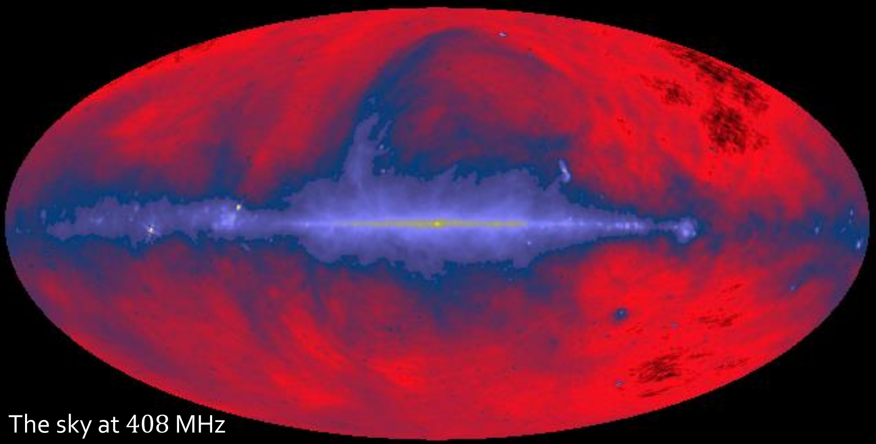
Radio Astronomy: The Dark Side of the Spectrum

Justin Linford (MSU)



The sky at 408 MHz
C. Haslam et al., MPIfR, SkyView

Saturn as seen by the VLA image from NRAO

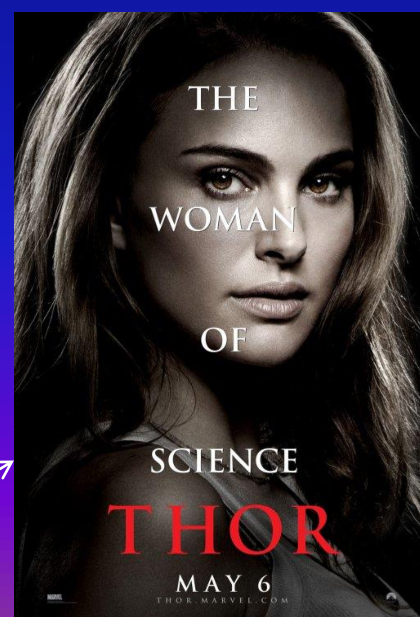
NGC 5128 at 1.4 GHz , image from CSIRO

MICHIGAN STATE UNIVERSITY
Department of Physics and Astronomy

Radio Astronomers

What most people think of when I tell them I'm a radio astronomer

SETI INSTITUTE



If I'm really lucky…

Only occasionally

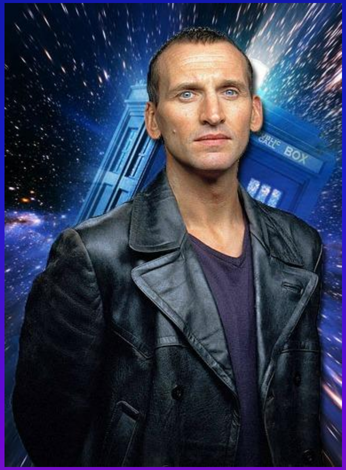
Radio Astronomers

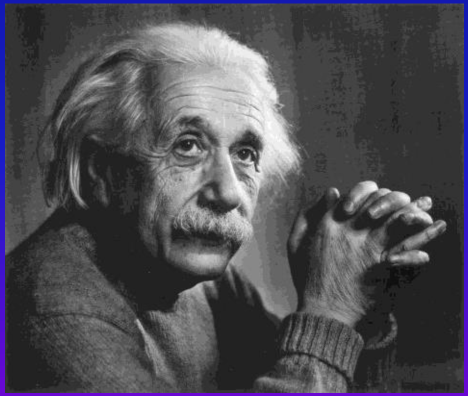
How other astronomers see radio astronomers

I have no idea what's going on in this picture…

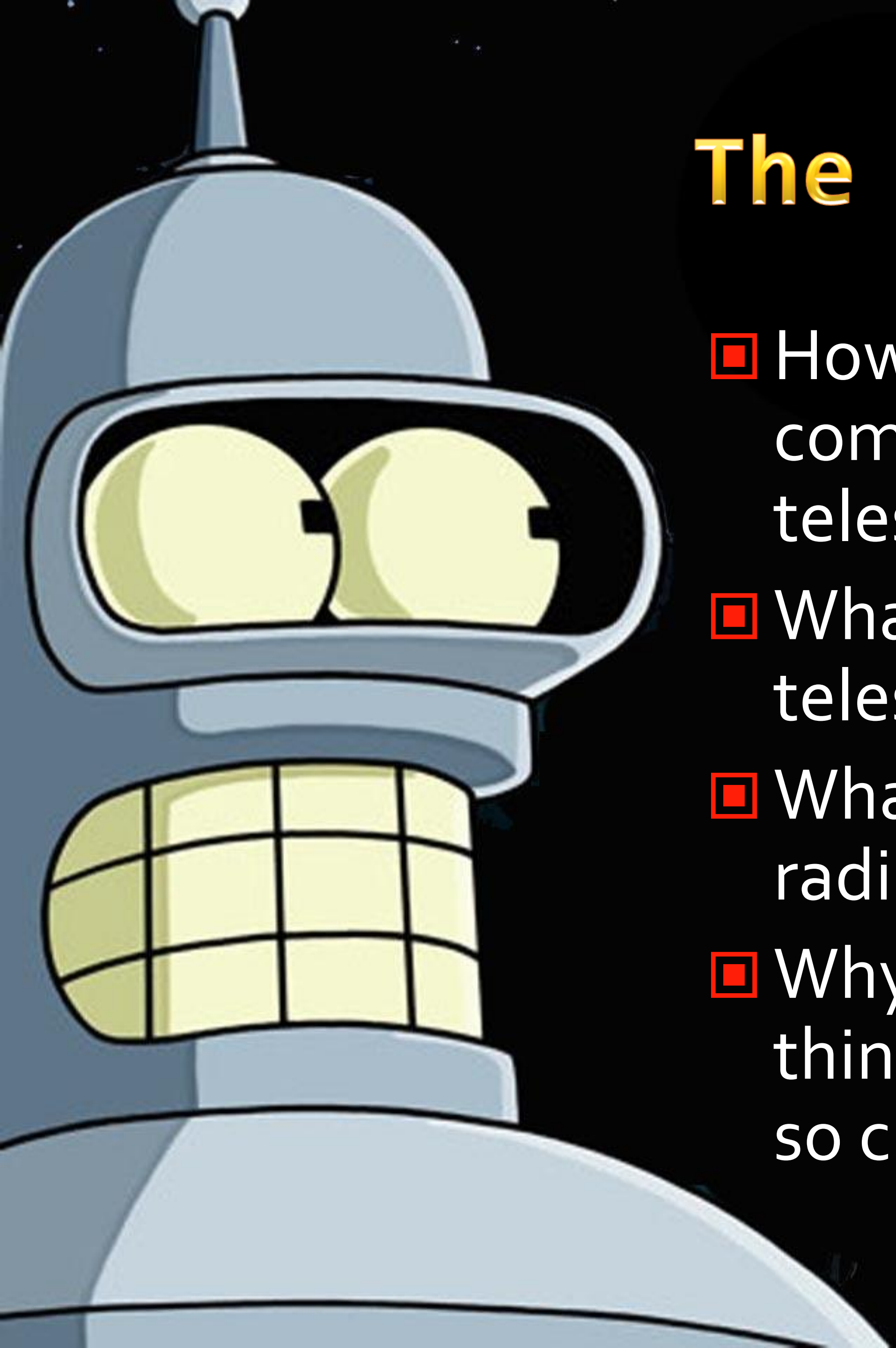
Radio Astronomers

How radio astronomers wish people thought of them





Or maybe it's just me…



The Questions

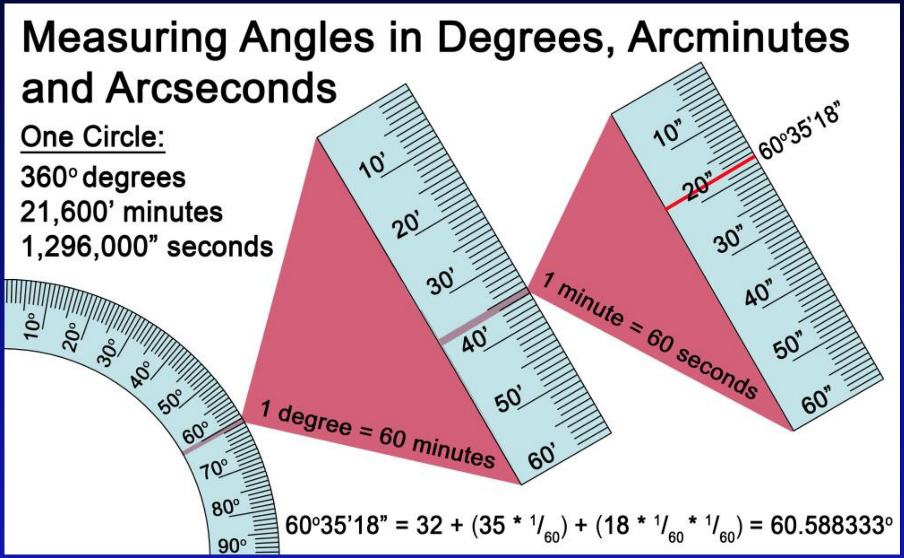
- How do radio telescopes compare to optical telescopes?
- What kinds of radio telescopes are out there?
- What can you learn from radio observations?
- Why do other astronomers think radio astronomers are so crazy?


CAUTION
SCIENCE
AHEAD

Astronomy Units

- Arcsecond (or arcsec)
  - 1 degree = 3600 arcsec
  - 1 arcsec = 0.000278 degrees
- Metric measurements
  - 1 meter (m) = 39.4 inches
  - 1 centimeter (cm) = 0.01 m
  - 1 nanometer (nm) = 0.000000001 m

From astro.unl.edu/classaction



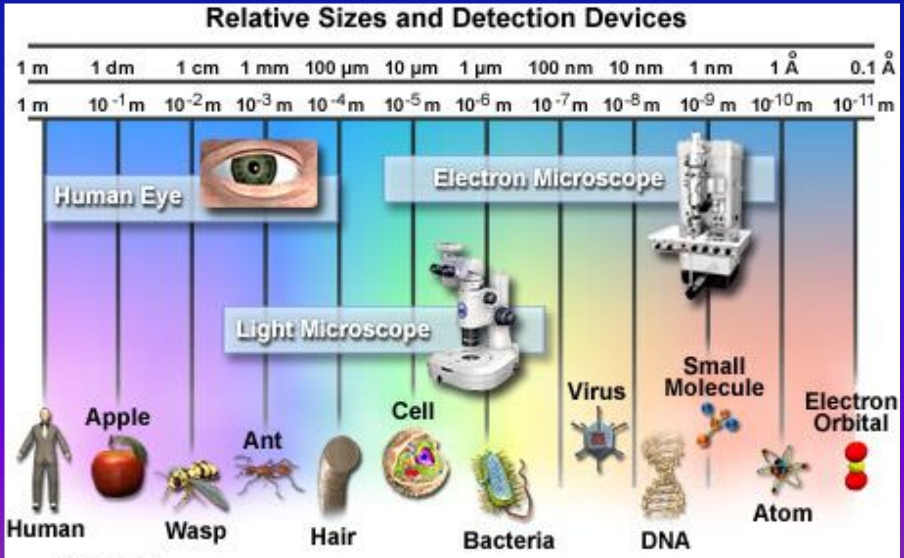
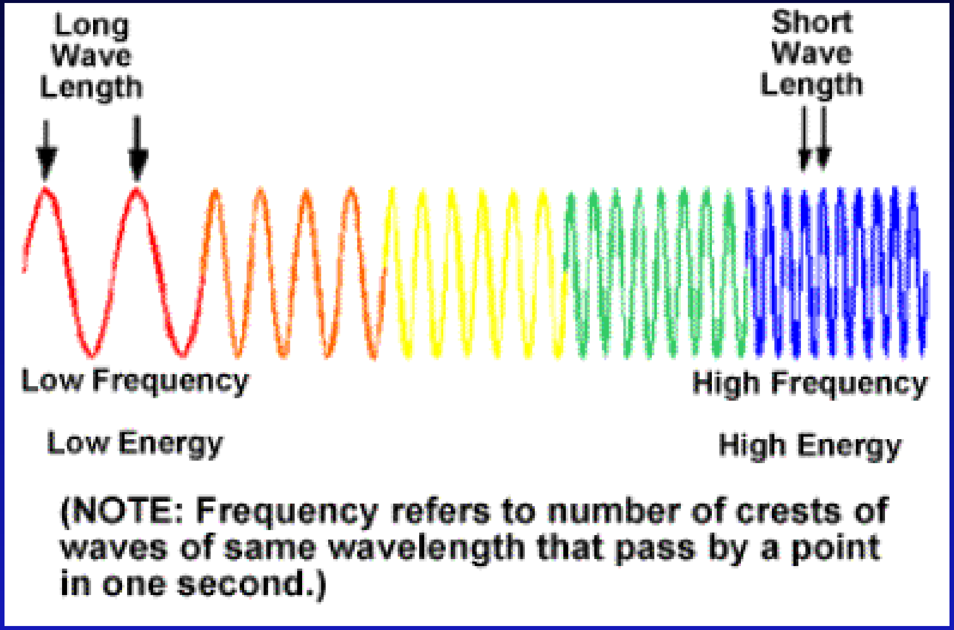


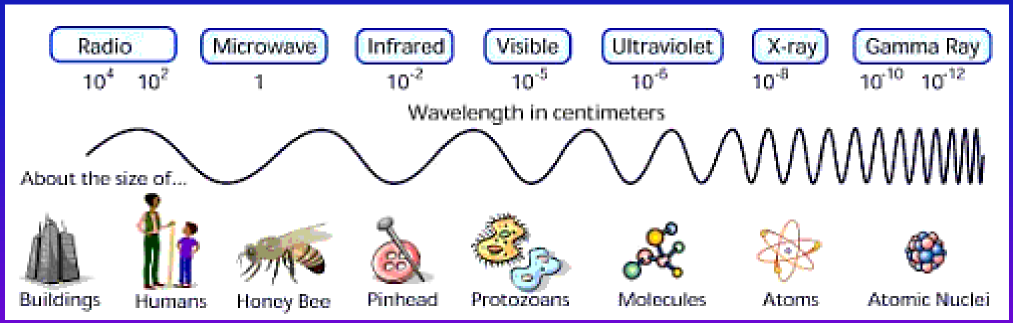
Figure 1

From biosiva.50webs.org

Astronomy Terms

- Wavelength
  - The distance between 2 successive peaks in a wave
  - Has units of length (nm, cm, m, etc.)
- Frequency
  - The number of peaks that go past in a second
  - Usually measured in Hertz (Hz)





Astronomy Terms

- Sensitivity
  - "Light bucket" – telescopes collect light like buckets collect rain
  - More sensitivity means more light in less time
- Resolution
  - The ability to image distinct features or objects
  - Also called "angular resolution"

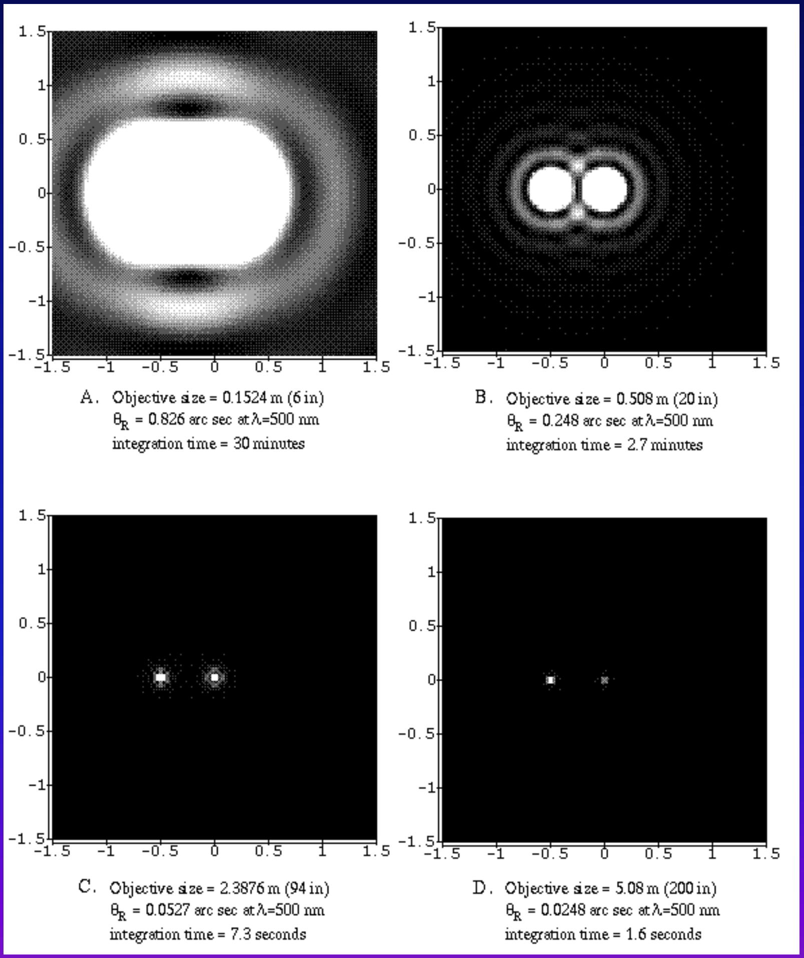


Image by Nick Stroebel

The Fourier Transform

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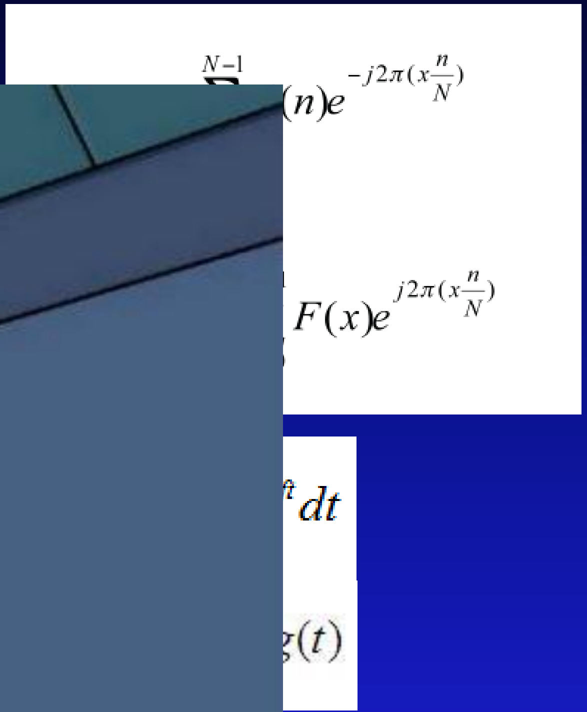

