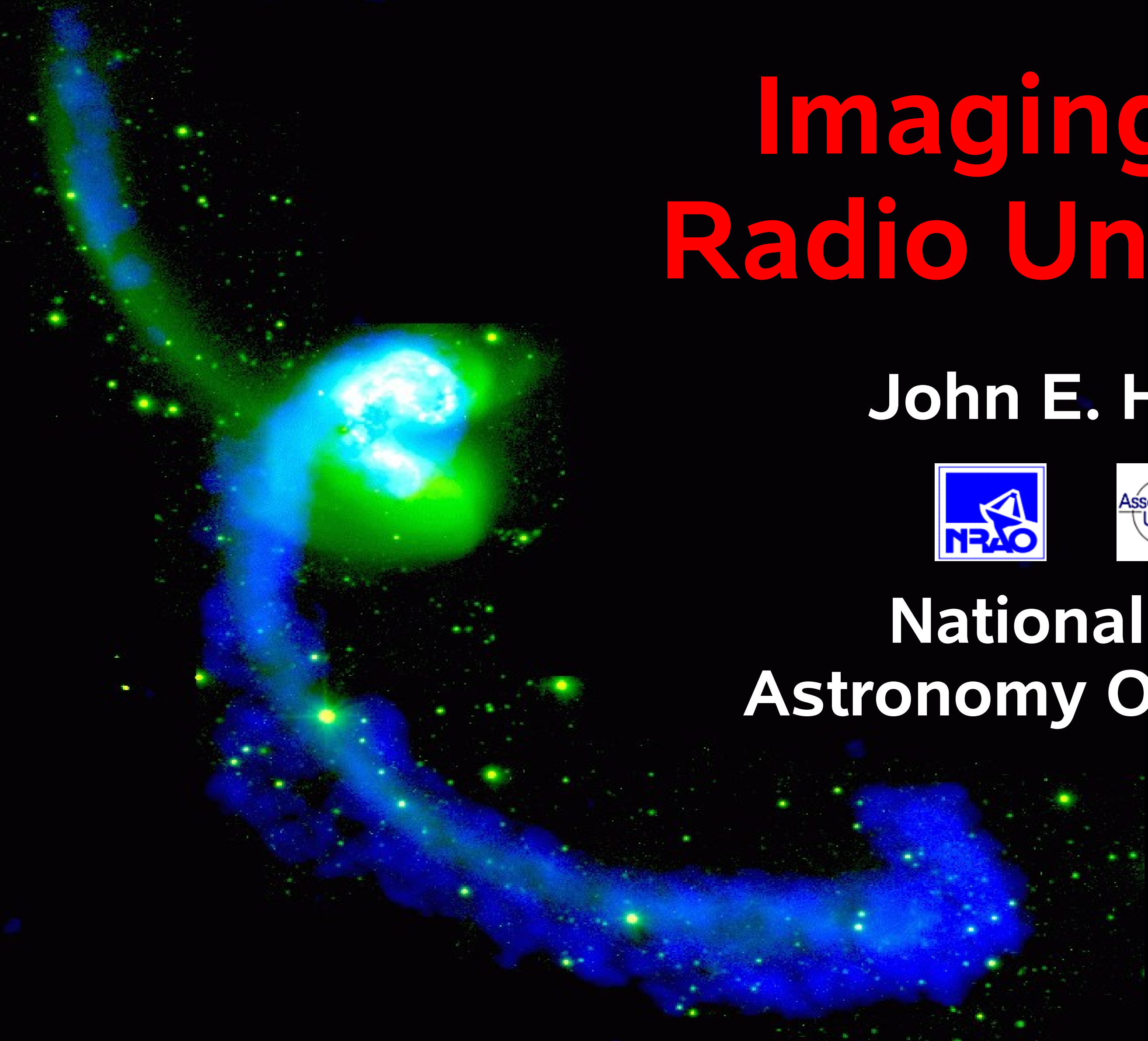
Imaging the Radio Universe



John E. Hibbard

National Radio Astronomy Observatory

El Universo en el Radio

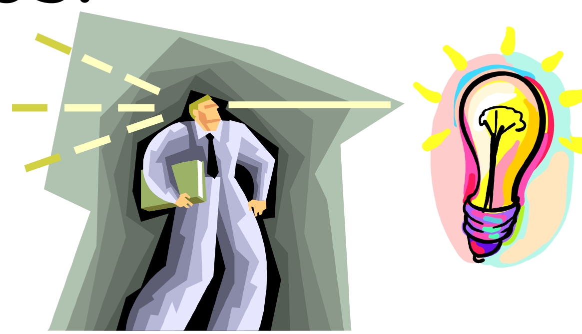
Traduccion

National Radio Astronomy Observatory

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Que es “viendo”?

- Vemos un objecto quando la radiacion electromagnetico emitido o reflejedo del objecto interactia con cellulares en nuestra ojos.



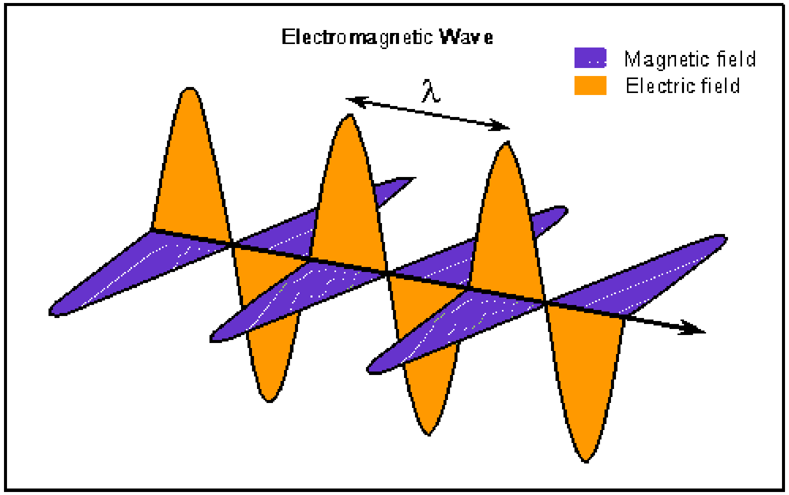
Astronomos vemos un objecto quando la misma radiacion interactia con nuestra detectores.

Entonces que es radiacion electromagnetica?

- Una bolsa de energia, sin mass, viajando, correspondiente a un campo electrico y magnetico oscillando.
  - otro nombres: radiacion, onda de luz, foton

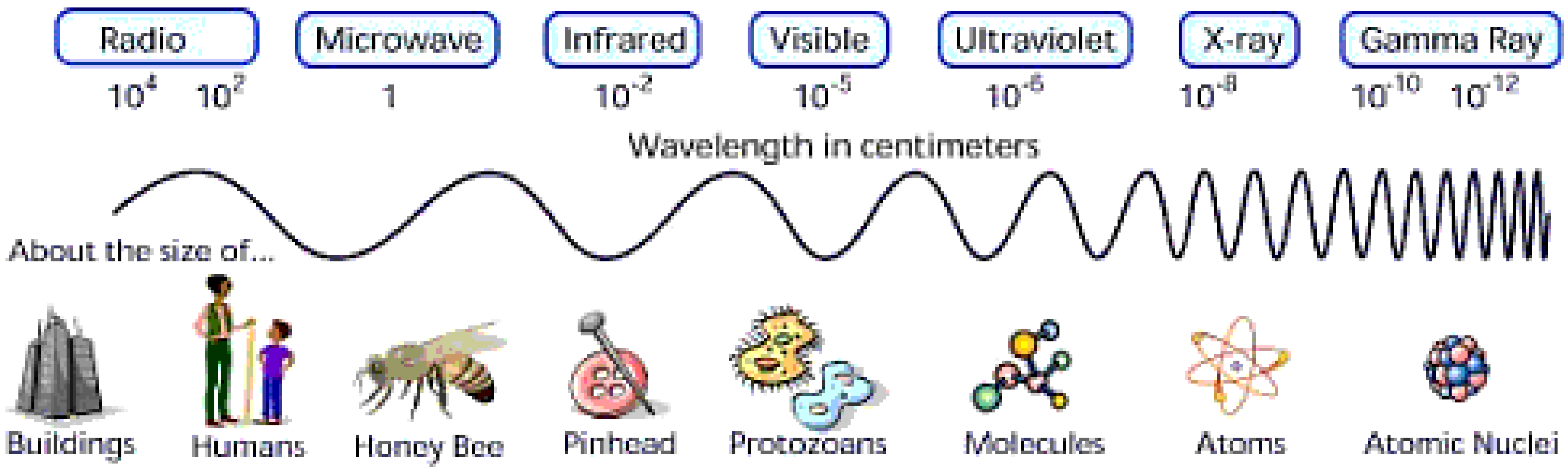
Viajas con velocidad de luz (por supuesto!).

