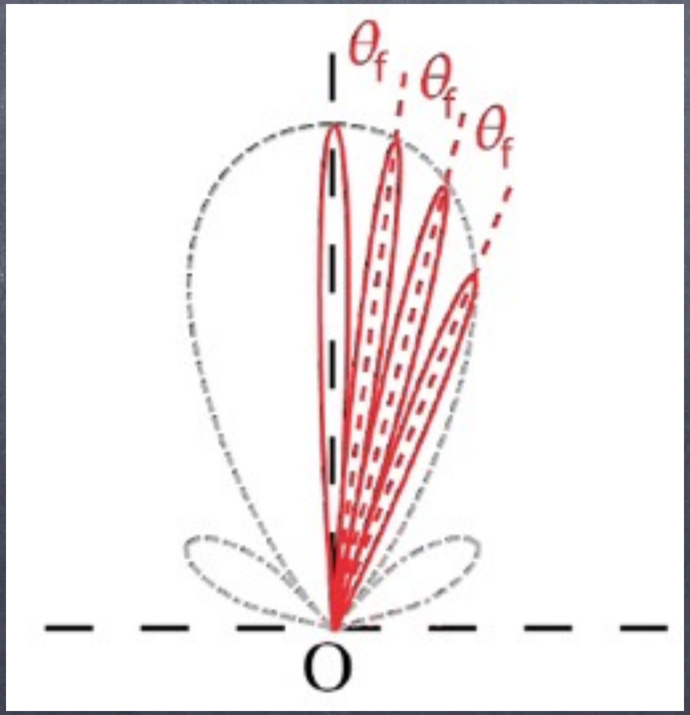
Interferometry

As the Earth turns, the source position changes giving a series of interference fringes. The distance between fringes corresponds to a difference in phase of 2π giving :

$$\sin\theta_1 - \sin\theta_2 = \lambda/L$$

for small angles $\sin\theta \approx \theta$ and $\Delta\theta = \lambda/L$

So the spatial resolution is equivalent to a telescope with a diameter L.



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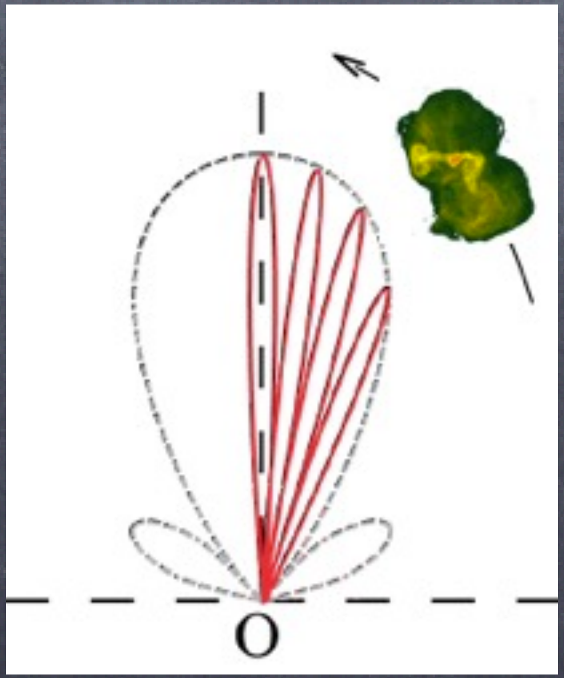
Interferometry - Cont.

Interferometry is done for narrow bandwidths. Differences in wavelength lead to different paths lengths and interference patterns.

As the Earth rotates a source smaller than the resolution moves across the fringe pattern and is fully sampled at fringe peaks.

For an extended source some part of the source will always interfere destructively and the full source power is never measured at a given time.