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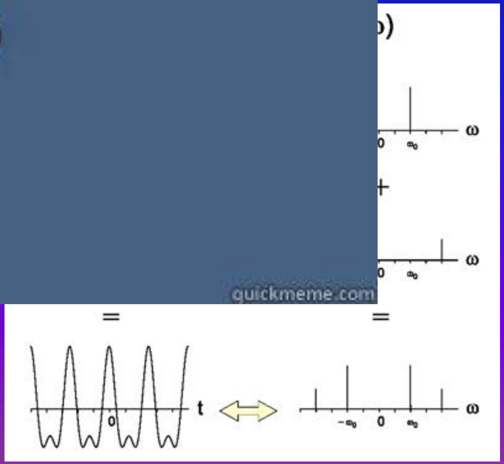
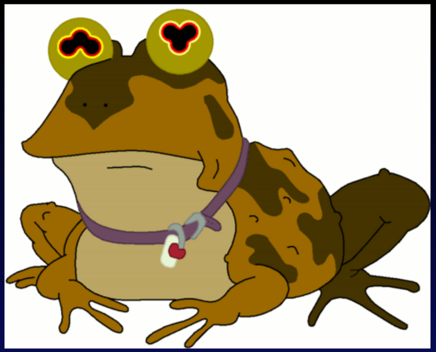
  - Position → Momentum

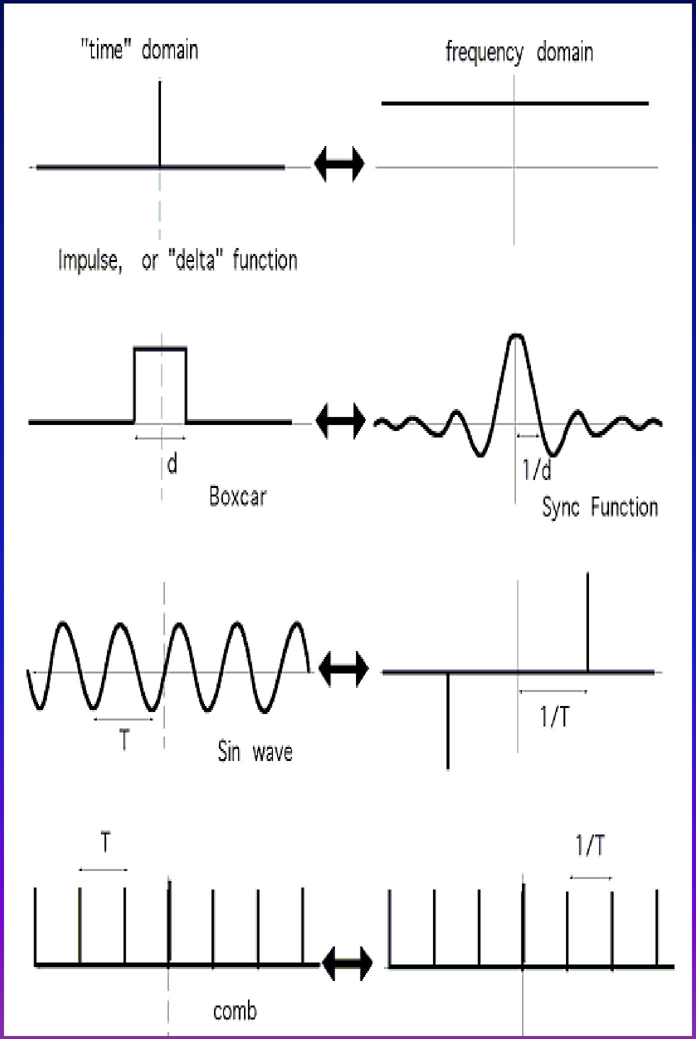


The Fourier Transform



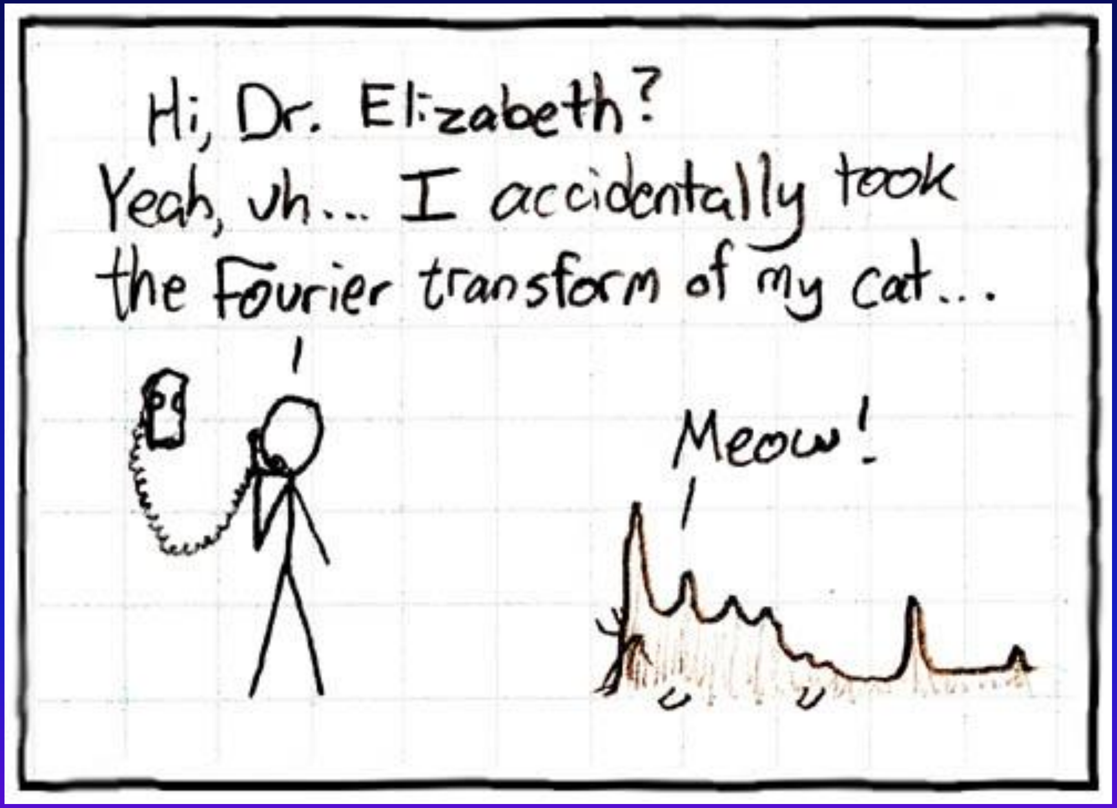
Stay with me, here

- There is mathematical tool called the Fourier transform
- It allows us to look at a problem from a different mathematical perspective
- It gives you both the positive and negative results



Science Joke!

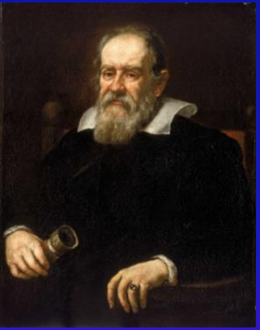
From XKCD.com

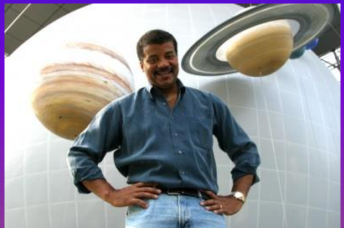


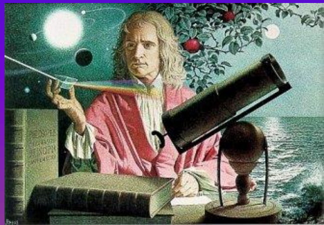
But where is the negative cat transform?

What Every Astronomer Wants

- Astronomy: the continuing quest for more photons and better resolution
  - Sensitivity is proportional to the collecting area of your telescope
    - Bigger telescope means more sensitivity
  - Angular resolution = observed wavelength ÷ telescope diameter (Equation: $\theta=\lambda/D$)
    - Bigger telescope means better resolution
- So, bigger telescopes give you everything you ask for (kind of)

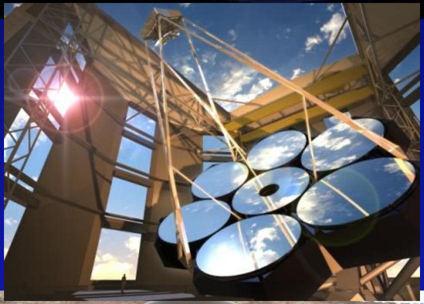


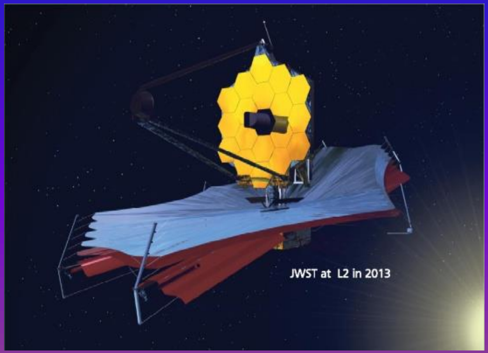




Optical

- The big guys:
  - Keck (10m)
  - Gemini (8.1m)
  - Hubble (2.4m)
- Coming soon:
  - LSST (8m)
  - JWST (6.5m)
  - GMT (24.5m) ?
  - TMT (30m) ?

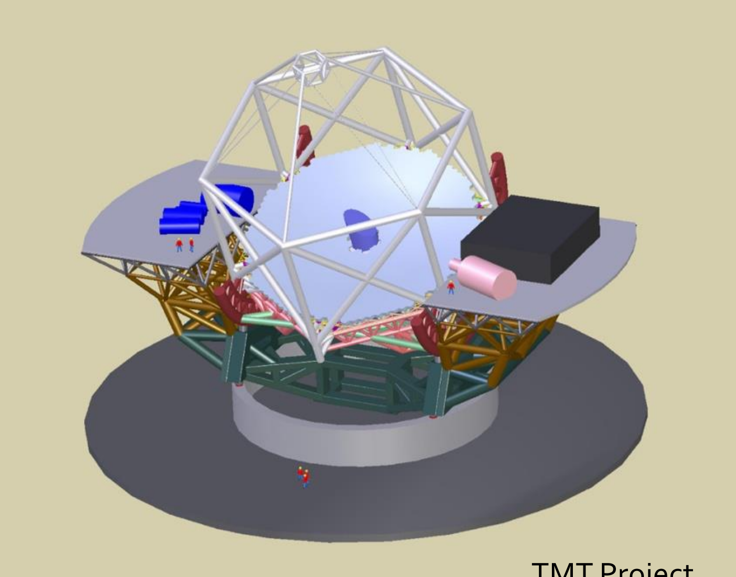




The Quest for Resolution

- The best possible resolution right now
  - Keck: 10 m primary with adaptive optics
  - At 550 nm (~visible) λ/D = 0.01 arcseconds
- The best possible resolution in the near future?
  - Thirty Meter Telescope: 30 m primary
  - At 550 nm, λ/D = 0.004 arcseconds
- There is a catch: the atmosphere limits your resolution (even if you have adaptive optics)

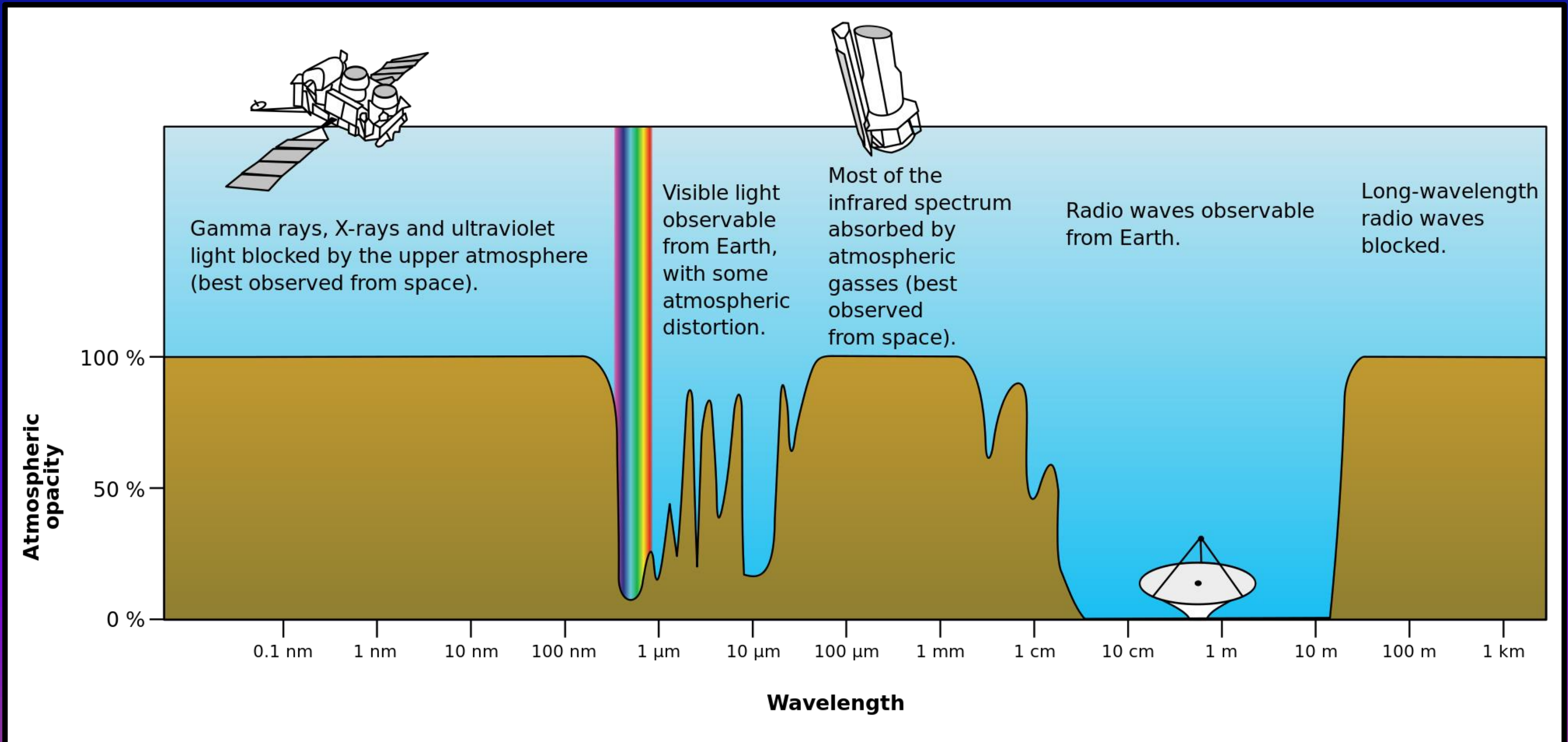
Photo credit: Dan Birchall



TMT Project

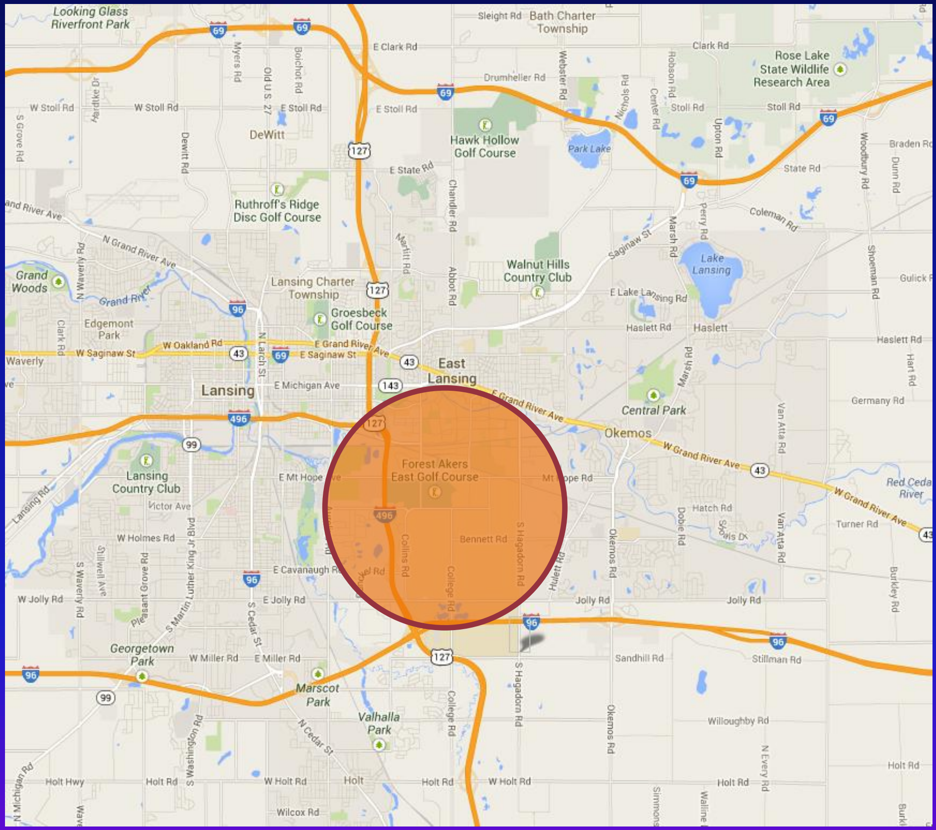
What About Radio?