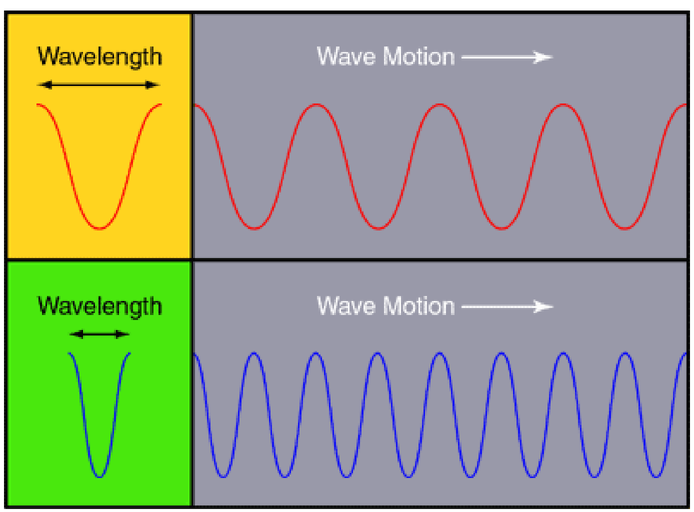
Todos tipos de radiacion EM viajan con esta velocidad, independientemente de que tiene mucho o poco energia

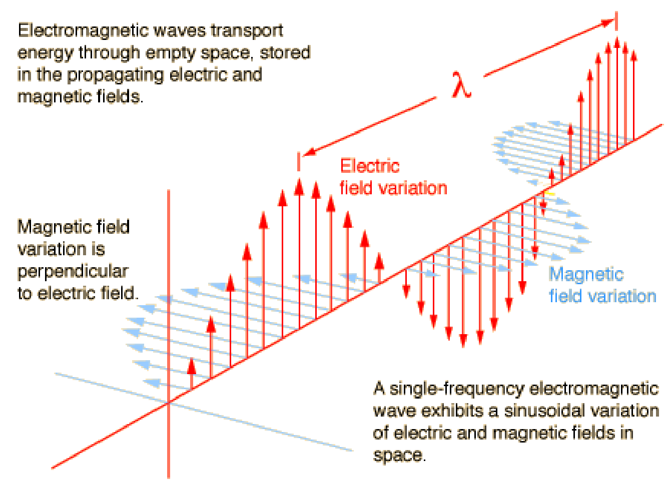


Animation from Nick Strobel's Astronomy Notes (www.astronomynotes.com)

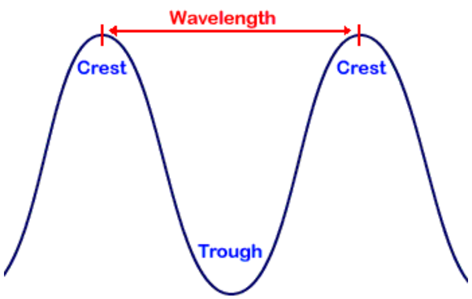
Un onda EM es un onda EM, independiente de su largesa ...

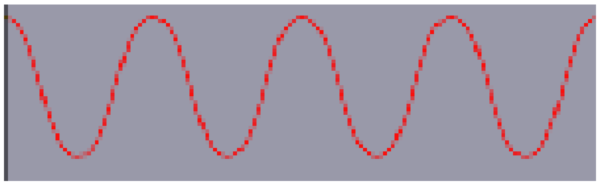






La propridad del radiacion es definido con su longitude de onda y/o frecuencia y/o energia





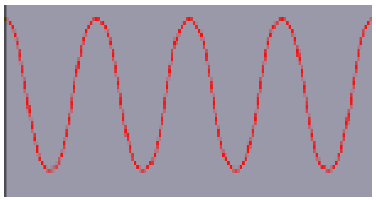
Distanza entre maximos=longitude del onda, λ

Numero de maximas que pasa cada segundo = frecuencia, ν

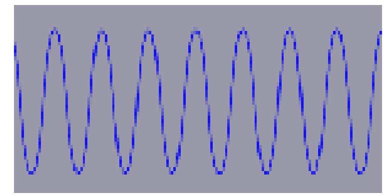
$$\lambda = \frac{\text{velocidad de luz}}{\nu}$$

Larga longitudes de ondas = bajo frecuencias
Corto longitudes de ondas = alto frecuencias

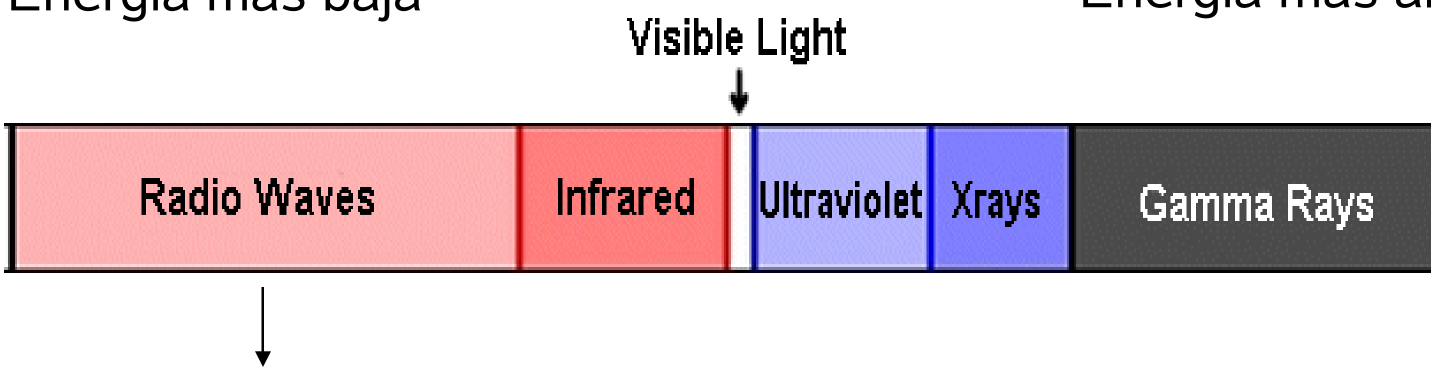
The Electromagnetic Spectrum



long. de onda mas larga
frecuencia mas baja
Energia mas baja



long. de onda mas corte
frecuencia mas alta
Energia mas alta



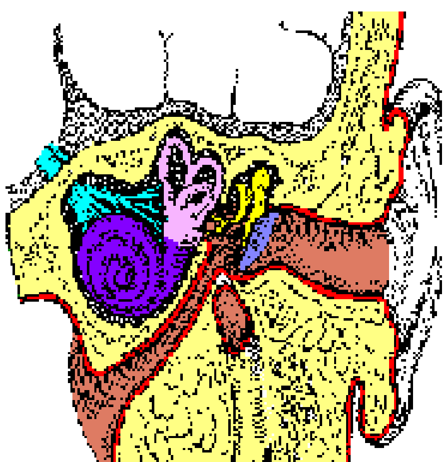
long. de onda: 300 metros a 0.5 milimetros
frecuencia: 1 MHz (1 million Hertz or ciclos cada segundo)
a 500 GHz (500 billion Hertz)

Una cosa muy importante para conocer:

No "escuchamos" a datos Radios

Ondas de Radio no son Ondas Sonidos

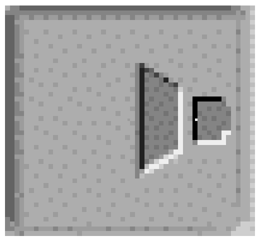
- Ondas de radio son ondas de radiacion electromagneticos, como luz (y rayos-X, microondas etc.).
- Ondas de sonido son ondas de presion. Requiren un medio (aire, aqua, etc.) para transmisar.
- Sonidas son creado via ondas de presion moviendo un membrano en tu oyo. Tu cerebro convertes esta vibraciones en “sonidos”.