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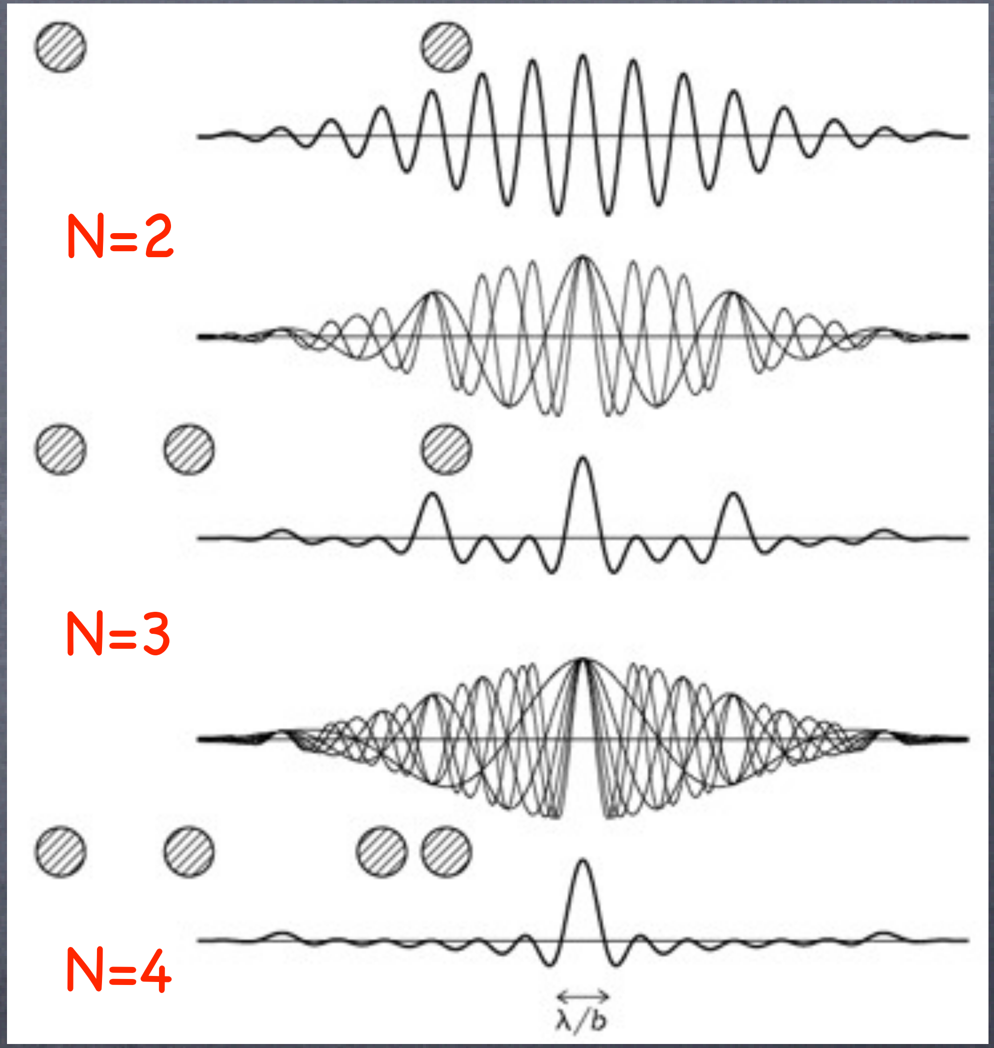
Aperture Synthesis

A combination of N telescopes gives N(N-1)/2 pairs of 2 telescope interferometers whose output can be combined.

Each pair measures one Fourier component of the source brightness distribution (new fringe spacing or direction). These outputs are combined to “synthesize” the resolution of a telescope with a size equal to the longest baseline in the array.

Using multiple elements allows one to sample the source distribution faster, on different scales. Using multiple baselines with different orientations allows one the sample the 2D source distribution.