- Modern radio telescopes operate at wavelengths anywhere between 30 m and 0.3 mm
- Realistically, “radio” consists of 3 regimes
  - Long wavelength: 30 m to ~21 cm
  - “Classical” Radio: 1 m to ~7 mm
  - mm/Sub-mm: ~7 mm to ~0.3 mm



Radio Resolution

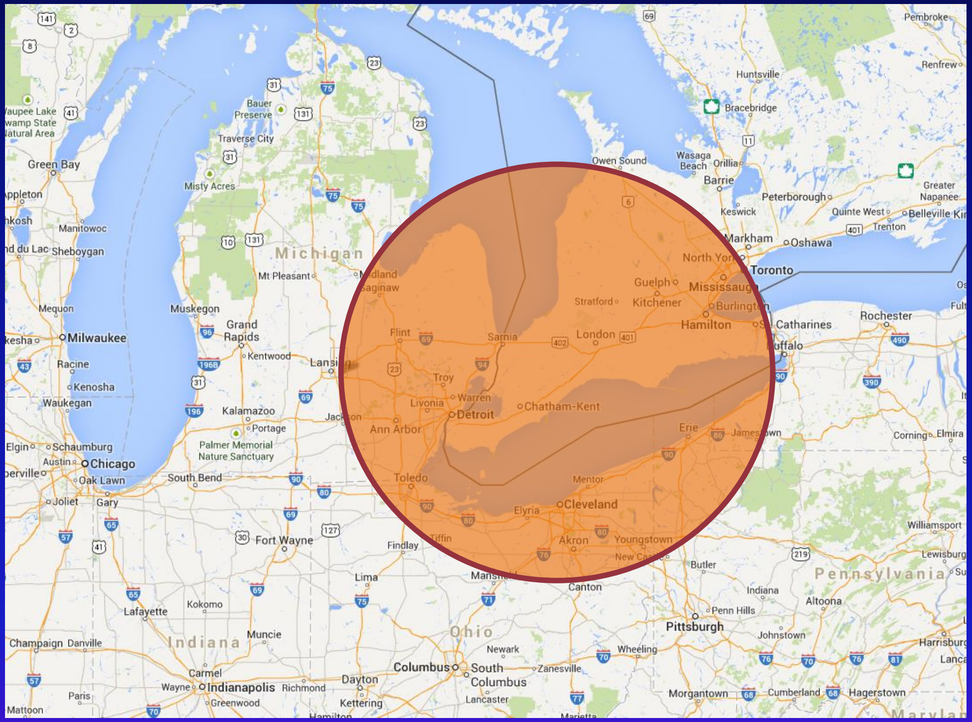
- At 0.3 mm, to get 0.01 arcsec resolution, we would have to build a telescope 6.2 km (4 miles) in diameter
  - This would cover almost the entire MSU campus



Map from Google Maps

Radio Resolution

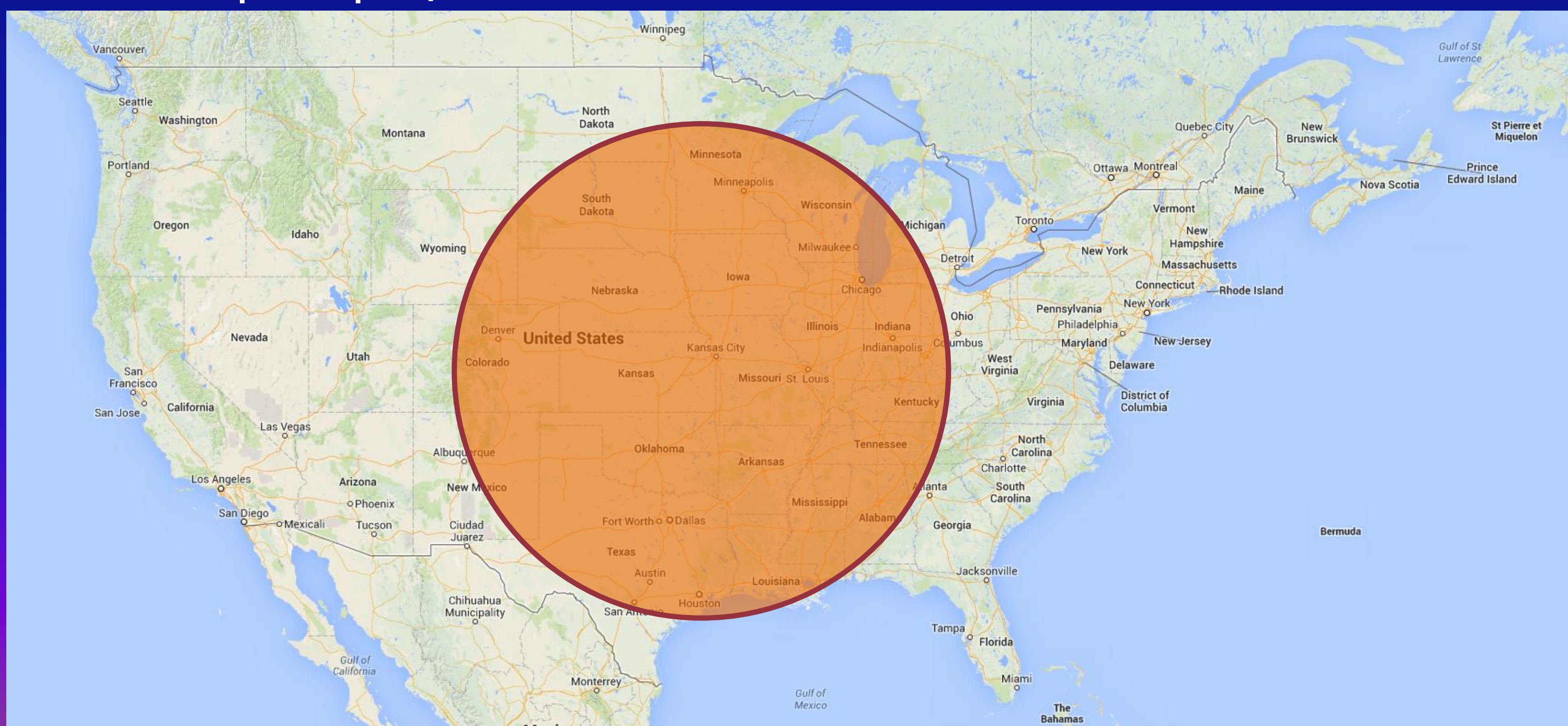
- At 21 cm, to get 0.01 arcsec resolution, we would have to build a telescope 433 km (269 miles) in diameter
  - A little less than the distance from East Lansing, MI, to Buffalo, NY



Map from Google Maps

Radio Resolution

- At 30 m, to get 0.01 arcsec resolution, we would have to build a telescope 2063 km (1282 miles) in diameter
  - A little less than the distance between East Lansing, MI, and Albuquerque, NM



Map from Google Maps

The Two Largest Radio Telescopes

Arecibo: 305 m

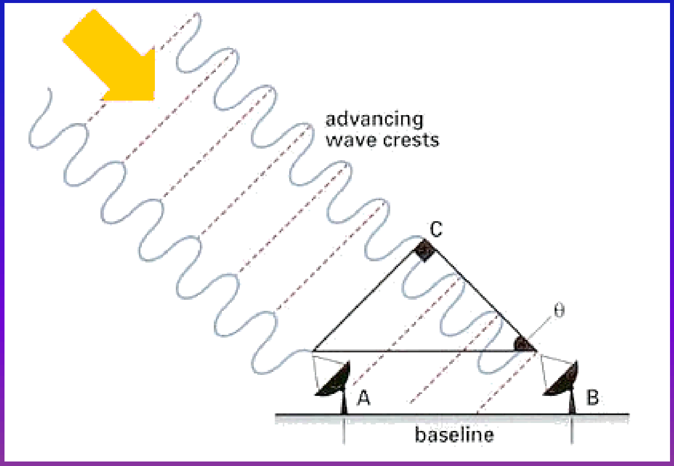
Shortest available wavelength: 3 cm
Maximum resolution: 25 arcsec

Green Bank: 110 m

Shortest available wavelength: 3 mm
Maximum resolution: 7 arcsec

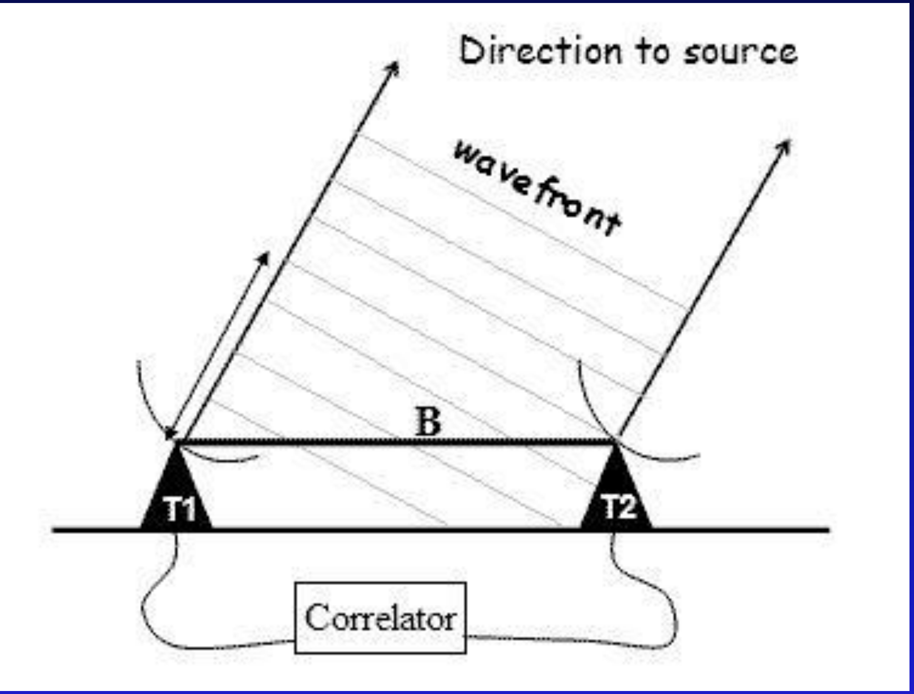
Interferometry

- A major strength of radio telescopes is the ability to link multiple smaller dishes into a large array
- The angular resolution is then determined by the largest distance between two dishes.
  - This is called the maximum baseline



Interferometry Basics

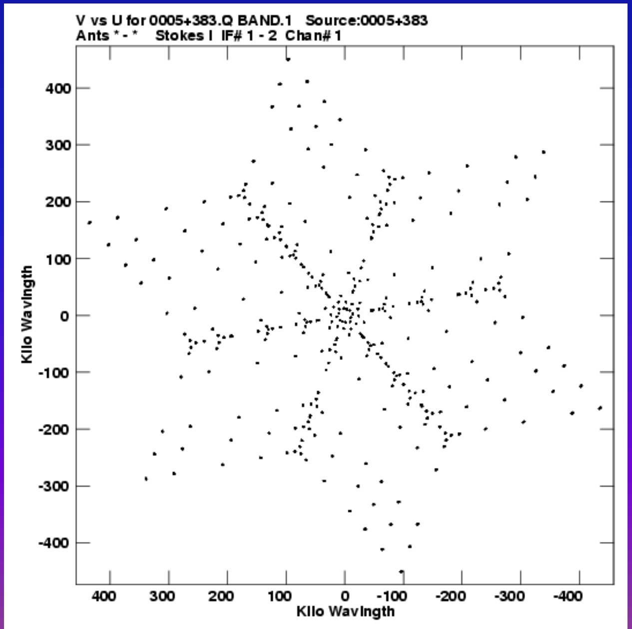
- Correlator
  - Computer which combines the signals from all the antennas
- Visibilities
  - The data output by the correlator
  - The (difficult) trick is to turn the visibilities into an image



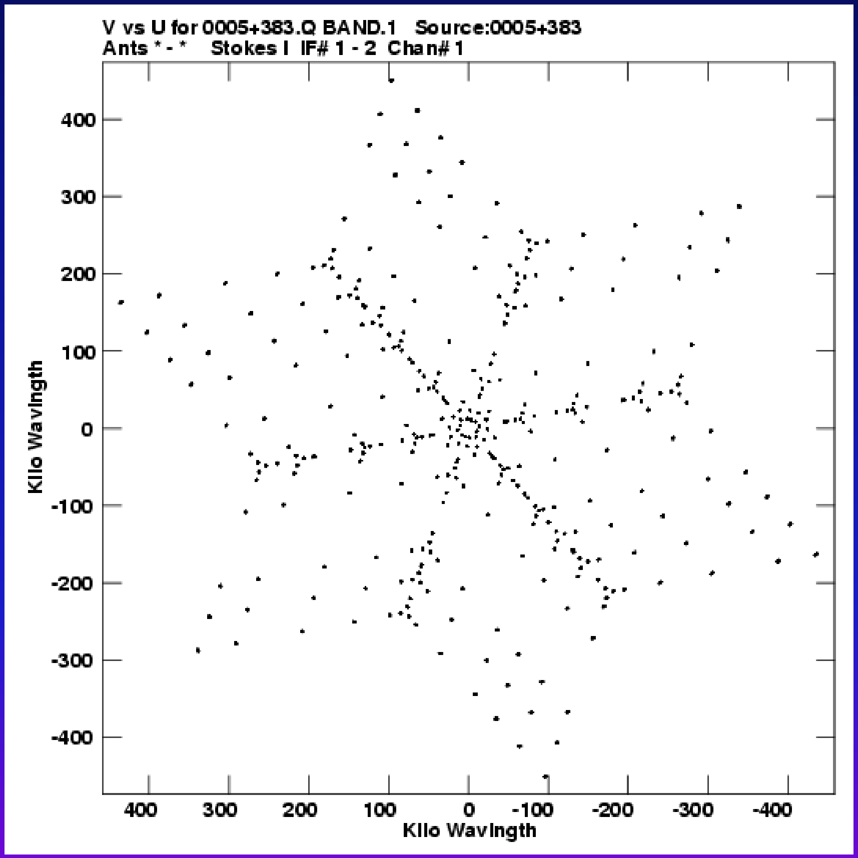
Synthesized Telescope

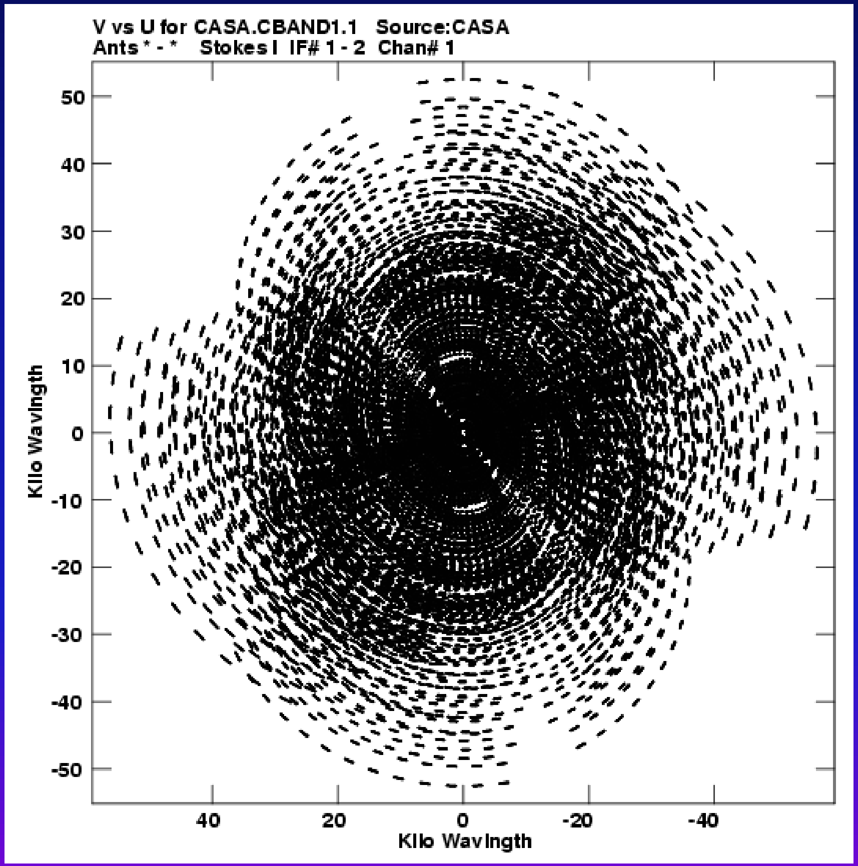
- (u,v) plane
  - 2-D coordinate system perpendicular to the source direction, in units of wavelength
- (u,v) coverage
  - Baseline distribution as seen by the source, in units of wavelength

VLA
(image from NRAO)



Earth Rotation Synthesis





Snapshot and full track (u,v) coverage of the VLA (NRAO/AUI)

Some Major Radio Interferometers

- Karl G Jansky Very Large Array (VLA)

- Westerbork Synthesis Radio Telescope (WSRT)

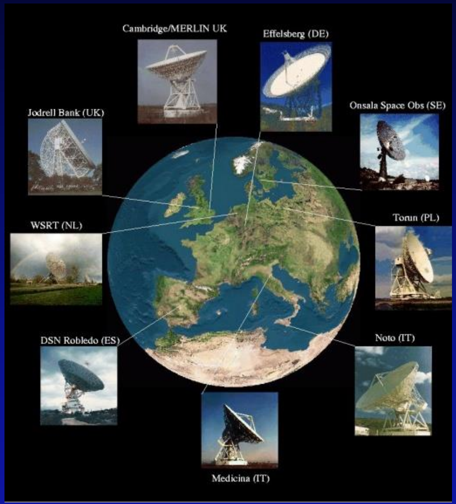
- Australian Telescope Compact Array (ATCA)
- Atacama Large Millimeter Array (ALMA)

Interferometer Resolution

- VLA
  - Maximum baseline: 36.4 km (22.6 miles)
  - Shortest observable wavelength: 7 mm
  - Maximum resolution = 0.05 arcsec
- ALMA
  - Maximum baseline: 15.3 km (9.5 miles)
  - Shortest observable wavelength: 0.32 mm
  - Maximum resolution = 0.005 arcsec

Big = Good → BIGGER = BETTER

- Very Long Baseline Interferometry (VLBI) gives the highest resolution possible at any wavelength.
- “Long baseline” usually means >100 km baseline
- “Very long baseline” usually means >1000 km baseline



The Very Long Baseline Array (VLBA): The World's Only Dedicated VLBI Instrument

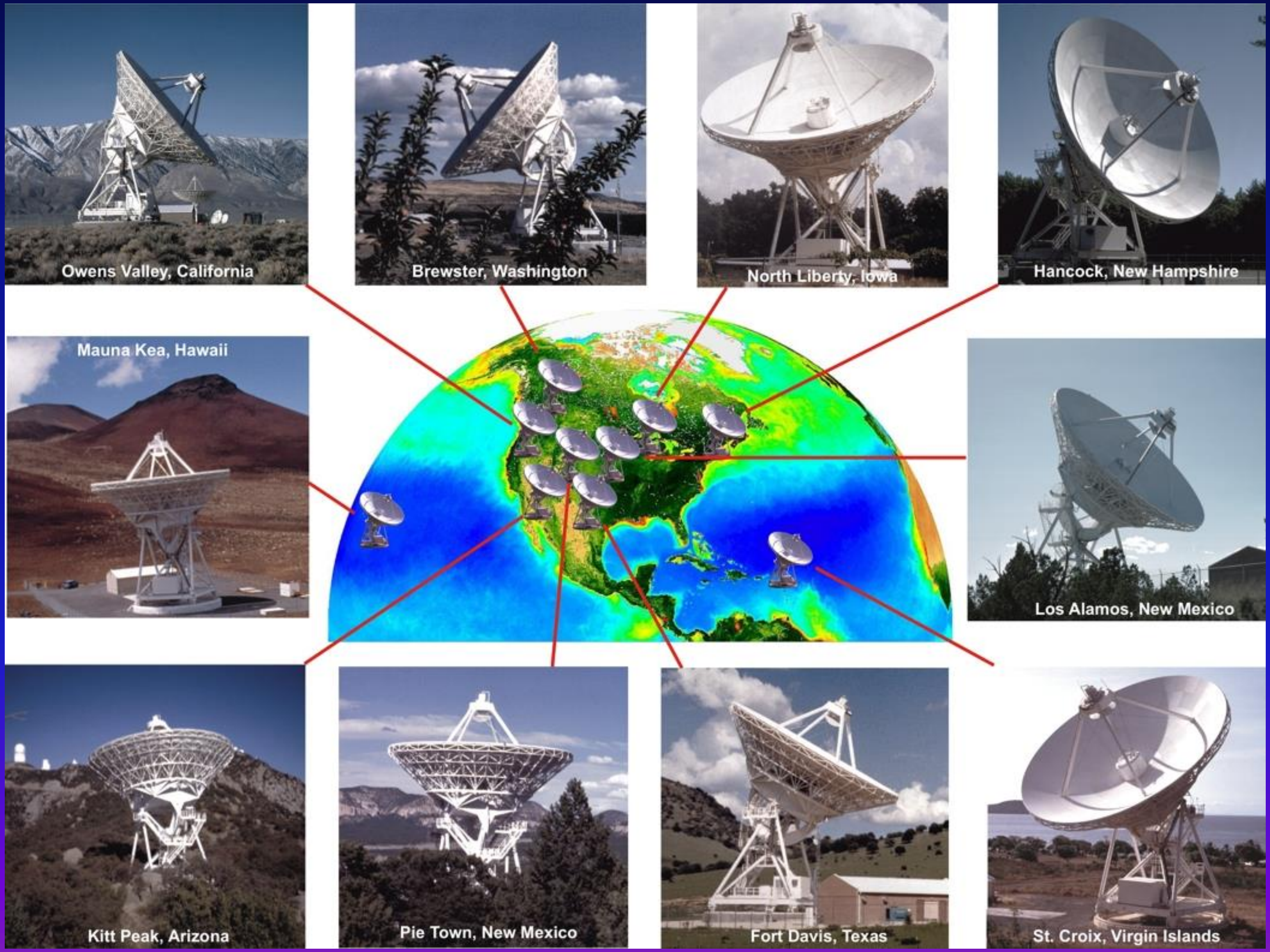


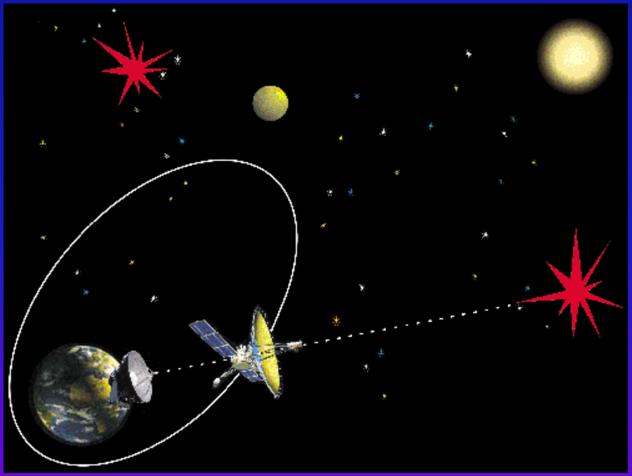
Image credit: NRAO/AUI & NASA/GSFC

Maximum baseline = 8600 km (5344 miles)