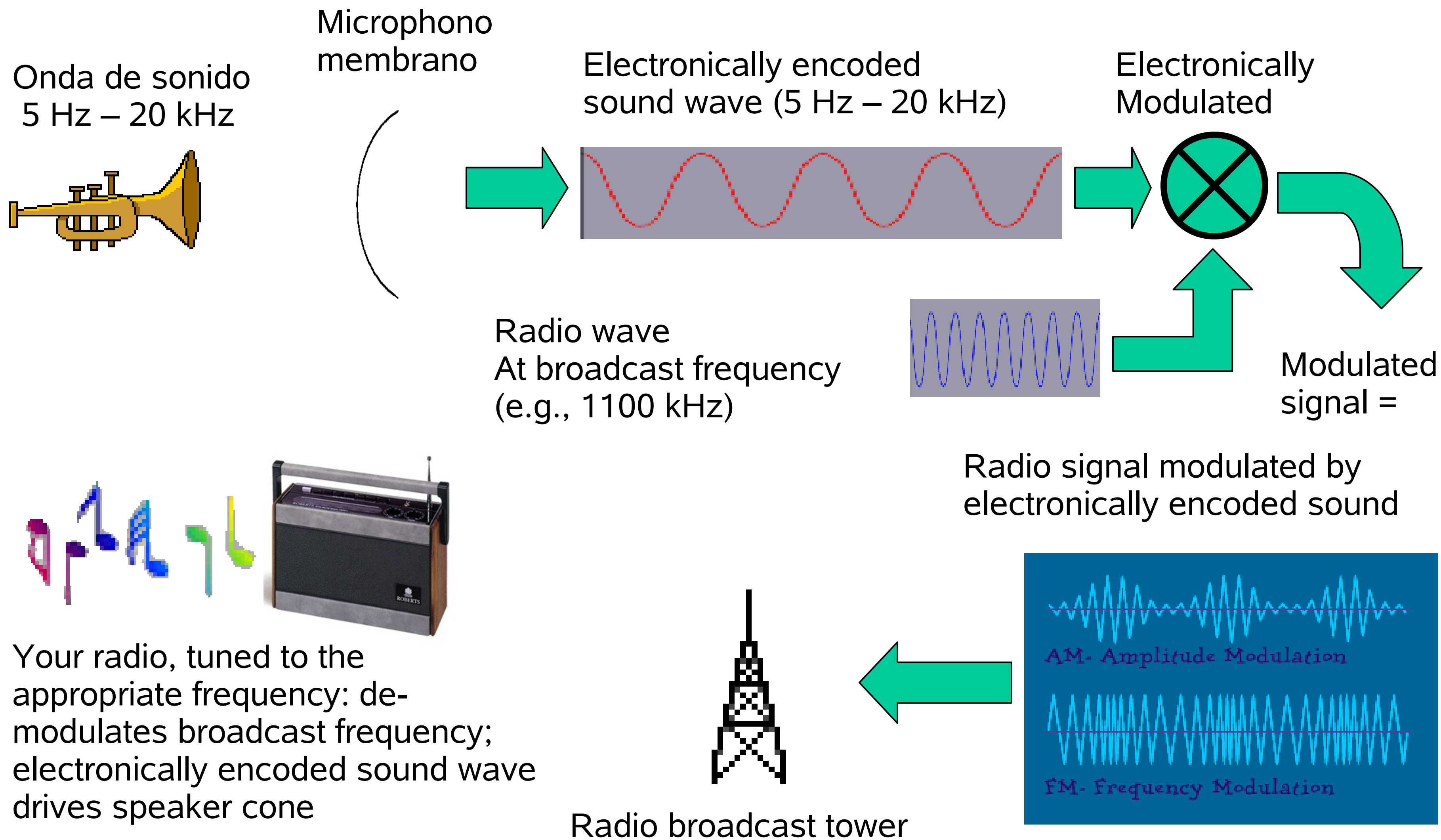
Ear

Medium

Sound

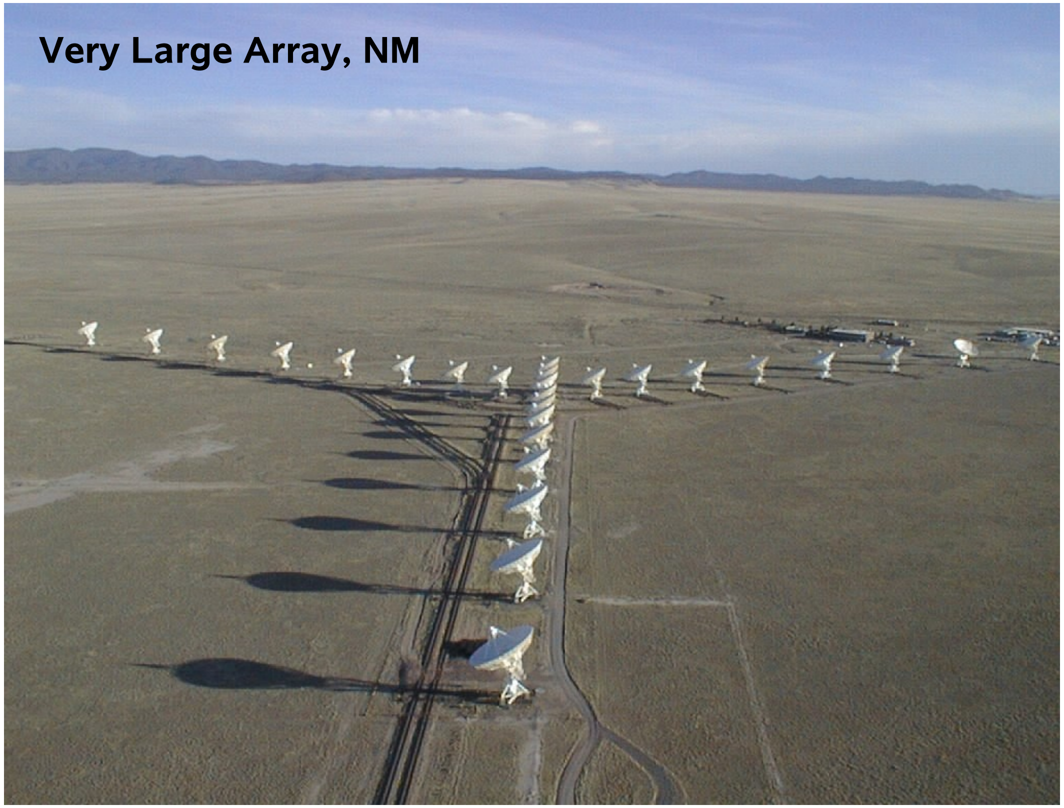


Tu no escuchas ondas de radio con un radio



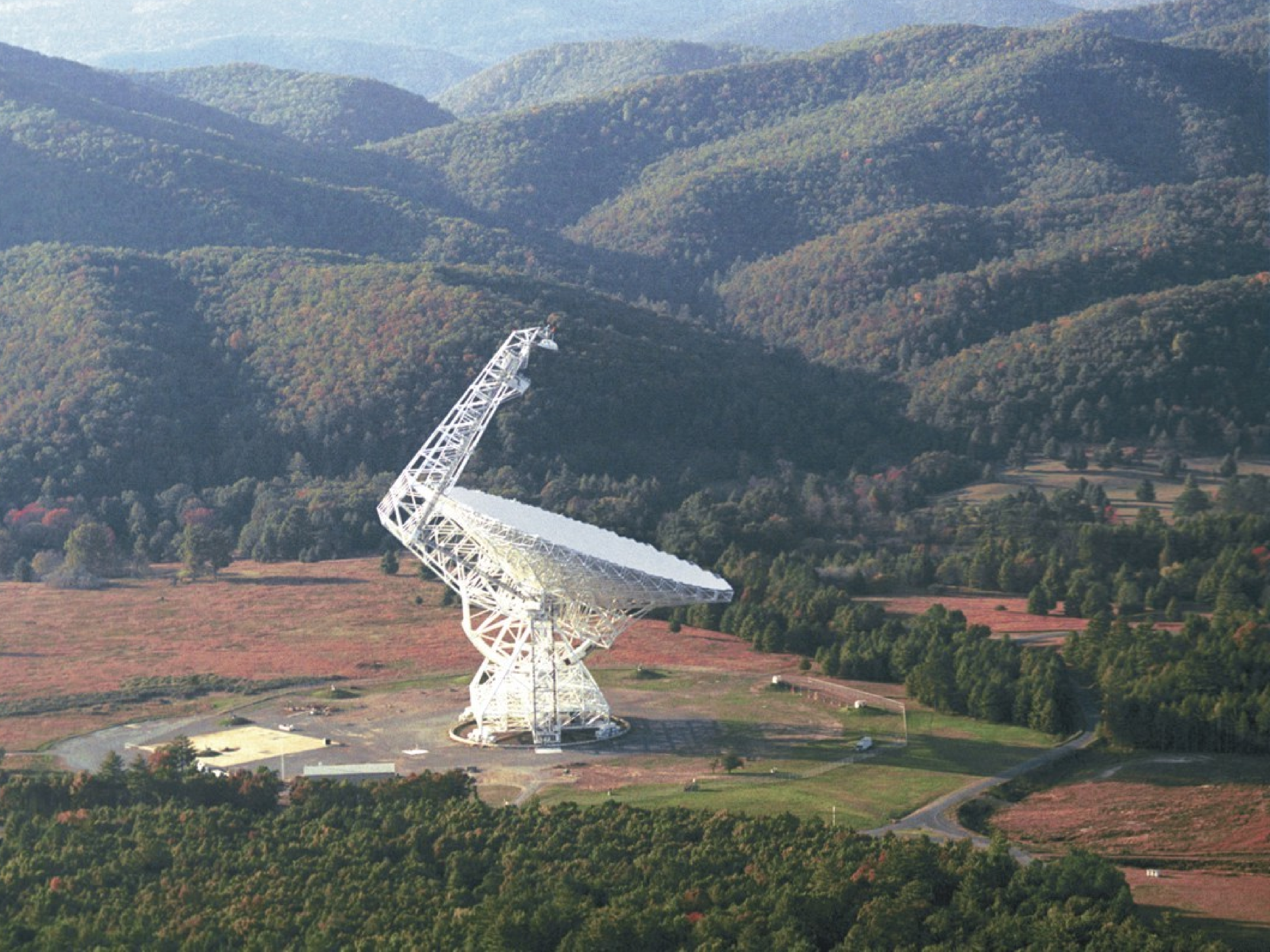
Radio Telescopios

- dos tipos basicos:



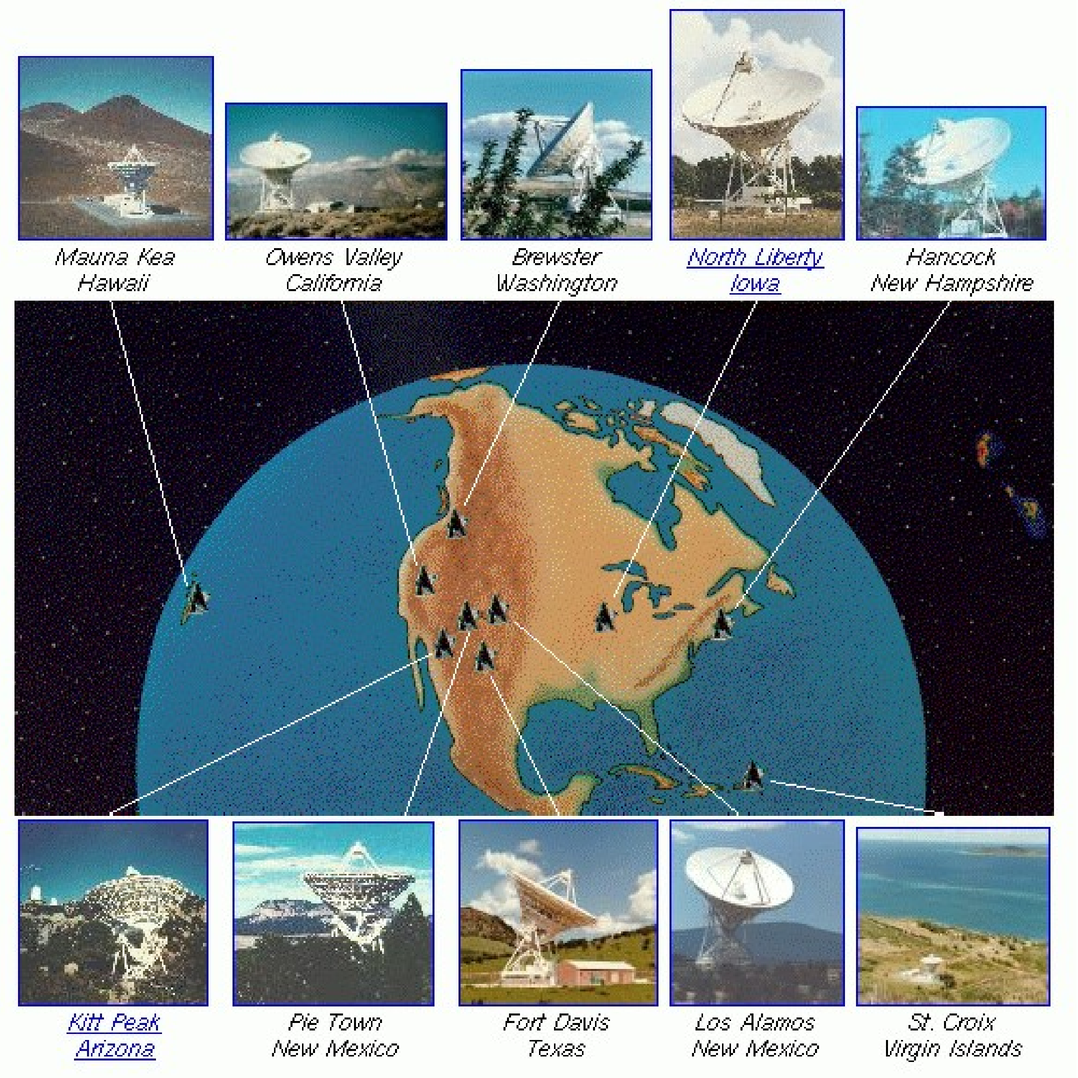
telescopios simples

Redes

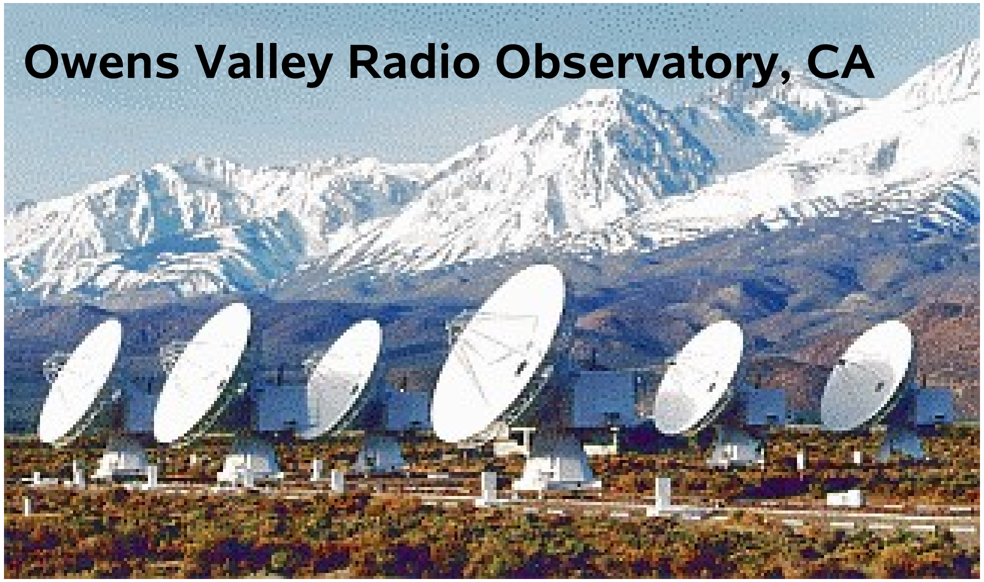


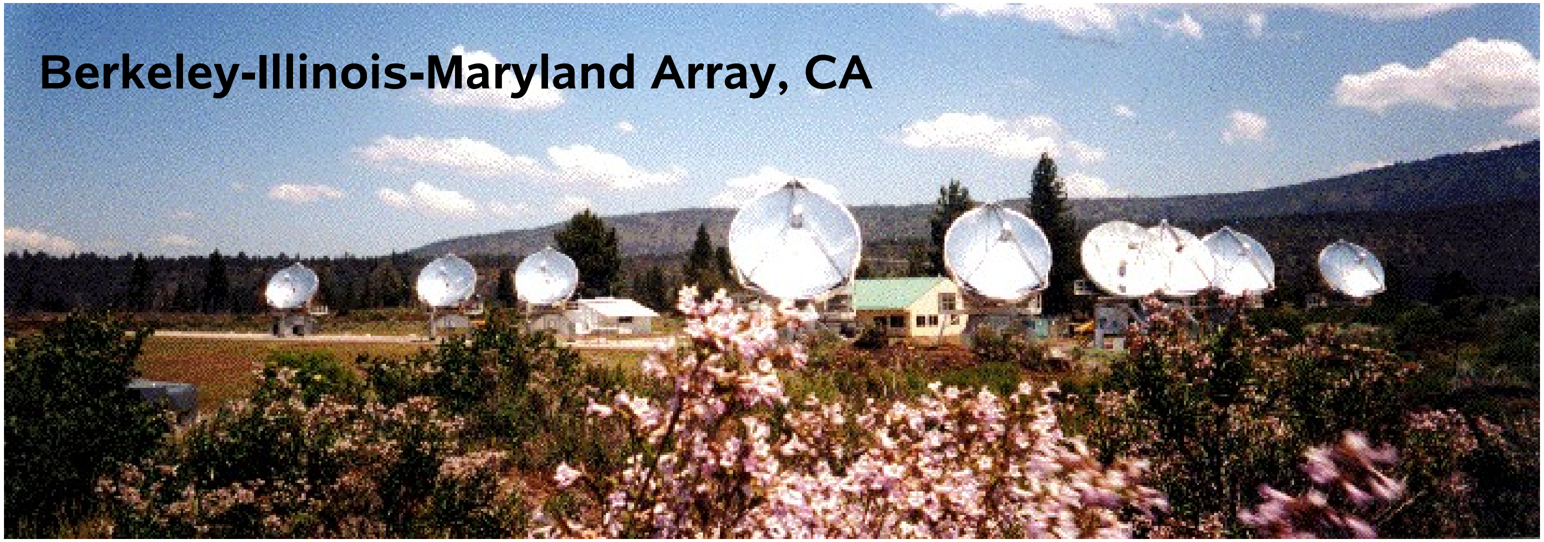
Very Long Baseline Array (VLBA)

- 1993 dedication
- Operado desde Socorro,EE.UU
- Diez antenas de 25-m: U.S. Canada, P. Rico
- Resolucion de imagens mas alto del mundo.