“ESSENTIAL RADIO ASTRONOMY”, Condon and Ransom

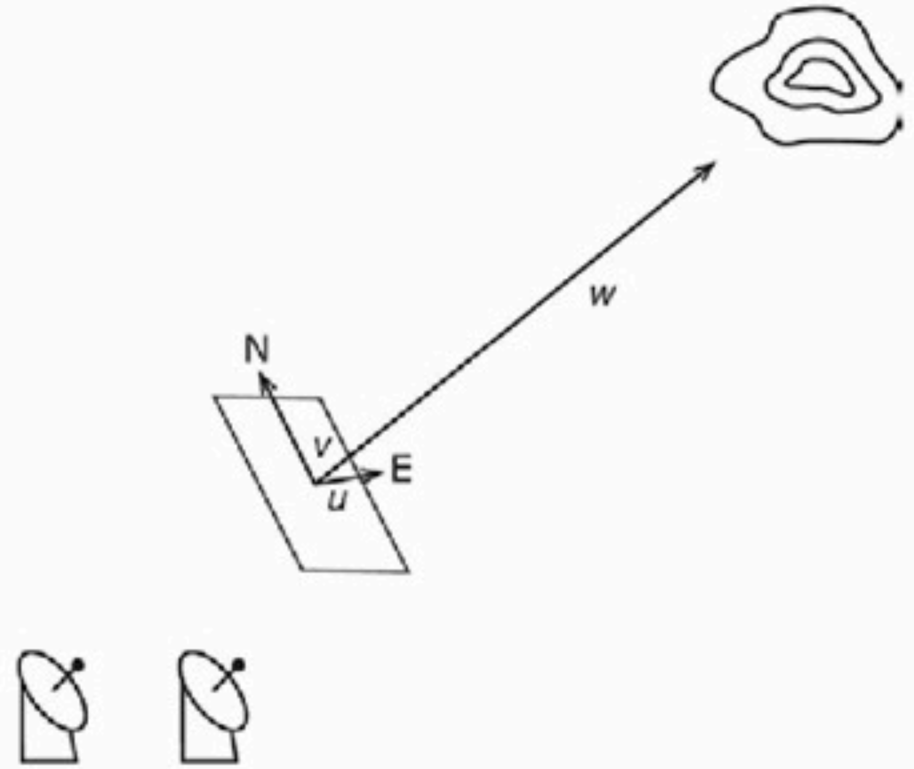


Figure 9.4. Definition of the *uv* plane.

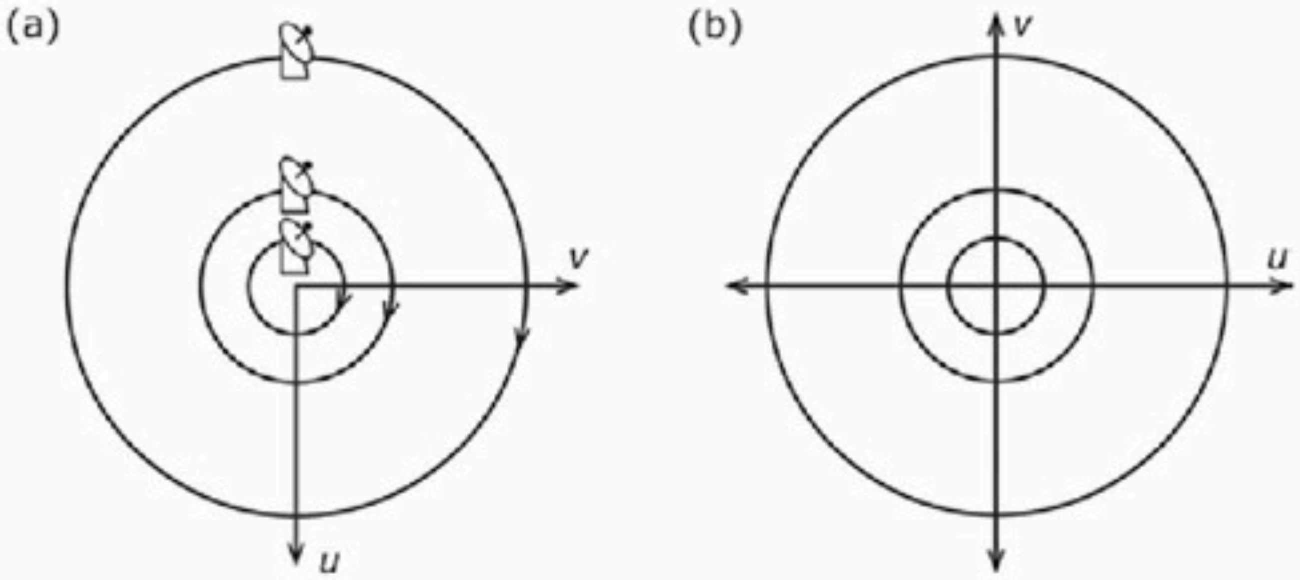


Figure 9.5. The rotation of a linear interferometer can fill out the *uv* plane coverage.