VLBI Resolution

- VLBA
  - Maximum baseline: 8600 km
  - Shortest observable wavelength: 3 mm
  - Maximum resolution: 0.00007 arcsec*
- Radio Astron (satellite + ground-based)
  - Maximum baseline: 360,000 km
  - Shortest observable wavelength: 1.35 cm
  - Maximum resolution: 0.000009 arcsec
  - The catch: very low sensitivity

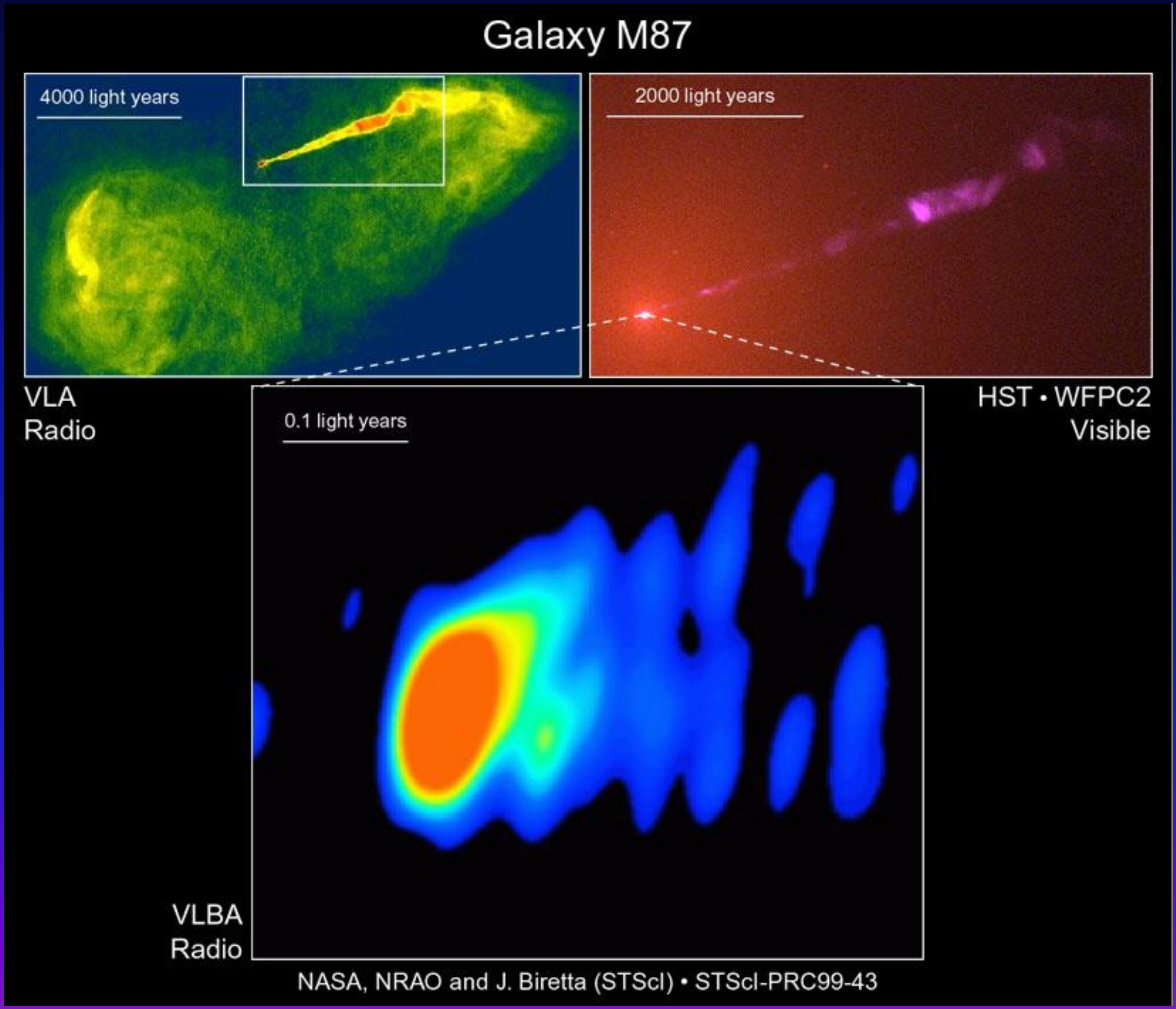
NRAO/AUI



http://www.asc.rssi.ru

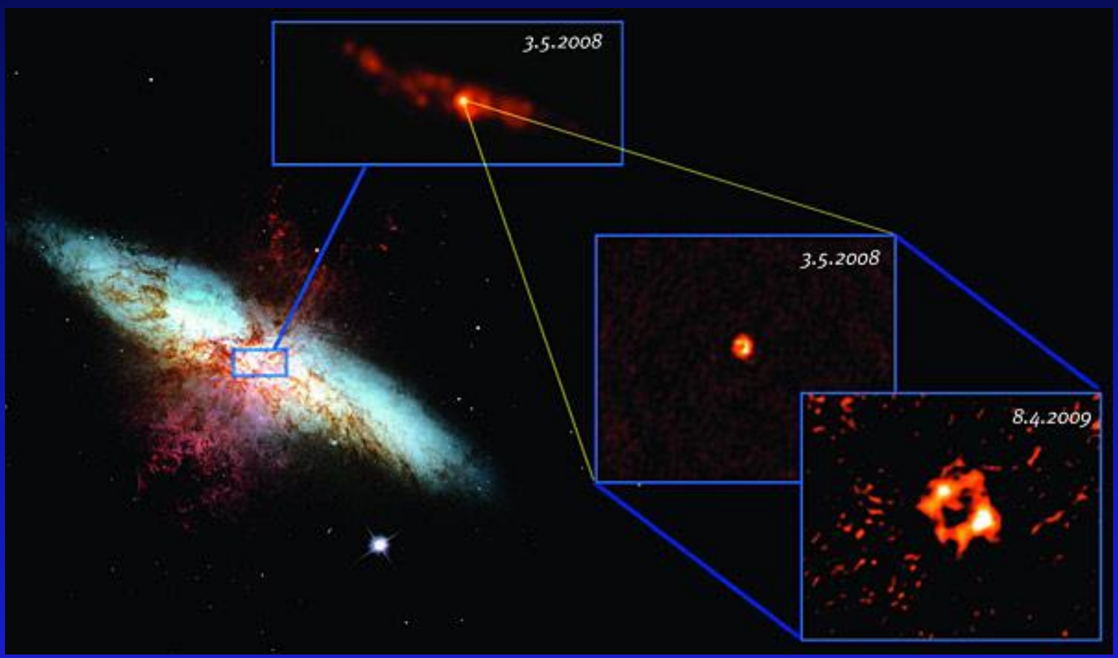
*Currently, no 3 mm receiver on St. Croix or Hancock antennas, so maximum baseline is only 6156 km, giving a resolution of 0.00012 arcsec

You Say You Want Resolution*



*with apologies to the Beatles

A Supernova in M82 (Jan 2008)



HST image: NASA, ESA and the Hubble Heritage Team [STScI/AURA]
Radio images: A. Brunthaler, MPIfR

- A rare radio supernova in the starburst galaxy M82
- Completely obscured by dust in optical, UV, and X-rays
- VLBA observations show the expansion of the blast wave

Supernova SN 1993J

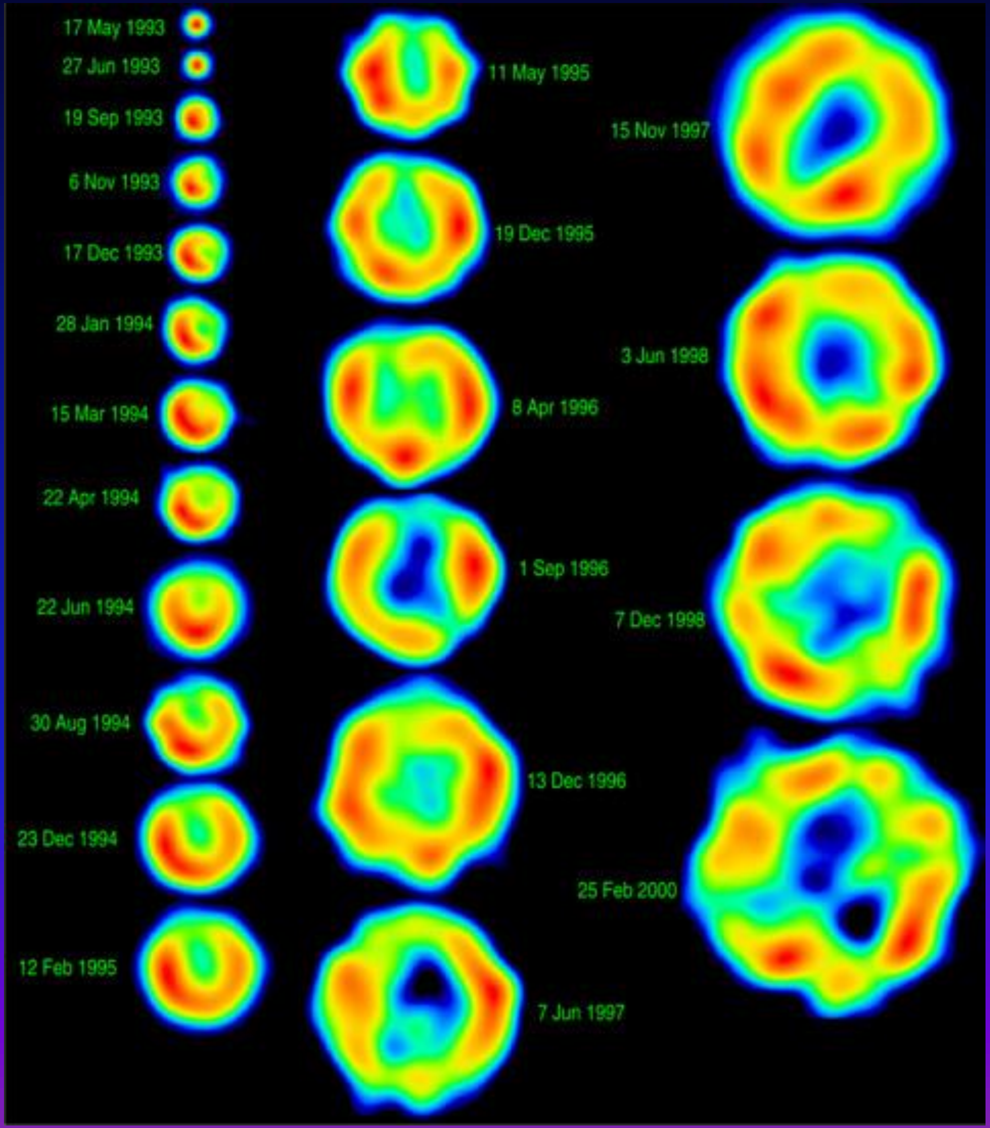


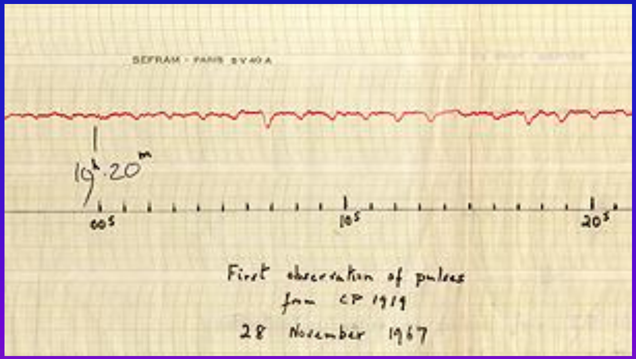
Image from NRAO/AUI and N. Bartel, M. Bietenholz, M. Rupen, et al.

- Supernova in M81 observed with the VLBA at regular intervals for 7 years

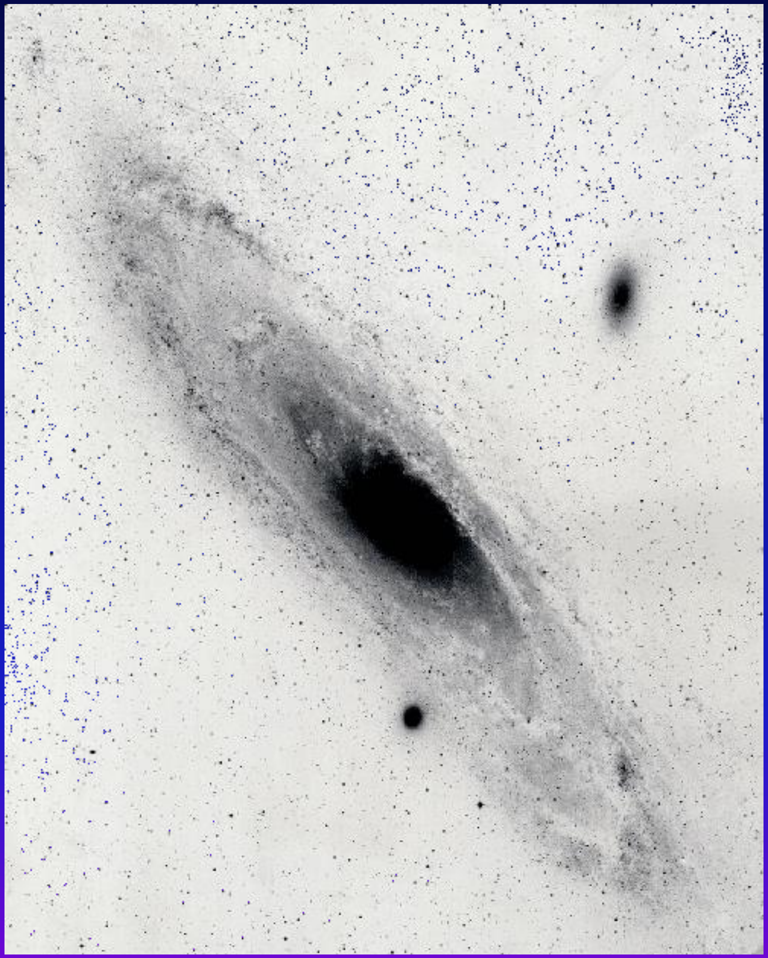
Movie from www.cfht.hawaii.edu/~lwells/supernovae.html

What Are We Actually Seeing?

- Optical telescopes see mostly thermal emission
- What types of emission do radio telescopes see?



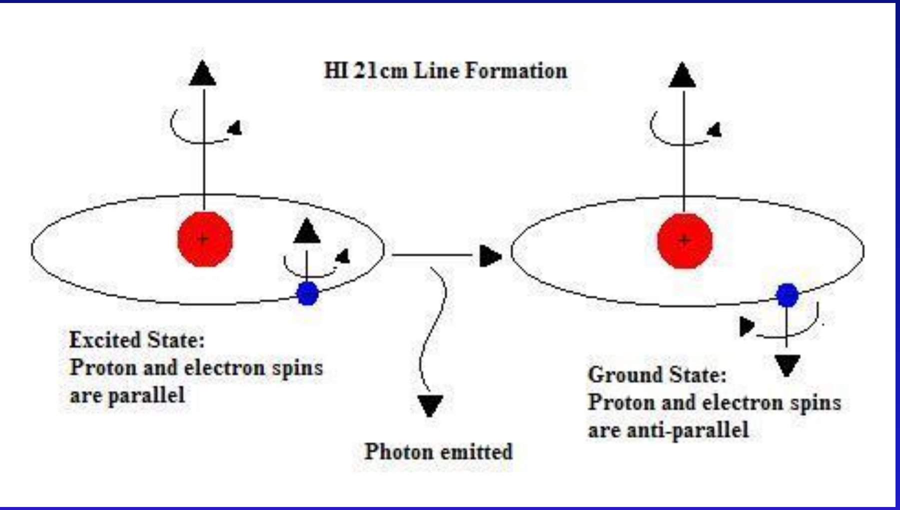
S. Jocelyn Bell Burnell's discovery of a pulsar, 1967