Otros Millimetro y Centimetro Radio Telescopios





Radio Telescopios: Resolucion

- Poder de resolucion (las mas pequena detaille que puedes "ver") depende del tamano del telescopio y el long. del onda de la radiacion.

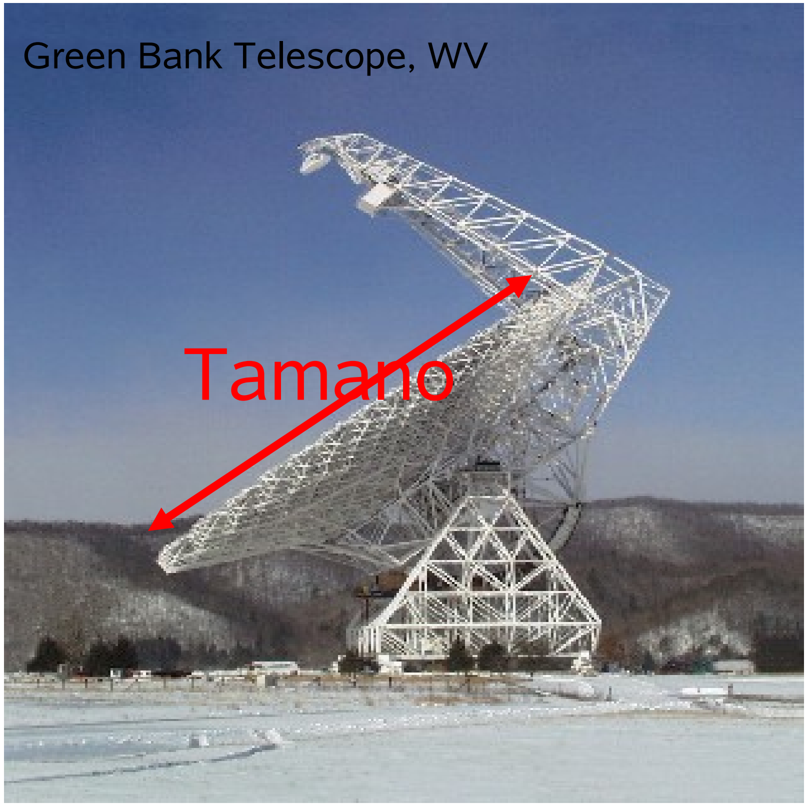
$$\frac{\lambda}{\text{size}}$$

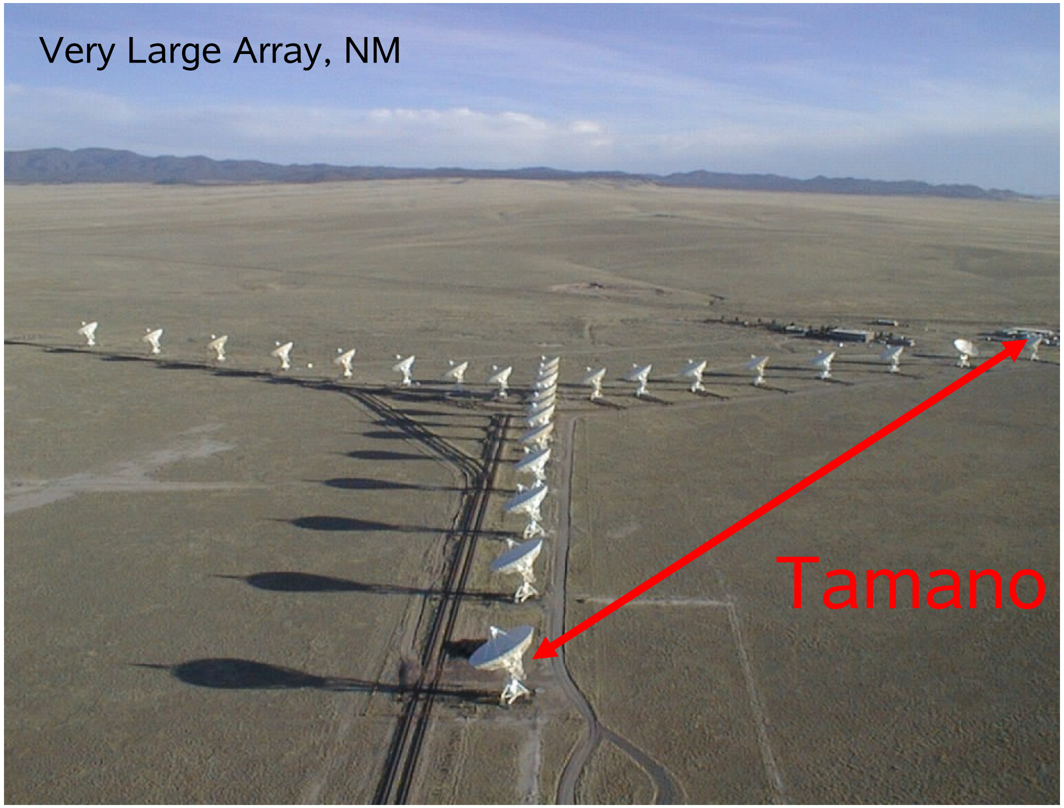
Para radio: esta es grande. (→ λ)

Entonces necisitas esta grande tambien (→ size)

- "Tamano" = diametro del telescopio para un telescopio simple. Distancia maxima entre telescopios para un red.

Radio Telescopes: Resolution





Single Dish

Arrays

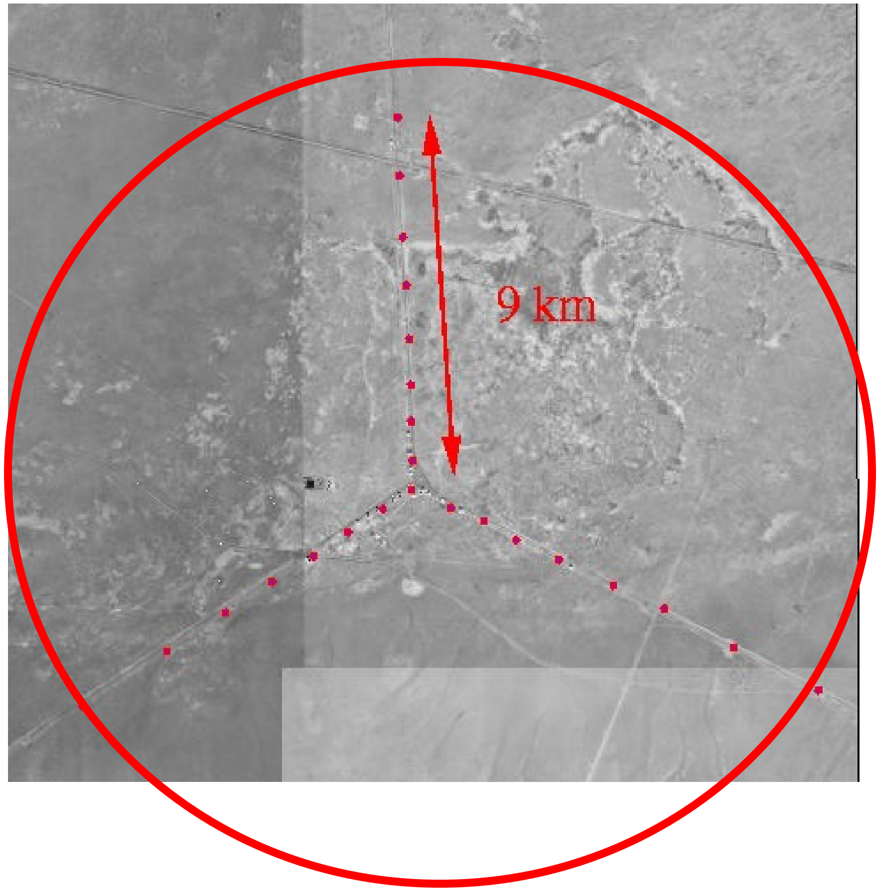
Reconfigurable Arrays: Zoom Lens Effect

VLBA

- La mas grande la distancia – las mas grande la resolucion.
- Pero la sensibilidad (area de colecion) es lo mismo independiente de resolucion.