"Measuring the Universe" - Rieke

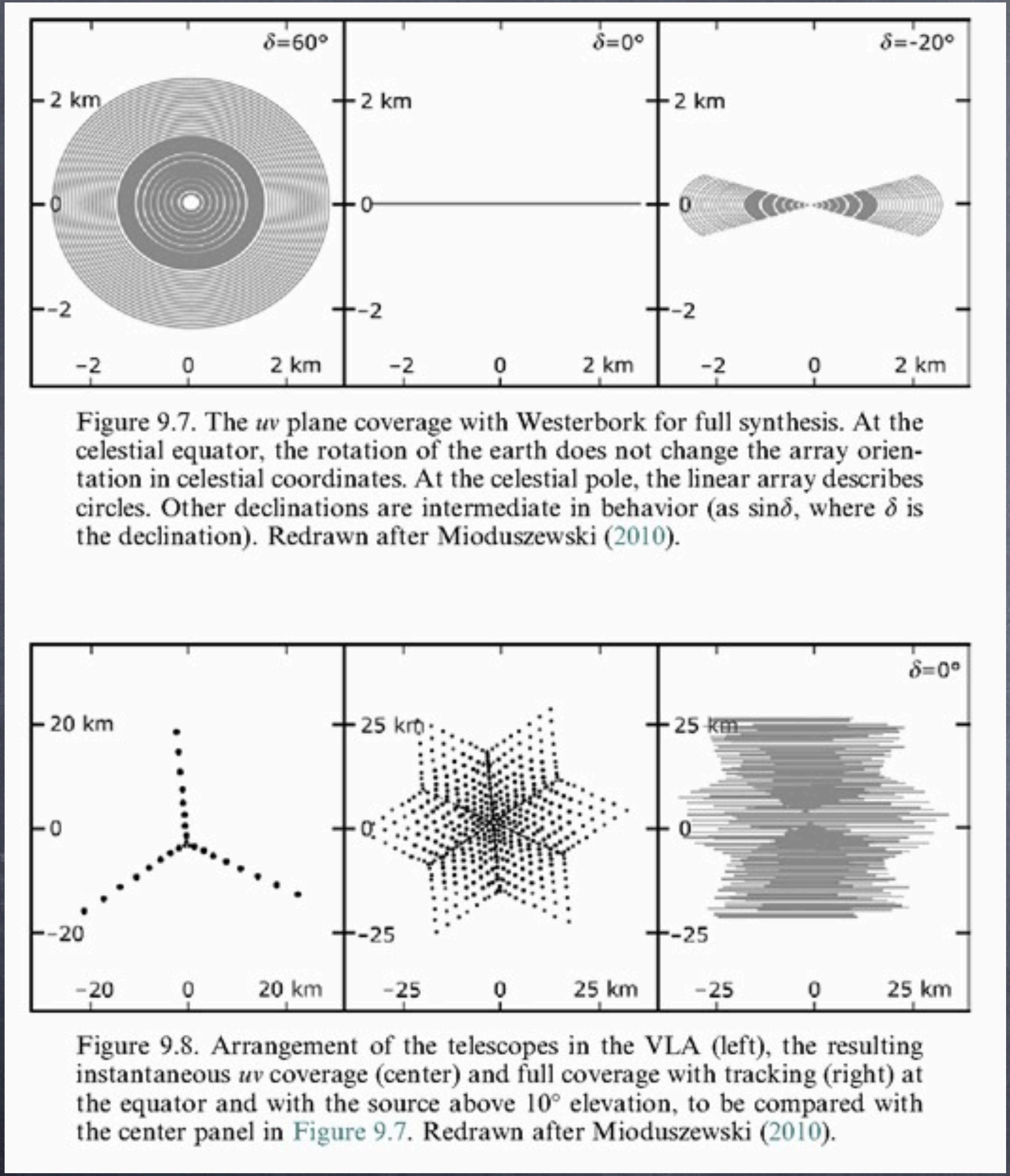


Figure 9.7. The *uv* plane coverage with Westerbork for full synthesis. At the celestial equator, the rotation of the earth does not change the array orientation in celestial coordinates. At the celestial pole, the linear array describes circles. Other declinations are intermediate in behavior (as sinδ, where δ is the declination). Redrawn after Mioduszewski (2010).

Figure 9.8. Arrangement of the telescopes in the VLA (left), the resulting instantaneous *uv* coverage (center) and full coverage with tracking (right) at the equator and with the source above 10° elevation, to be compared with the center panel in Figure 9.7. Redrawn after Mioduszewski (2010).

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Westerbork - 14 telescopes arranged East-West. Different u-v coverage depending on declination of source.

VLA telescopes arranged in a Y pattern.