Andromeda galaxy on photographic plate
Tautenburg 2.0m telescope, 1961

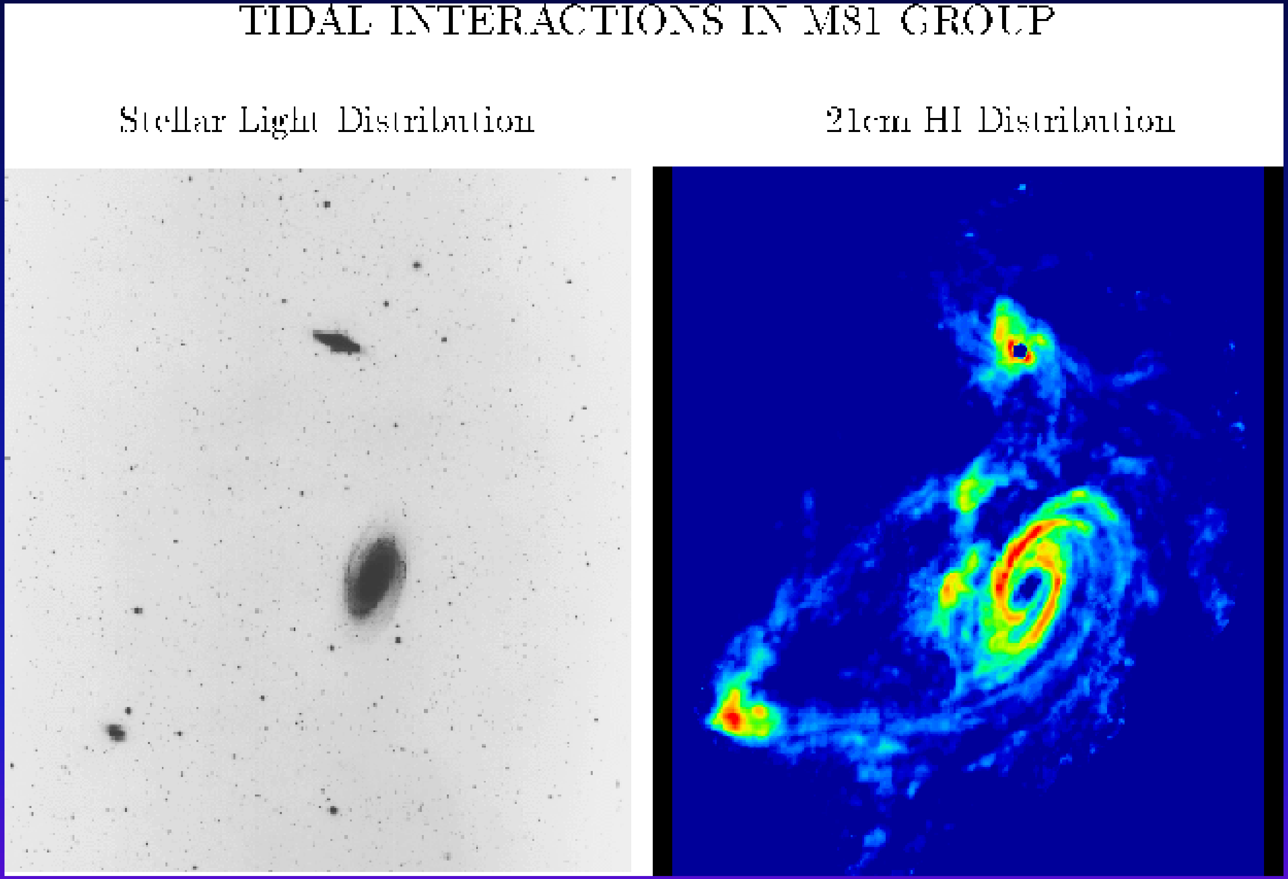
Hydrogen, Hydrogen, Hydrogen

- It accounts for ~75% of the ordinary matter in the universe
- Neutral hydrogen emits in the radio via the hyperfine line
  - The spin of the electron can be either parallel to or antiparallel to the proton spin
- Electron spin transition emits a photon with a wavelength of 21 cm



Hydrogen in the M81 Cluster

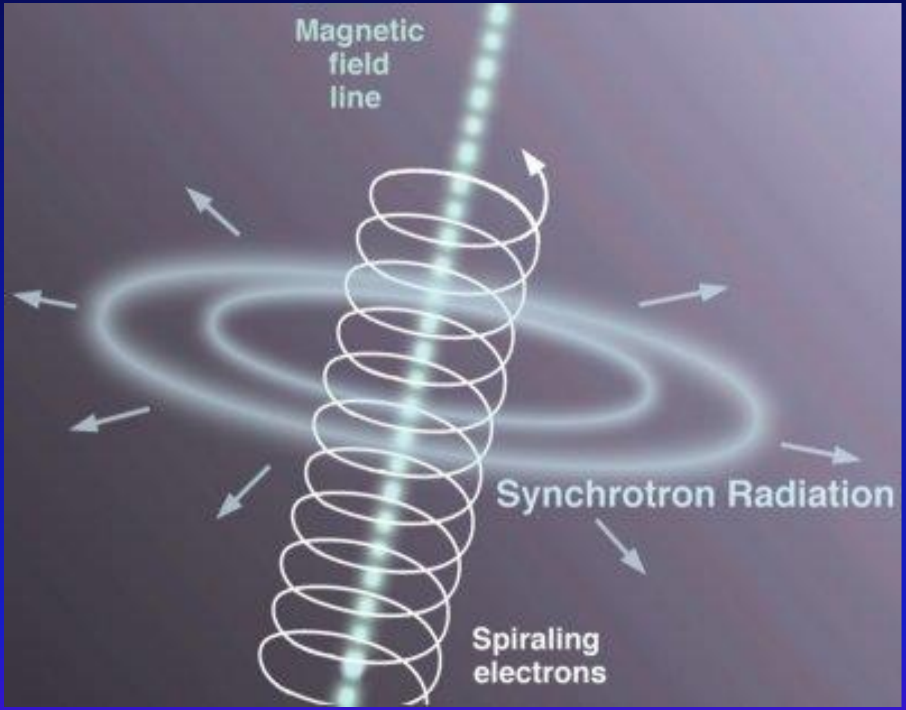
Image Credit: NRAO/AUI



21cm observations show hydrogen connecting the galaxies

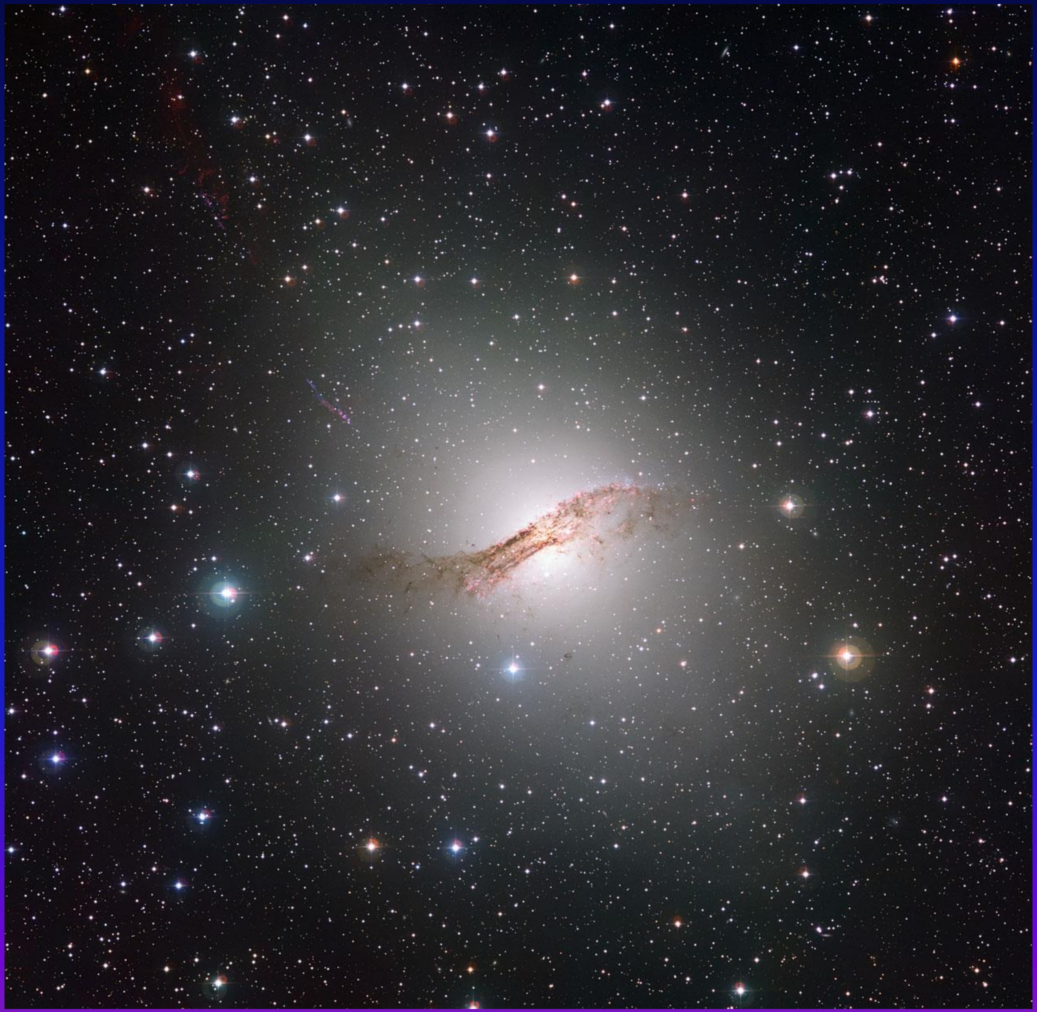
Synchrotron Radiation

- Electrons get trapped by strong magnetic fields
- They spiral around the field lines as they travel
- Accelerated electrons emit photons



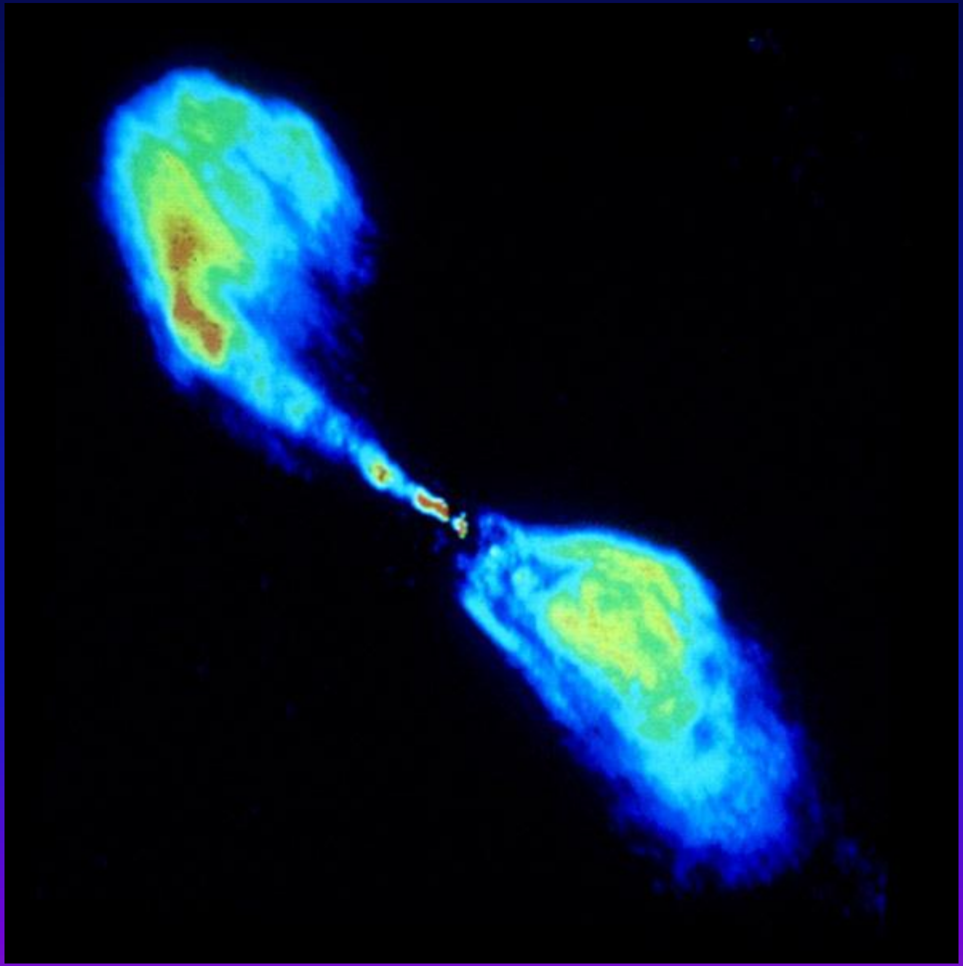
Centaurus A - Optical

MPG/ESO 2.2 m telescope in Chile



Centaurus A - VLA

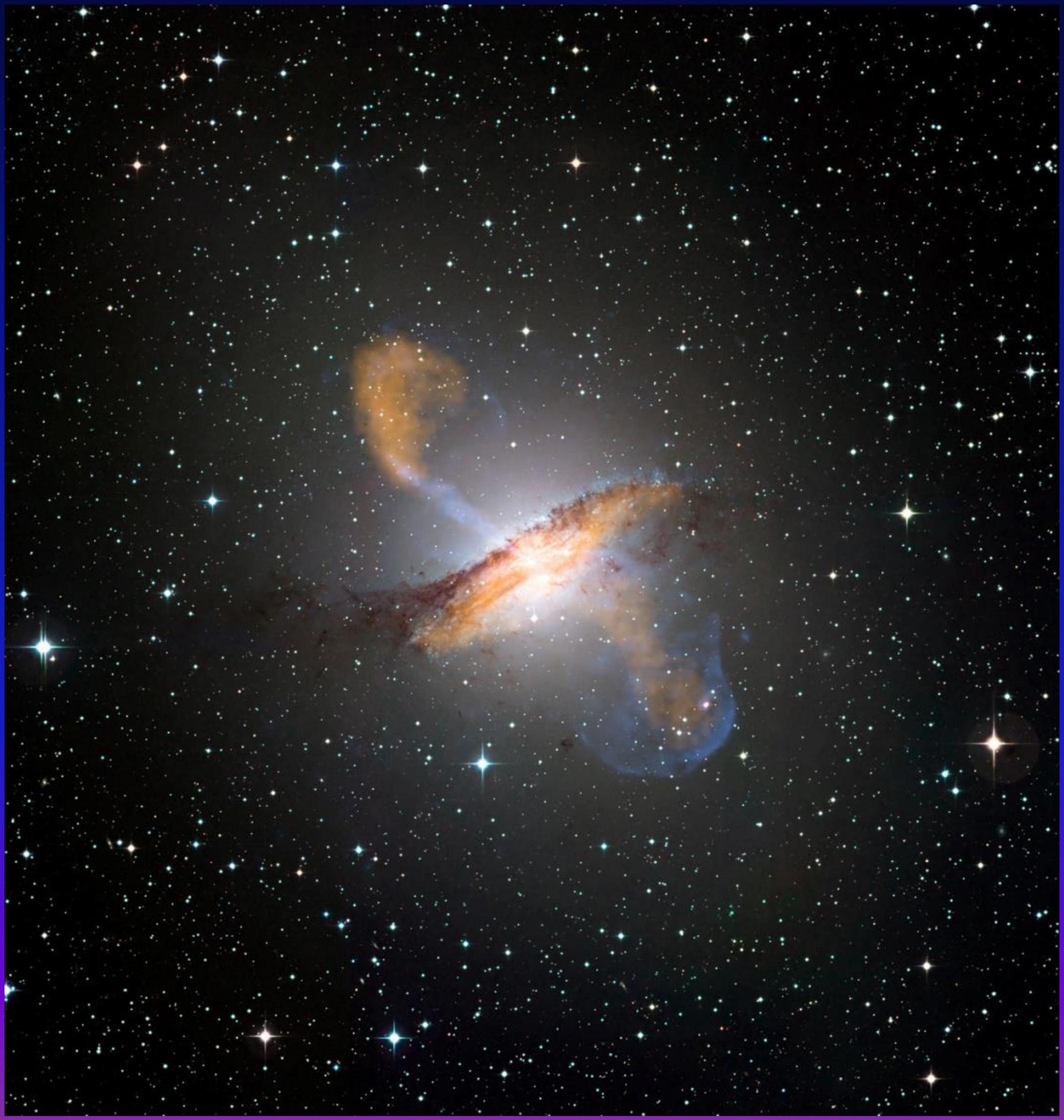
VLA 6 cm
Burns & Price
1983



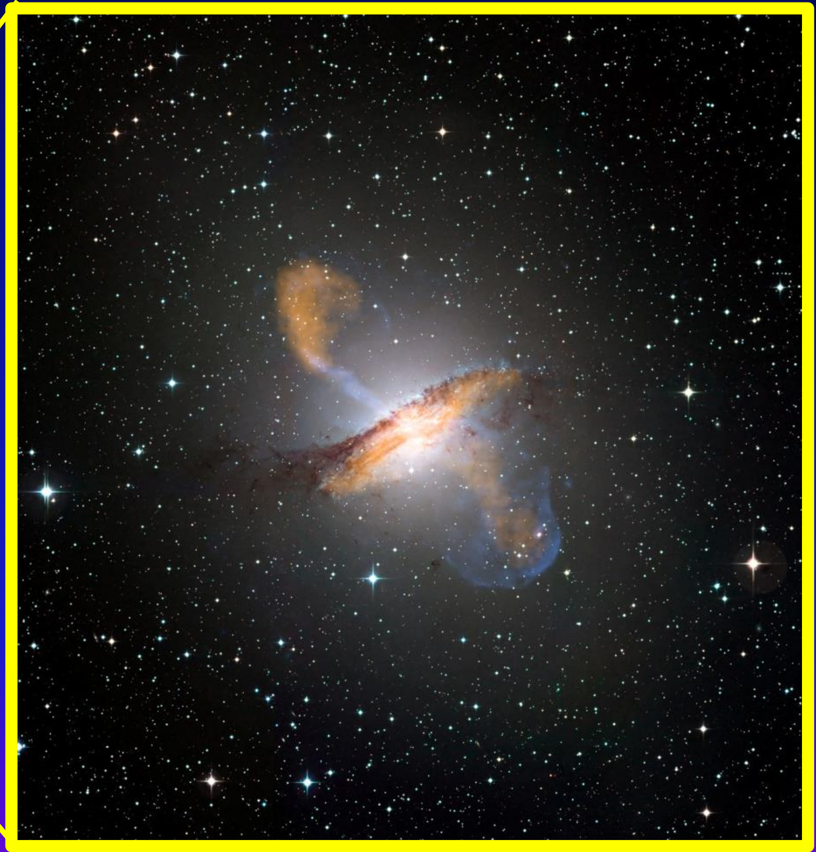
Centuarus A - Combined

X-ray (blue), optical (white), and radio (orange)

Credit: X-ray: NASA/CXC/Cfa/ R. Kraft et al.: sub-millimeter: MPIfR/ESO/AP EX/A.Weiss et al. Optical: ESO/WFI

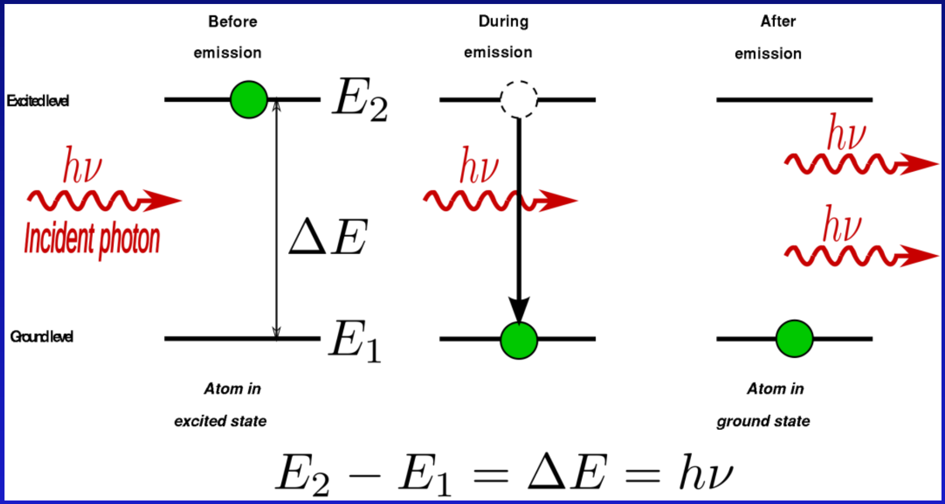


Centaurus A – A.K.A. NGC 5128



MASERs

- MASER: Microwave Amplification by Stimulated Emission of Radiation
- Radio equivalent of a laser
- Requires a population inversion; more molecules in excited state than in ground state