Radio Telescopes: Sensibilidad

- Sensibilidad (la fuente mas debil que puedes detectar) depende de que quanto area del telescopio/red es actualmente collecionando datos.
  - VLA B-array: area de collecion de los telescopios es solo 0.02% del area del terreno.



- Redes de largas distancias puedes hacer imagenes de solo fuentes luminosas y compactos.

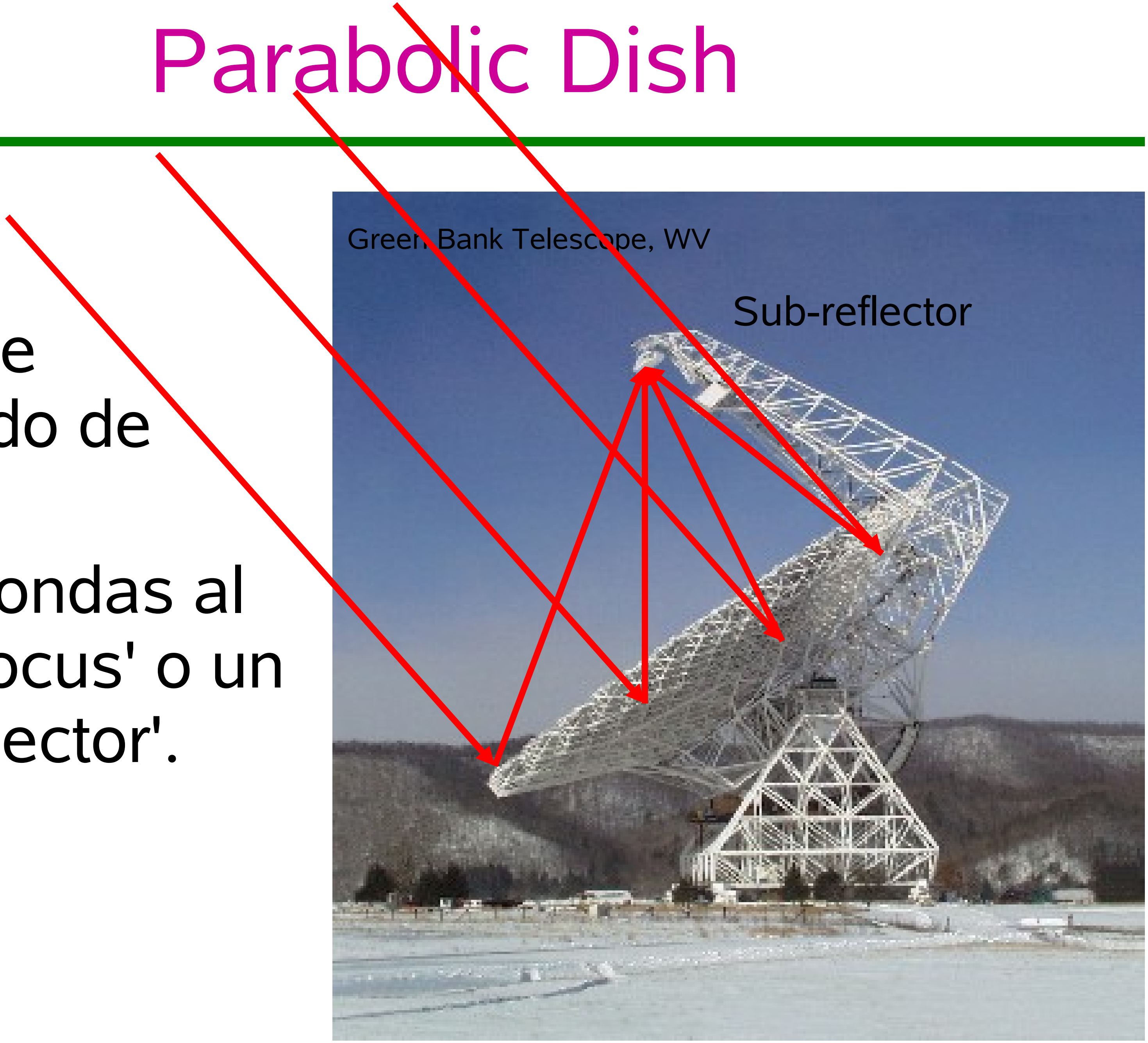
Elementos Basicos de un radio antena

VLBA Antenna:

- 25 metros (82 feet) in diametro
- En alteza como un edificio de 10 pisos.
- Se pesan 240 toneladas

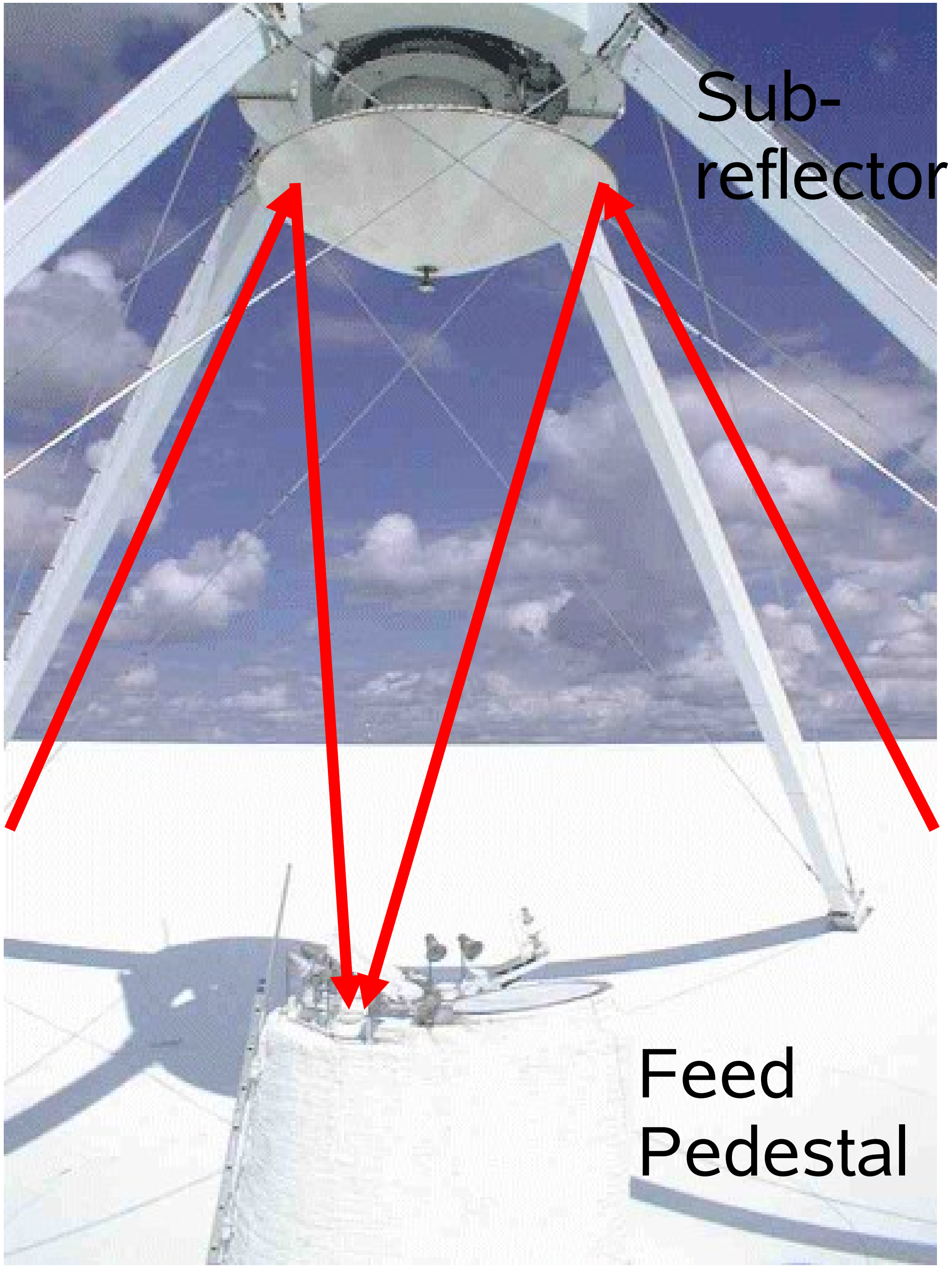
Parabolic Dish

- superfice reflejando de alumino
- Enfoce ondas al 'prime focus' o un 'sub-reflector'.