Dirty Map

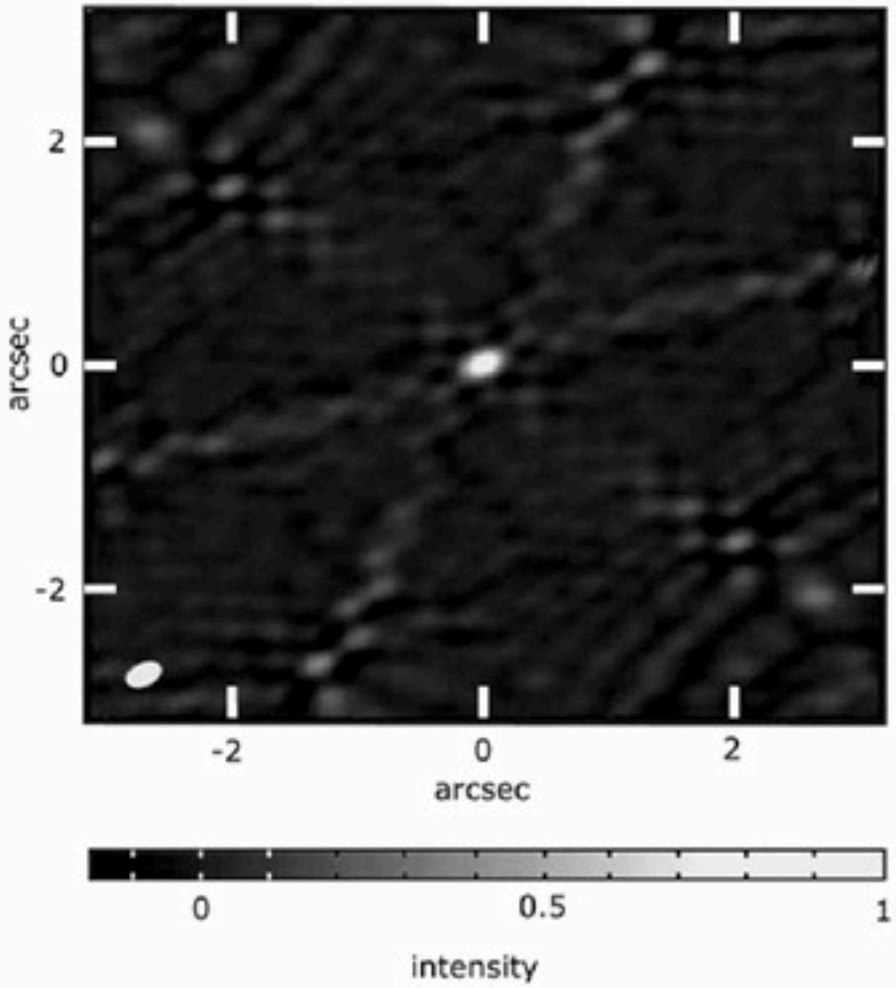

Figure 9.9. The instantaneous beam for the VLA (e.g., from the center panel in Figure 9.8) at 8.4 GHz. The synthesized beam (0.27″ × 0.18″) is the white ellipse to the lower left. The sidelobes reach 20% of the peak response. After Fomalont (2006).

"Measuring the Universe" - Rieke

Realistic arrays leave holes in the uv coverage. The PSF is called the "dirty beam". A superposition of several sources gives a messy image called a "dirty map".

Radio Telescope Arrays

Major radio telescope arrays:

Very Large Array (VLA/EVLA):

27 25-m dishes in a Y shape, in New Mexico
max 36 km baseline
wavelengths of 0.7cm-4m

Very Long Baseline Array (VLBA):

10 25-m dishes
stretches from Hawaii to the Virgin Islands with longest baseline of 8611 km
the signals are time stamped and later combined

Low Frequency Array for radio astronomy (LOFAR):

~20,000 small antennas over 100 km
currently being constructed with some stations operational, Netherlands and Europe
wavelengths of 1.3-30 m

Radio Telescope Arrays

Resolution:

The VLA has 4 configurations (A, B, C, D) with maximum separations of 36.4 km, 11.1 km, 3.4 km, and 1 km.

So spatial resolution at 21cm of:

$L = 36.4\text{km}$, $\theta = \lambda/L = 1.2''$
$L = 1.0\text{km}$, $\theta = 43''$

VLBA: $L = 8611$ km, at 21cm $\theta = 5$ milliarcsec

Radio Telescope Arrays

Sensitivity:

In the limit of large N, the point source sensitivity of an array approaches the sensitivity of a single telescope with an area equal to the sum of the individual telescope areas.

The sensitivity to extended sources in much worse, because the synthesized beam solid angle of an interferometer is much smaller.

Choose the minimum baseline for the angular resolution needed for your science goals!