MASERs

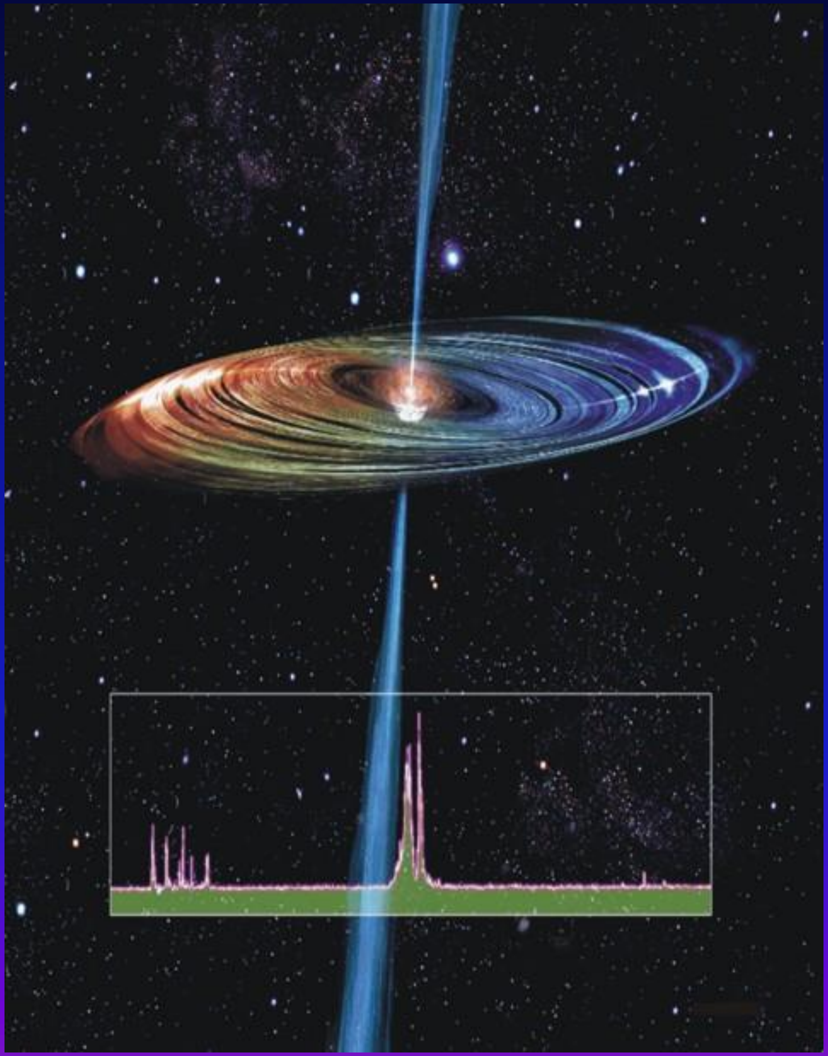
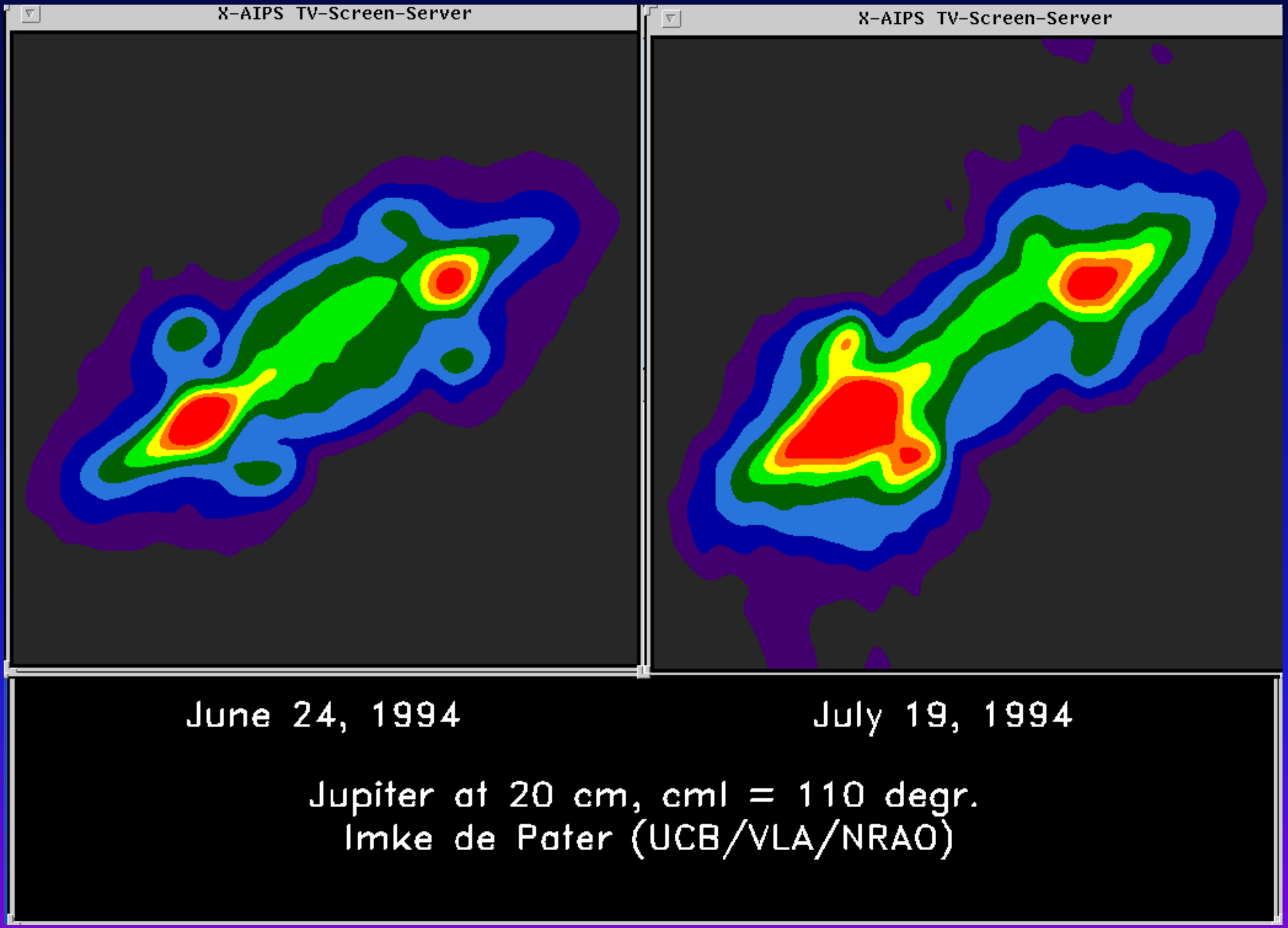


Image credit: NRAO/AUI and Artist: John Kagaya (Hoshi No Techou)

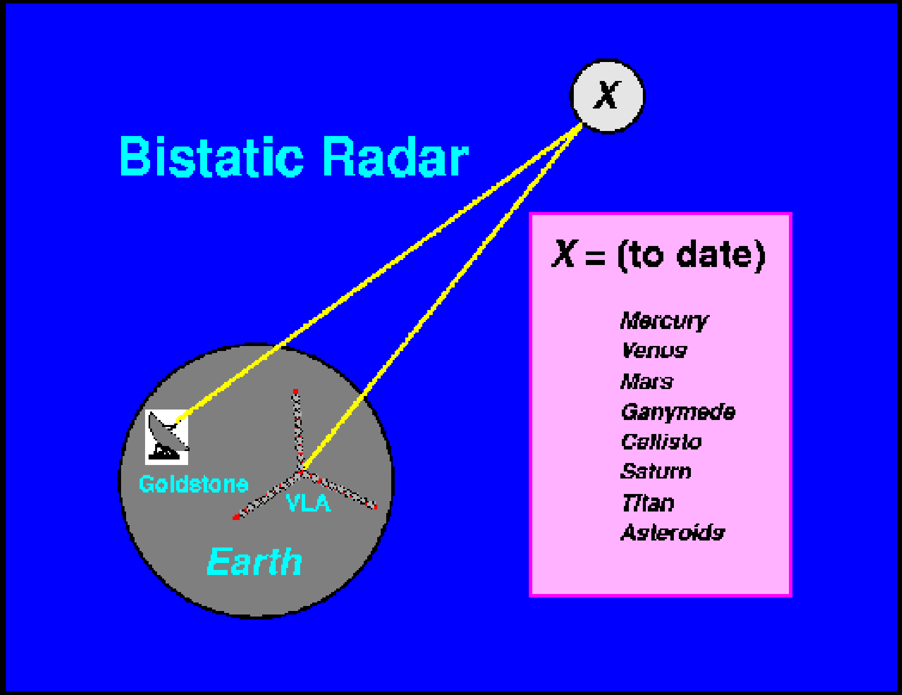
- Herrnstein et al. (1999) used the VLBA to get the positions and speeds of water MASERs in an accretion disc around a black hole in the active galaxy NGC 4258
- Results showed a warp in the disc

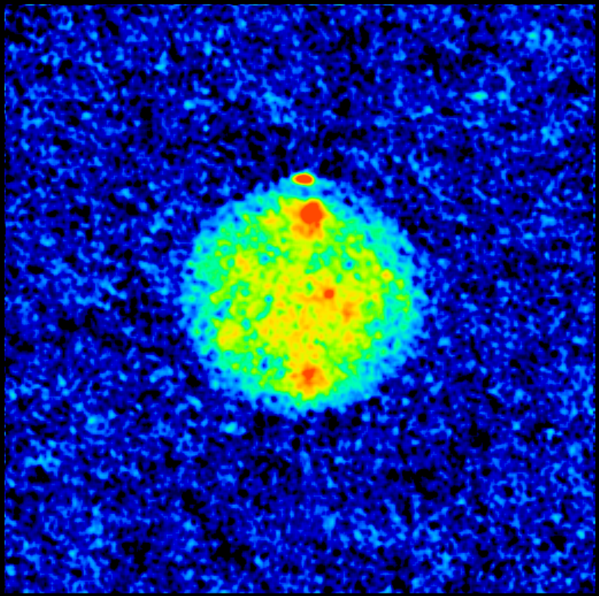
Planets



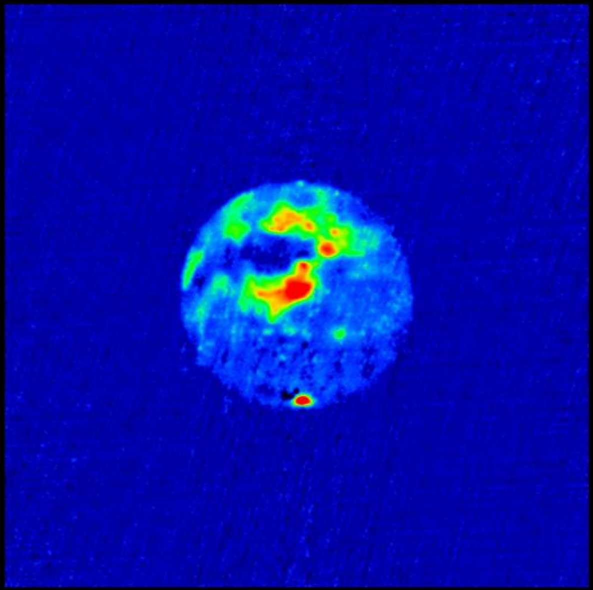
Jupiter before and after comet Shoemaker-Levy 9 struck it

Planetary Radar





Mercury



Mars

The Long Wavelength Array

10-88 MHz usable Galactic noise-dominated (>4:1) 24-87 MHz

4 independent beams x 2 pol. X 2 tunings each ~16 MHz bandwidth

SEFD ~ 3 kJy (zenith) S_{min} ~ 5 Jy (5s, 1 s, 16 MHz, zenith)

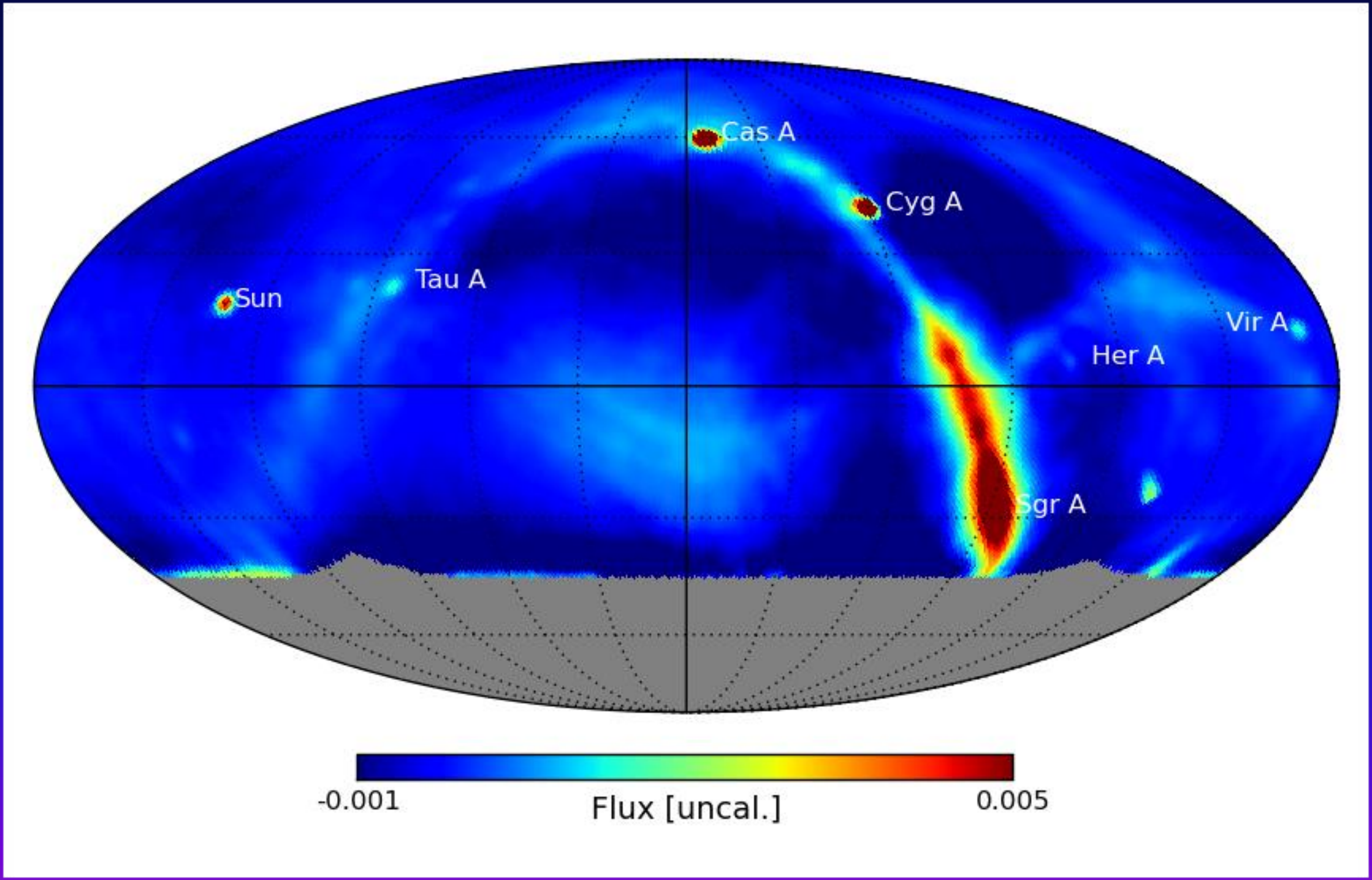
All sky (all dipoles) modes: TBN (70 kHz-bandwidth; continuous), TBW (78 MHz-bandwidth, 61 ms burst)

LWA1 science emphasis: transients, pulsars, Sun, Jupiter & Ionosphere

Open skies – LWA1 is funded by NSF as a University Radio Observatory

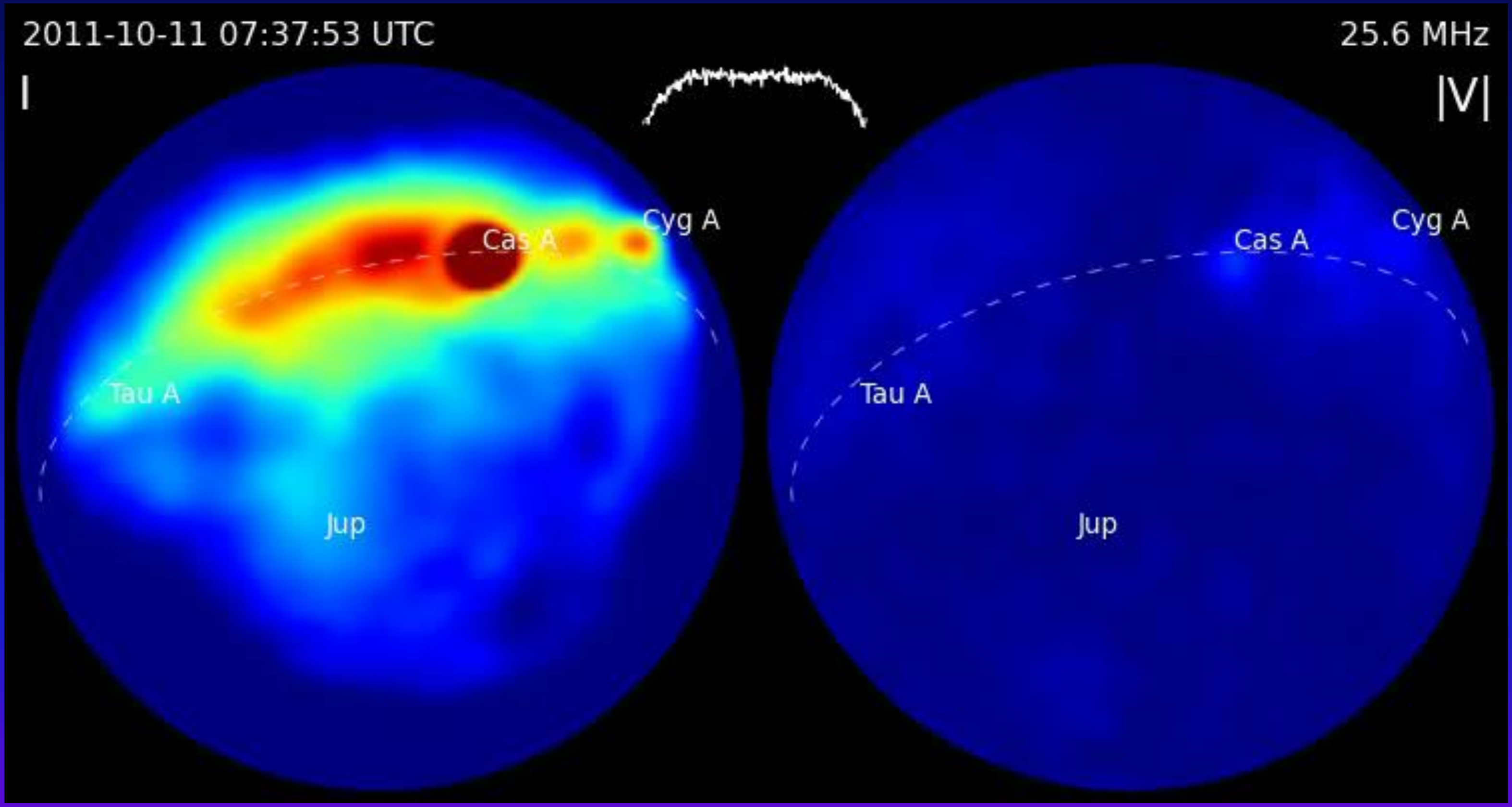
Next Call For Proposals is out, deadline March 15, 2013