Sub-reflector

- Re-directas ondas al `Feed Pedestal'
- Puede rotar el sub-reflector para redirecionar radiacion a varios receptores.



Feed Pedestal

1.5GHz	20cm
2.3GHz	13cm
4.8GHz	6cm
8.4GHz	4cm
14GHz	2cm
23GHz	1.3cm
43GHz	7mm
86GHz	3mm

327MHz	90cm
610MHz	50cm

Antenna Feed and Receivers

Advantajes de observar en el Radio

- Studiar procesos fisicos que no emiten nada en otros longitudes de ondas.
- Ondas Radio puedes pasar dentro de regiones con much polvo.
- Puedes medir la potencia del campo magnetico y su orientacion
- Puedes dar informacion sobre velocidades (linea de vision y tangential).
- Observaciones en el dia tambien (en el centimetro por lo meno)

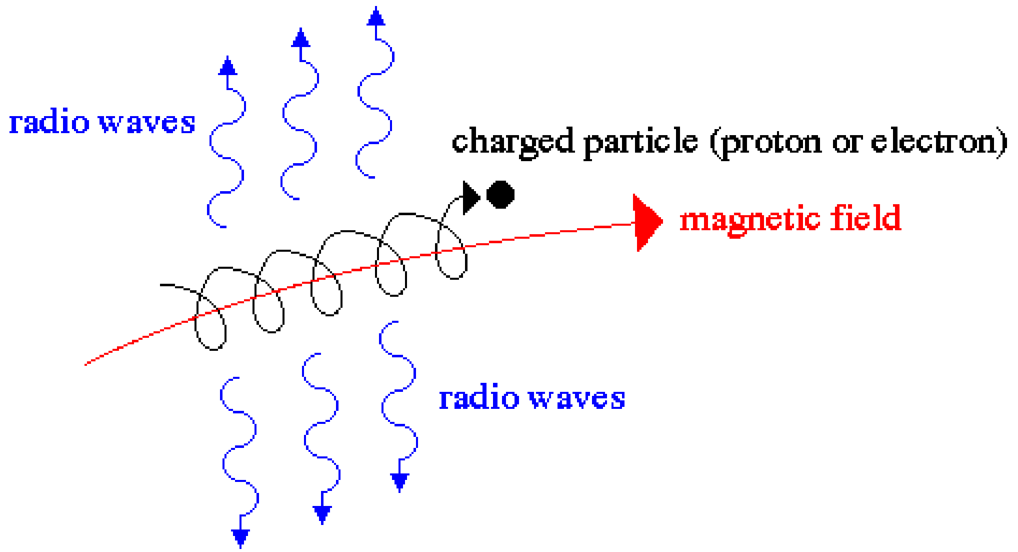
Procesos Astrophysicos Primarios que emiten radiacion radio

Quando particulos con carga cambian direccion,
se emiten radiacion

- Radiacion Sincrotron
  - particules con carga siguendo lineas del campo magneticos
- Emision termal
  - cuerpos frios
  - particulos con carga en un plasma que estan moviendo.
- Emision de lineas espectrales
  - transiciones discretas en atomes y moleculares

Radiation Sinctrotron

Synchrotron radiation

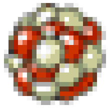


synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

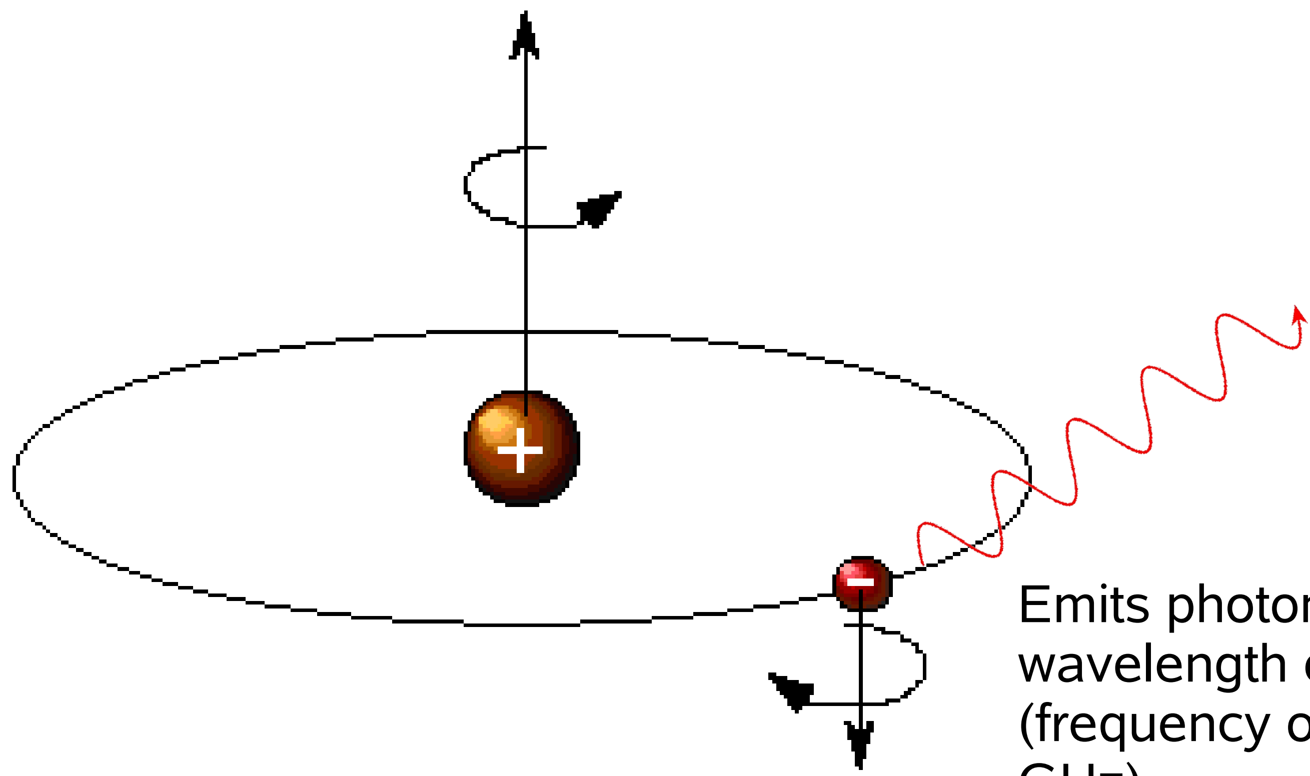
- Characteristicos del polarizacion del luz se dar informacion sobre la geometria del campo magnetico.

Emission Termal

- Emission de cuerpos con calor
  - radiacion "Blackbody"
  - Cuerpos con temperaturas ~ 3-30 K emiten en el mm & submm
- Emission de particulas con carga que estan en acceleracion
  - "Bremsstrahlung" o emision free-free emission de plasmas ionizadas



Emision lineas espectrales: hyperfine transition de Hidrogeno neutro

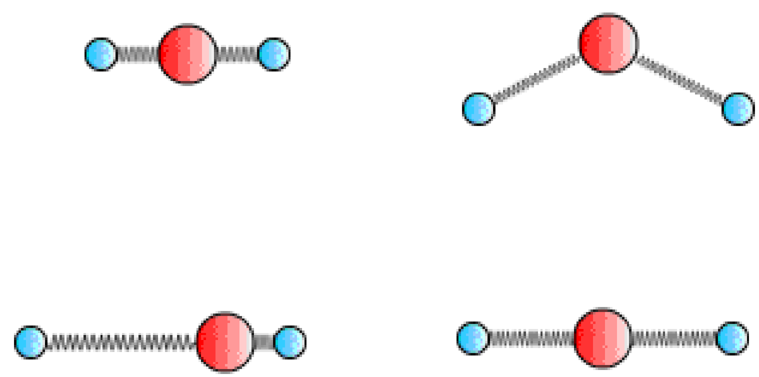


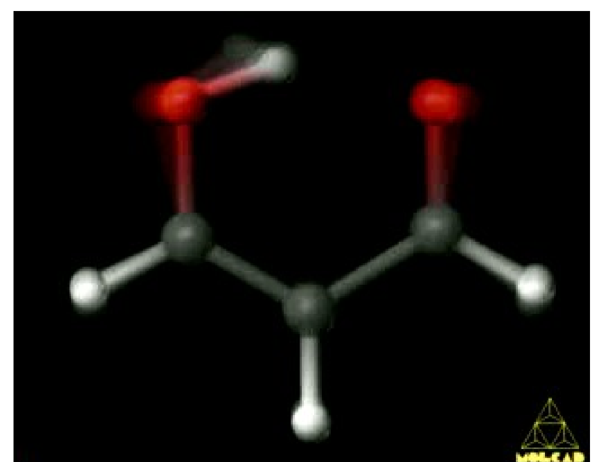
Emits photon with a wavelength of 21 cm (frequency of 1.42 GHz)