LWA – All Sky (52-53 MHz)



Dowell et al. 2012

LWA – Jupiter Bursts



LWA TV: Live pictures of the low frequency sky updated every 5 seconds
http://www.phys.unm.edu/~lwa/lwatv.html

Current Worries in the US

- The National Science Foundation has announced that the VLBA and GBT will have to be shut down for budgetary reasons
- ALMA, the VLA, and Arecibo are safe, for now

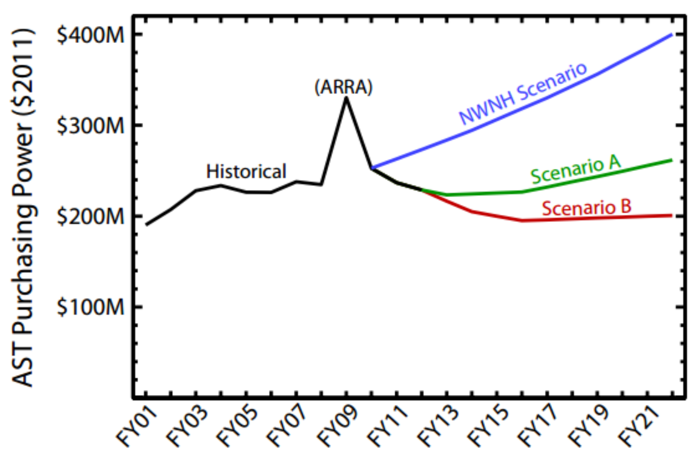
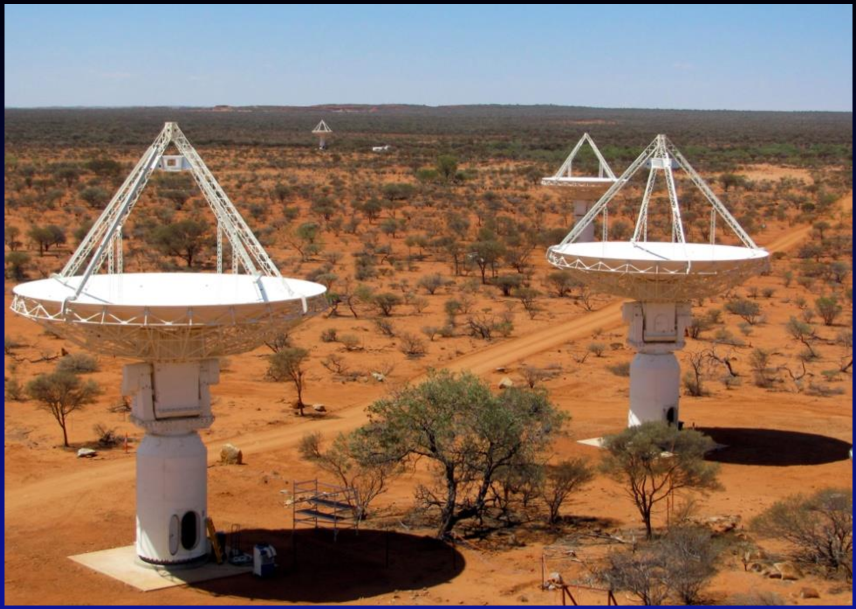


Figure 3.3 — Comparison of our two budget scenarios (A & B) for the AST budget, to the *NWNH* projection, along with actual AST budgets from FY01-FY12. Each is adjusted to FY11 purchasing power assuming 2.5% annual inflation. Scenario B purchasing power contracts by 25% from FY10 and then stabilizes; Scenario A contracts by 15% and slowly recovers by FY22. AST funding is already $45M (in FY12 dollars) below the *NWNH* projection. By FY22, our budget scenarios are only 50-65% of the *NWNH* projection.

The Future



ASKAP, Australia

MWA, Australia

MeerKAT, South Africa

The Square Kilometer Array

SKA
SQUARE KILOMETRE ARRAY

www.skatelescope.org

Radio Astronomy: It Ain't For Wimps




Back-ups and Extras

My Ph.D. Research

- I studied active galactic nuclei (AGN) which are emitting gamma-rays
- My dissertation focused on blazars detected by the *Fermi Gamma-ray Space Telescope*

painting by Don Dixon
for "Scientific American"

AGN Basics

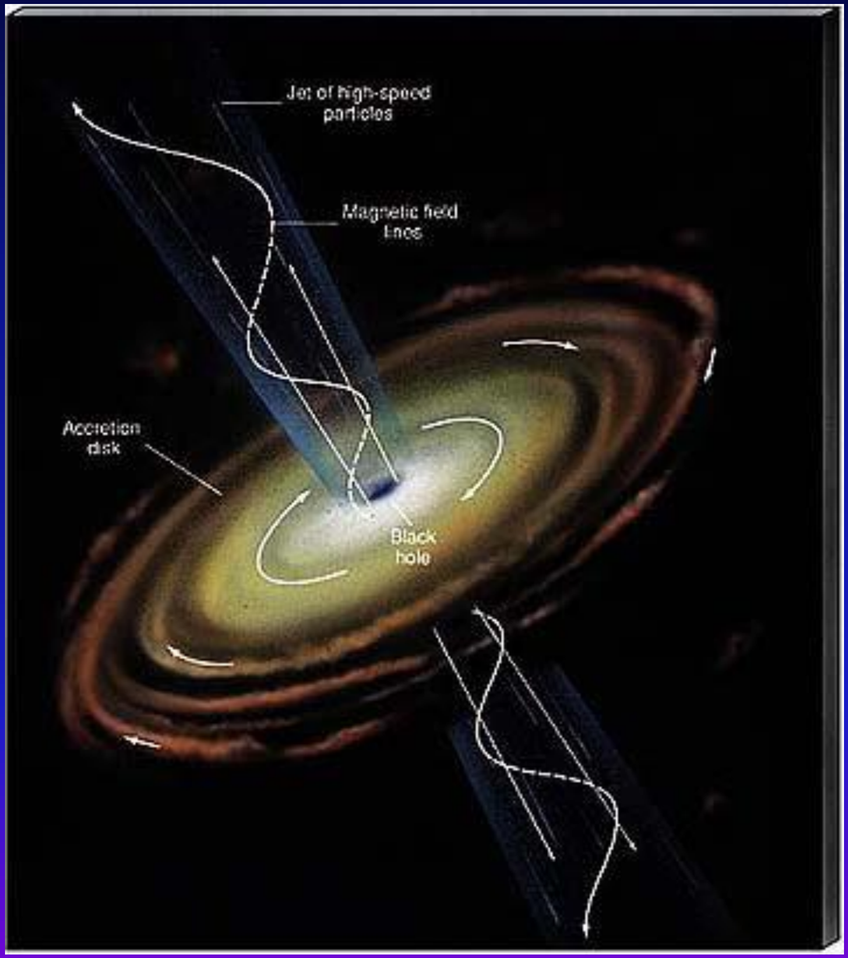
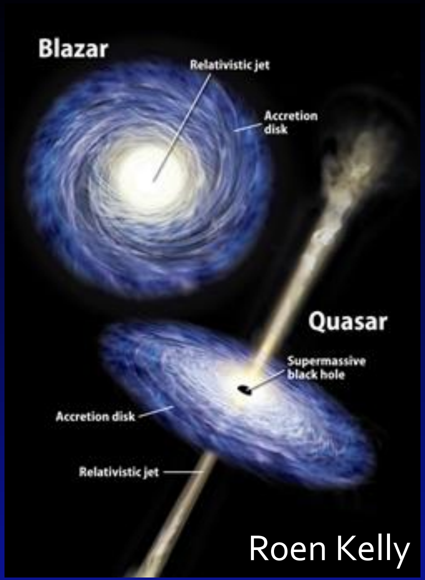
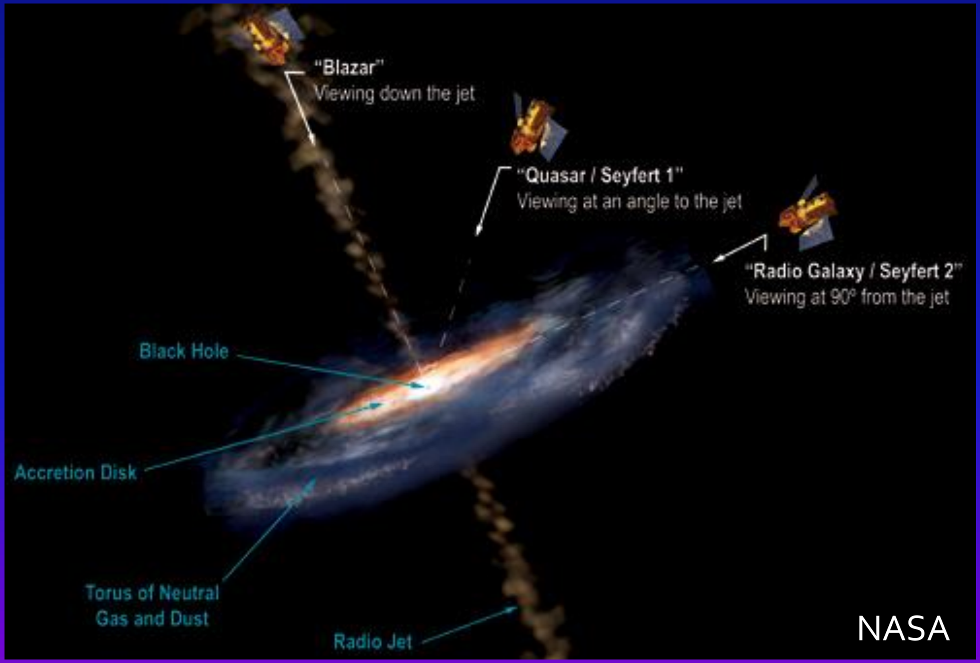


Image from Chaisson & McMillan 1998

- Supermassive black hole (central engine)
- Accretion disk
- Helical magnetic field
- Jets of high-energy particles
- Possibly surrounded by warm (IR) dusty torus

Blazars



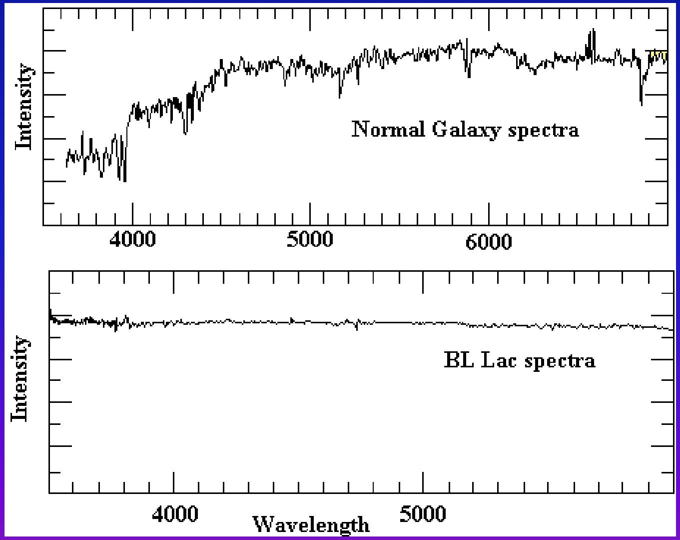


- AGN with one jet pointed nearly straight at us
- High variability
- Typically one-sided jet morphology
- Apparent superluminal motion in the jet

Blazar Types

BL Lacs

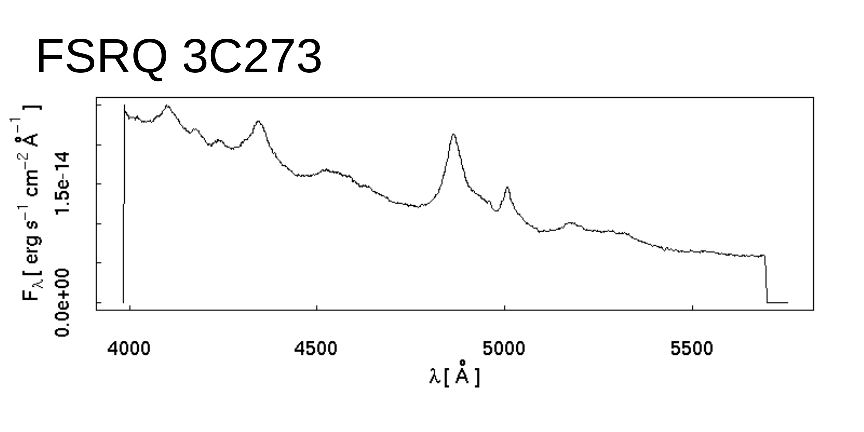
- BL Lacertae objects
- Flat, almost featureless optical spectra



Siobahn Morgan, UNI

FSRQs

- Flat-spectrum radio quasars
- Broad emission lines in optical spectra



Koratkar & Blaes 1999

The Tools: Fermi

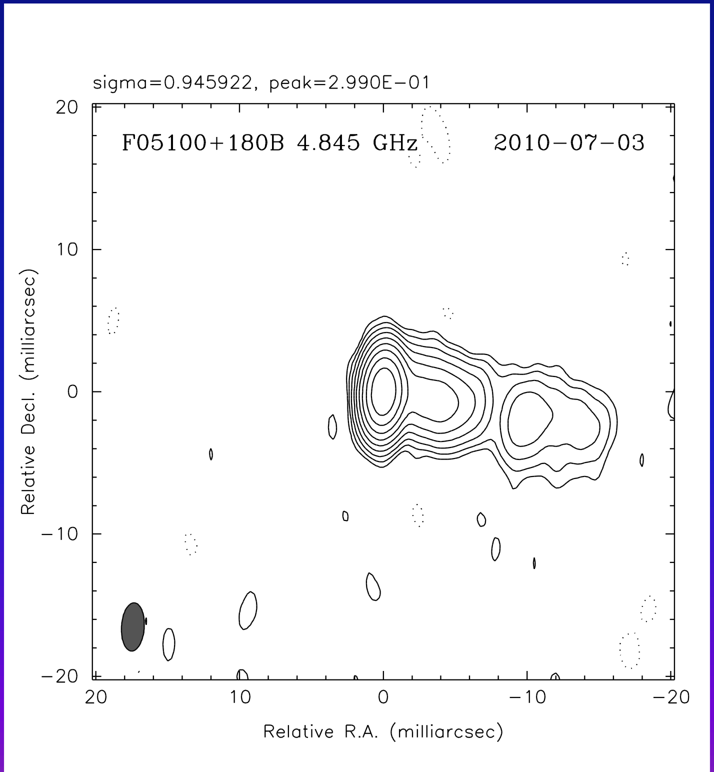
- The Fermi Gamma-ray Space Telescope
  - Large Area Telescope (LAT)
  - Wide-field (~2.4 sr)
  - Covers ~20 MeV to ~300 GeV
  - Surveys the entire sky every 3 hours

NASA

The Tools: VLBI

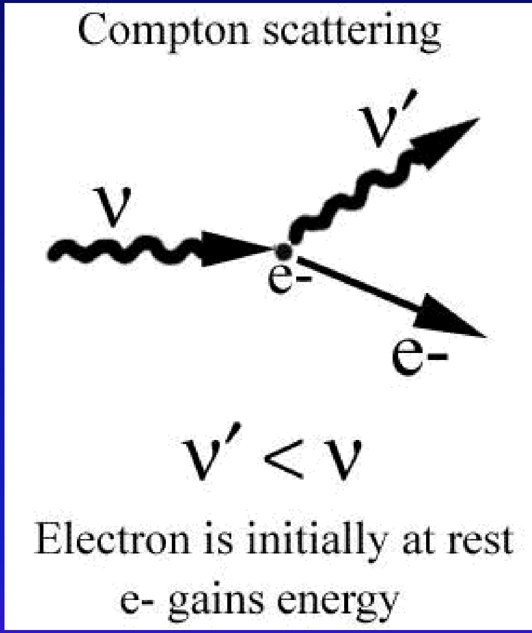
NRAO/AUI

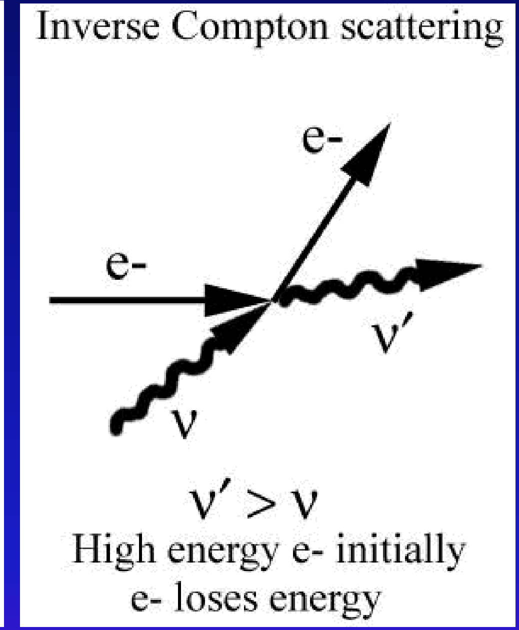
- Very Long Baseline Array (VLBA)
  - Extremely high resolution
  - Good polarimetry
  - Able to image the pc-scale synchrotron radiation in the jets
- Most observations at 5 GHz (6 cm)



γ-ray Production Mechanism

- Inverse Compton scattering
- 2 possibilities
  - Synchrotron Self-Compton (SSC) – seed photons are from the electrons' own synchrotron emission
  - External Inverse Compton (EC) – seed photons are from some external source





Diagrams from venables.asu.edu

Where Is the Gamma-ray Emitting Region?

- Correlation between radio flux density and LAT flux implies synchrotron and inverse Compton emission are related
  - γ-rays should be coming from jets
- Most of the differences between LAT and non-LAT samples are related to the cores
  - γ-rays should be coming from the BASE of the jets
- There is still much debate on this

Phantom BL Lacs

- Some of the low-synchrotron peaked BL Lacs (LBLs) may be FSRQs with exceptionally strong jets that swamp their broad lines
- In fact, BL Lacertae may not actually be a BL Lac object (Vermeulen et al. 1998)

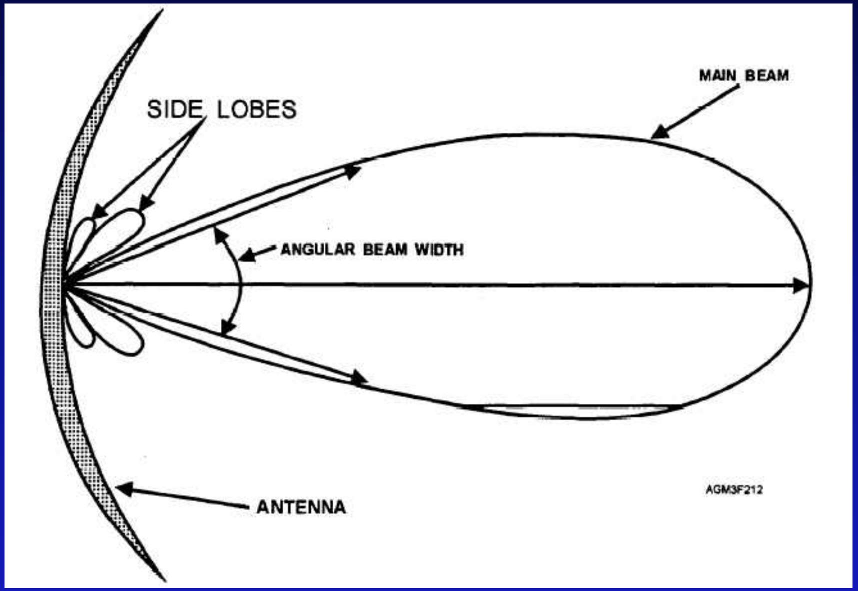
Radio Terms

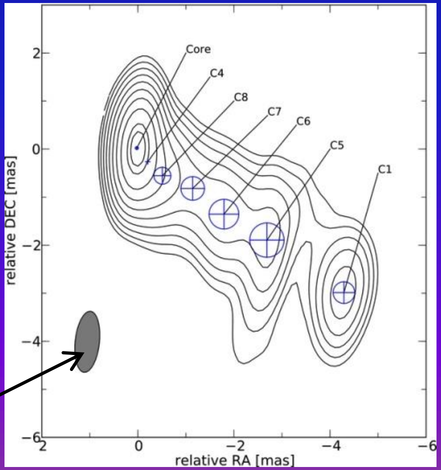
- Flux density (S_ν) = flux per unit frequency [Watts per square meter per Hertz]
  - Jansky: 1 Jy = 10^{-26} W m^{-2} Hz^{-1} = 10^{-23} erg s^{-1} m^{-2} Hz^{-1}
- Spectral Index: $S_\nu \sim \nu^\alpha$, α is the spectral index
  - α around zero is called "flat"
- IF = intermediate frequency (sub-band), also called "spectral window"
  - Each frequency band can be divided into multiple IFs. Each IF is divided into several channels.
- RFI = radio frequency interference
- System Temperature (T_{sys}): a way of talking about the total noise of the instrument; also important in determining sensitivity

Interferometry Basics

- Primary Beam
  - The most sensitive portion of a single antenna's response pattern
- Restoring Beam/Synthesized Beam
  - The response pattern of the entire array after correlation
- Sidelobes
  - Antenna response outside of the primary beam

Antenna pattern





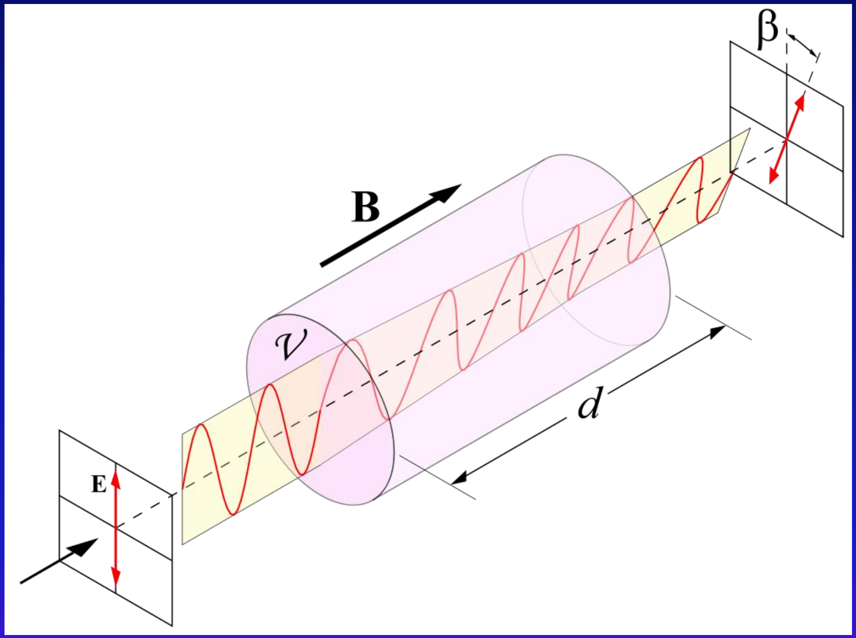
Restoring beam

3C279 from Bloom, Fromm, & Ros 2012

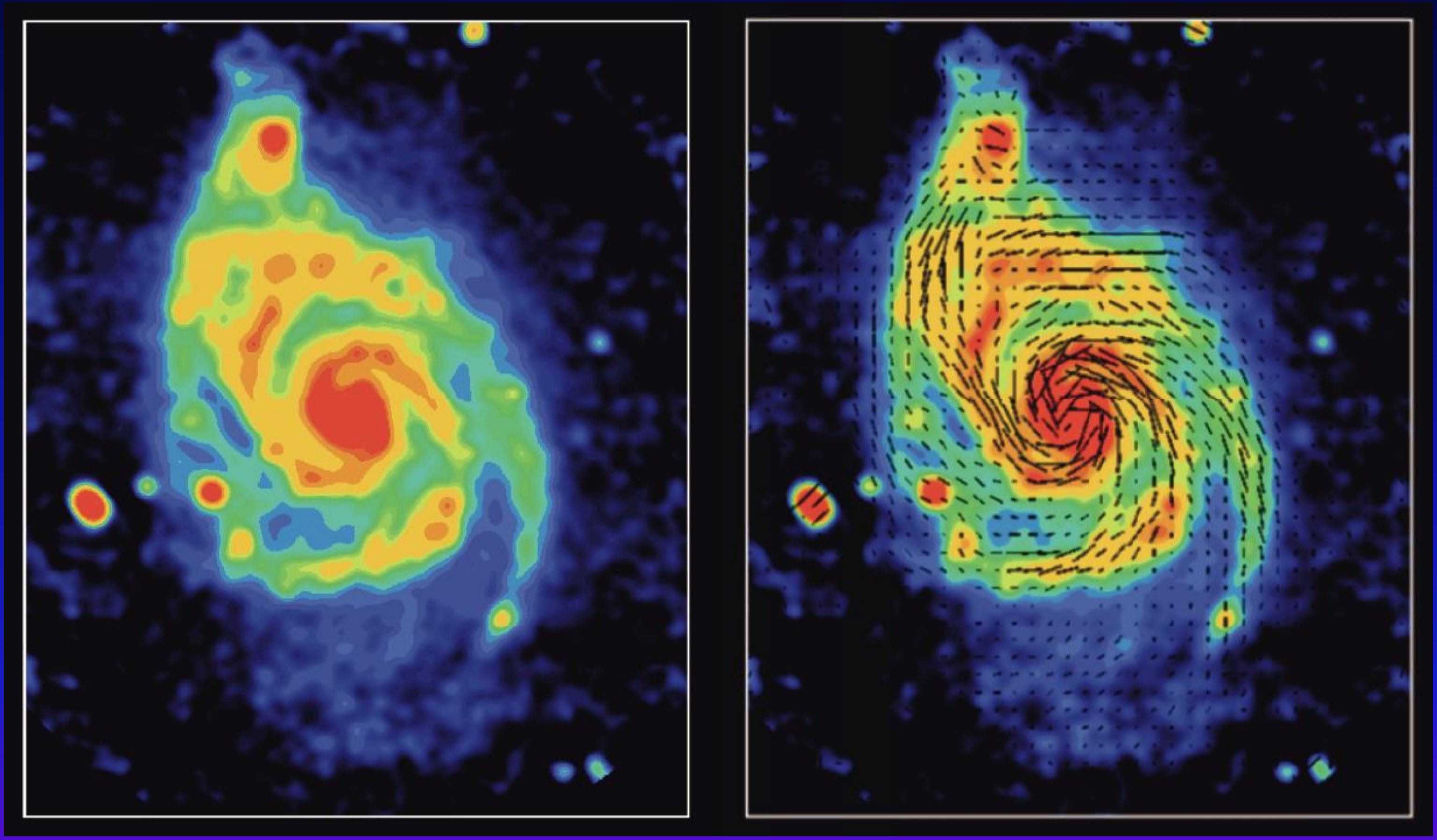
Polarimetry

- Synchrotron radiation is inherently polarized
- Measuring the polarization angles at multiple wavelengths gives you the rotation measure (RM)
- The RM and the polarization angles give you information about the magnetic field strength and structure

Faraday Rotation



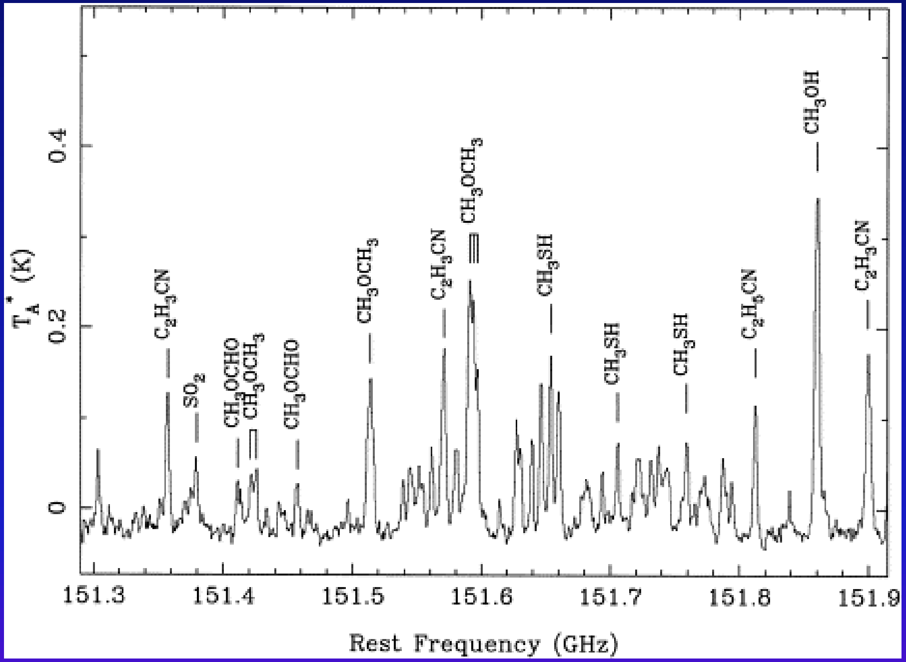
Magnetic Fields in M51



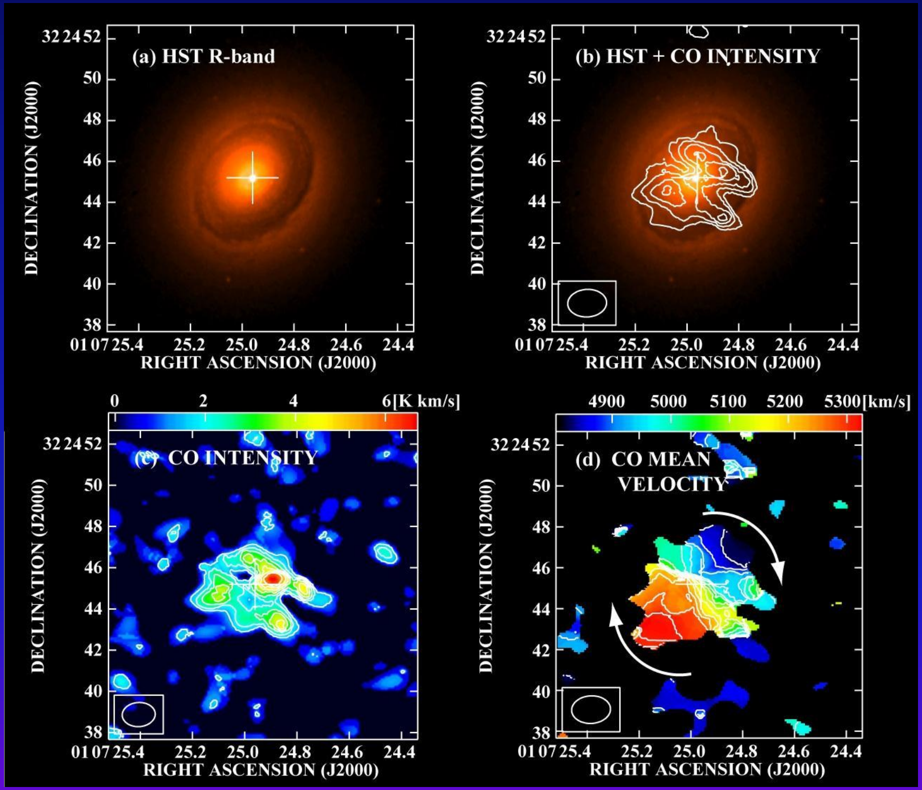
VLA + Effelsberg 6 cm images of M51 showing the orientation of the magnetic field lines
Image credit: NRAO/AUI, Investigators: Rainer Beck & Cathy Horellou

Molecular Emission Lines

- Spectral lines can tell you about
  - Composition
  - Temperature
  - Star formation
  - Kinematics (with Doppler shifts)



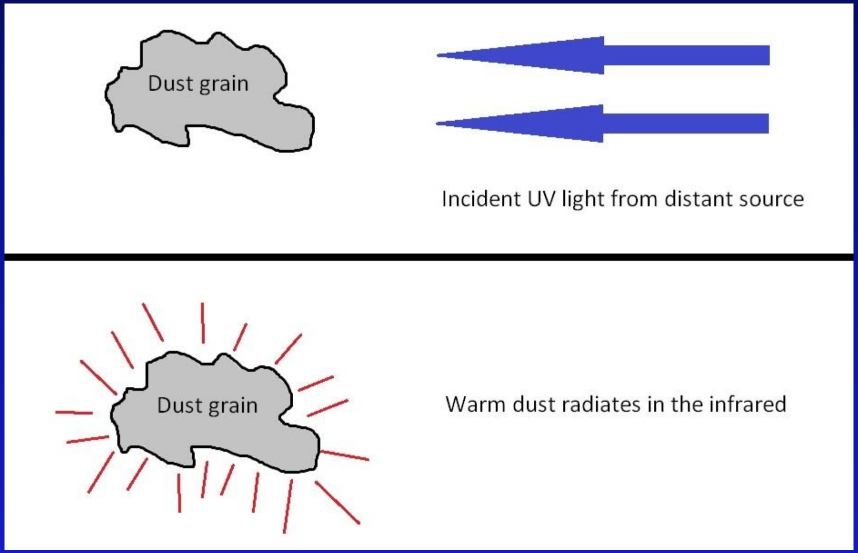
CO in NGC383

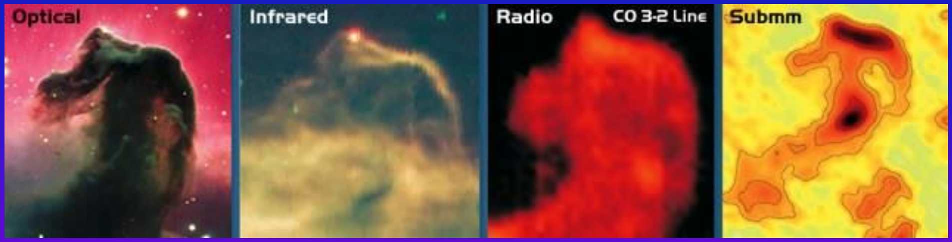


- Okuda et al. (2004) studied CO emission in NGC 383
- They found a gas disk with a mass of 9.7 x 10^8 solar masses rotating at a rate of 460 km/s

Thermal Dust

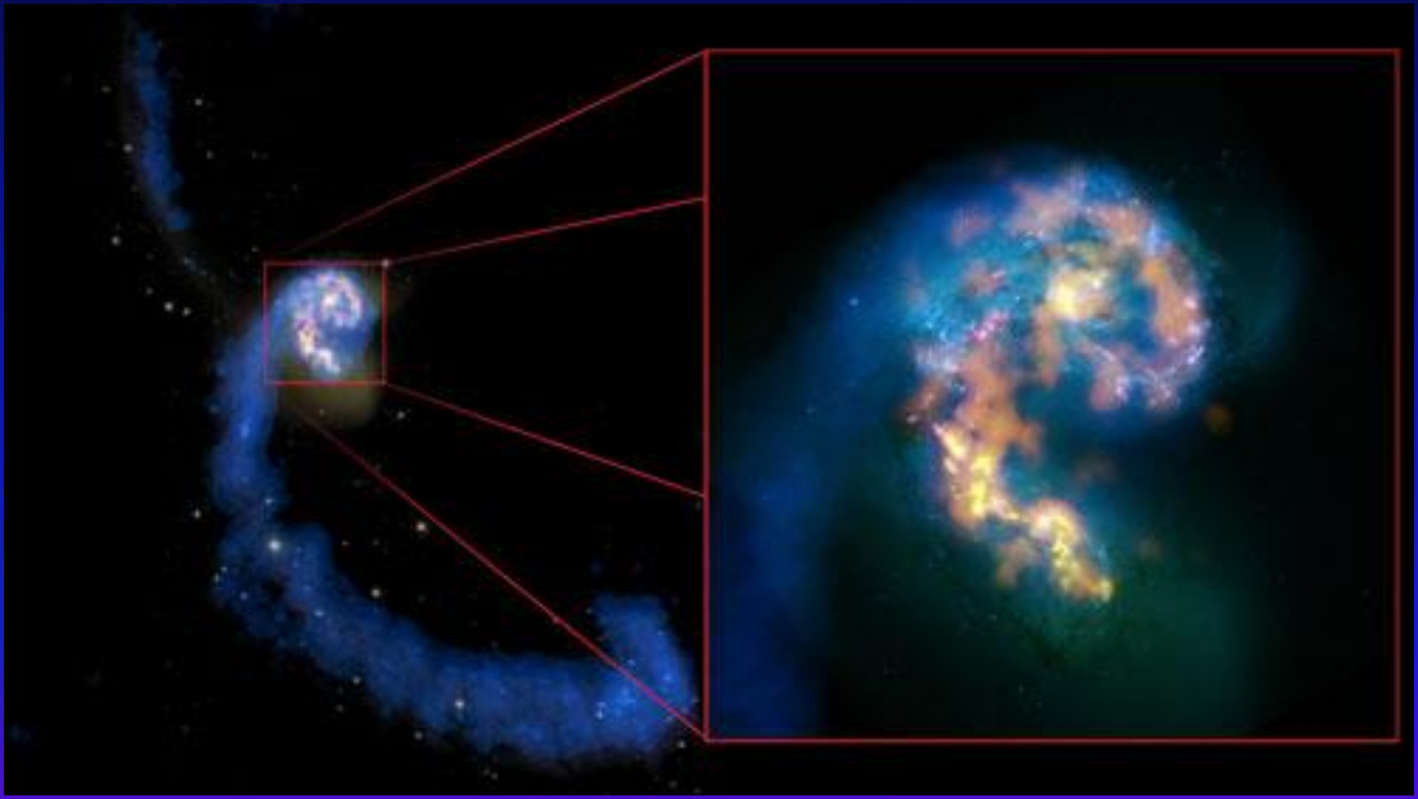
- At the high-frequency end of the radio spectrum you start merging with the far infrared
- Interstellar dust absorbs UV radiation, warms up, and emits at longer wavelengths (IR)





NRAO/AUI

ALMA View of NGC 4038/4039



Blue = radio, white & pink = optical, orange & yellow = sub-mm (ALMA)

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

LWA – Frequency Sweep