Transition probability=$3x10^{-15}$ s^{-1} = once in 11 Myr

Emission lineas espectrales: modos de rotacion y vibracion en moleculares

- Molecules commun en espacio:
  - Monoxido de Carbon (CO)
  - Agua (H_2O), OH, HCN, HCO^+, CS
  - Ammonia (NH_3), Formaldehyde (H_2CO)
- molecules meno commun:
  - Azucar, Alcohol, Antifreeze (Ethylene Glycol), …

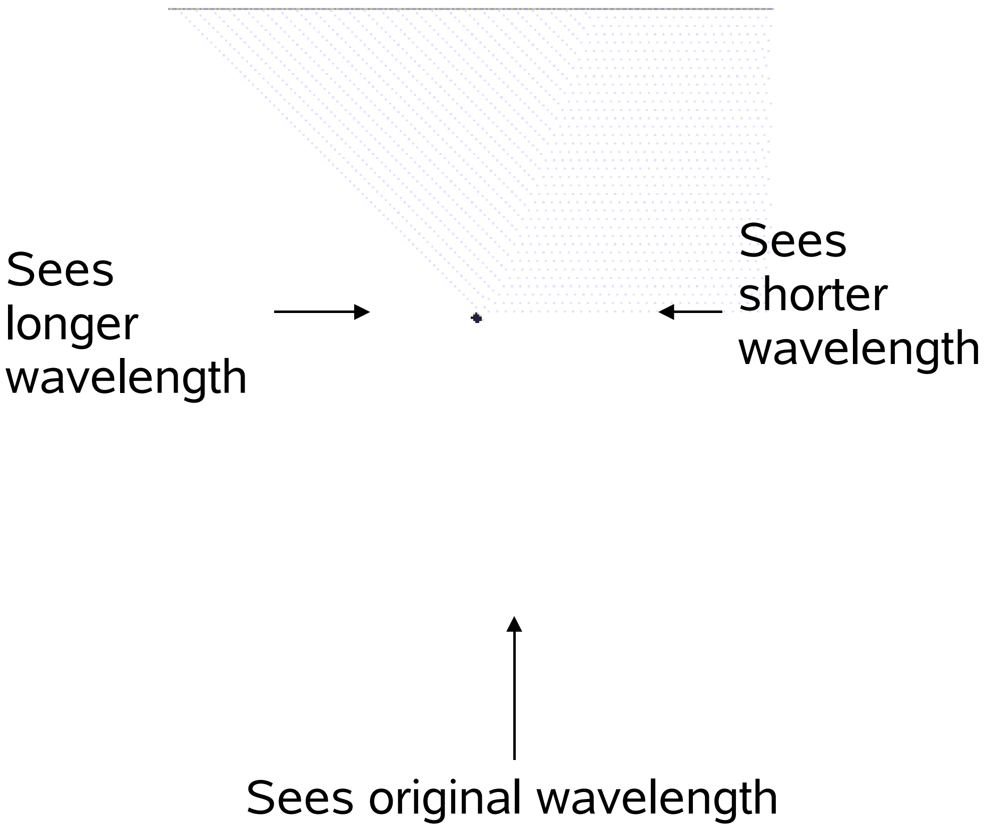




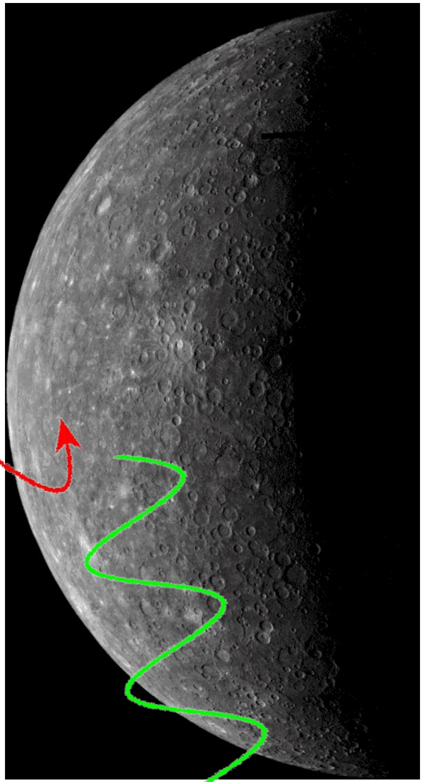
malondialdyde

Efecto de Doppler: lineas espectrales

- lineas espectrales tienen frecuencias fijo y muy bien determinados.
- La frecuencia de un fuente va a cambiar quando la fuente estan moviendo a mas circa o mas lejos a te.
- Un comparison de la frecuencia conocido y observado se dar la velocidad del fuente



Ejemplo especial de observacion de linea espectral: Doppler Radar Imaging

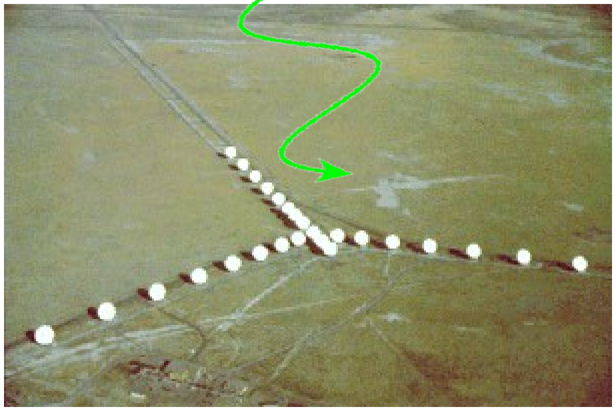


…bounce off object…

Transmit radio wave with well defined frequency…

..observe same frequency

NASA's Goldstone Solar System Radar



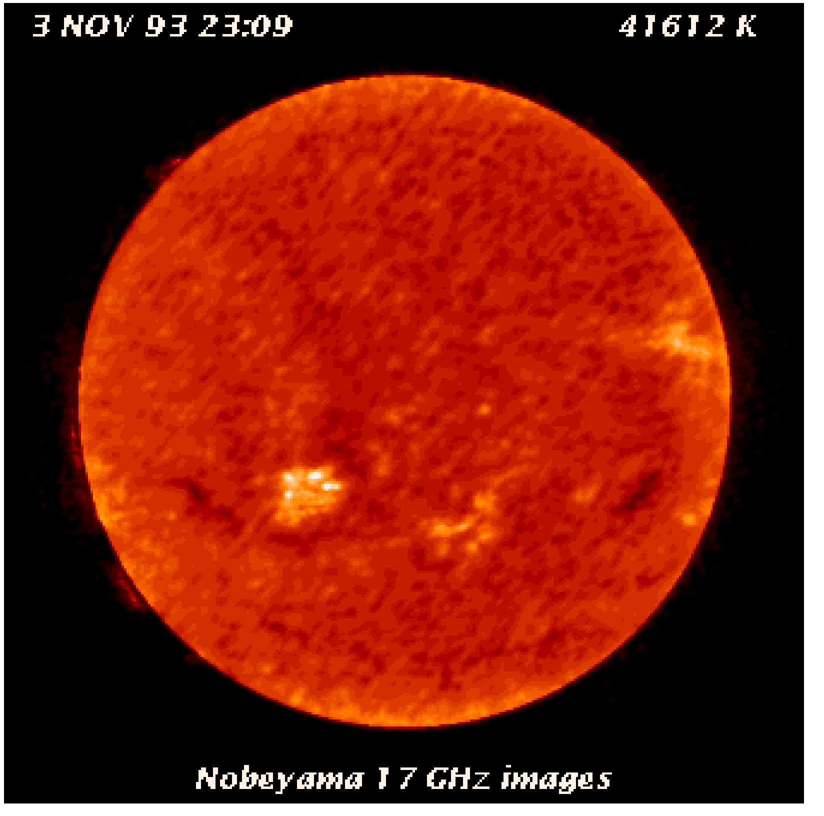
Very Large Array

Pasaje corte en el Universo Radio

- Sistema Solar
  - Sol, Planetas, Asteroides
- Objectos Galacticos
  - Nebulas oscuros, discos proto-estrellar, remnantes supernova
- Galaxias
  - Campos Magneticos, Hidrogeno neutro
- Chorros radios
- El Universo..

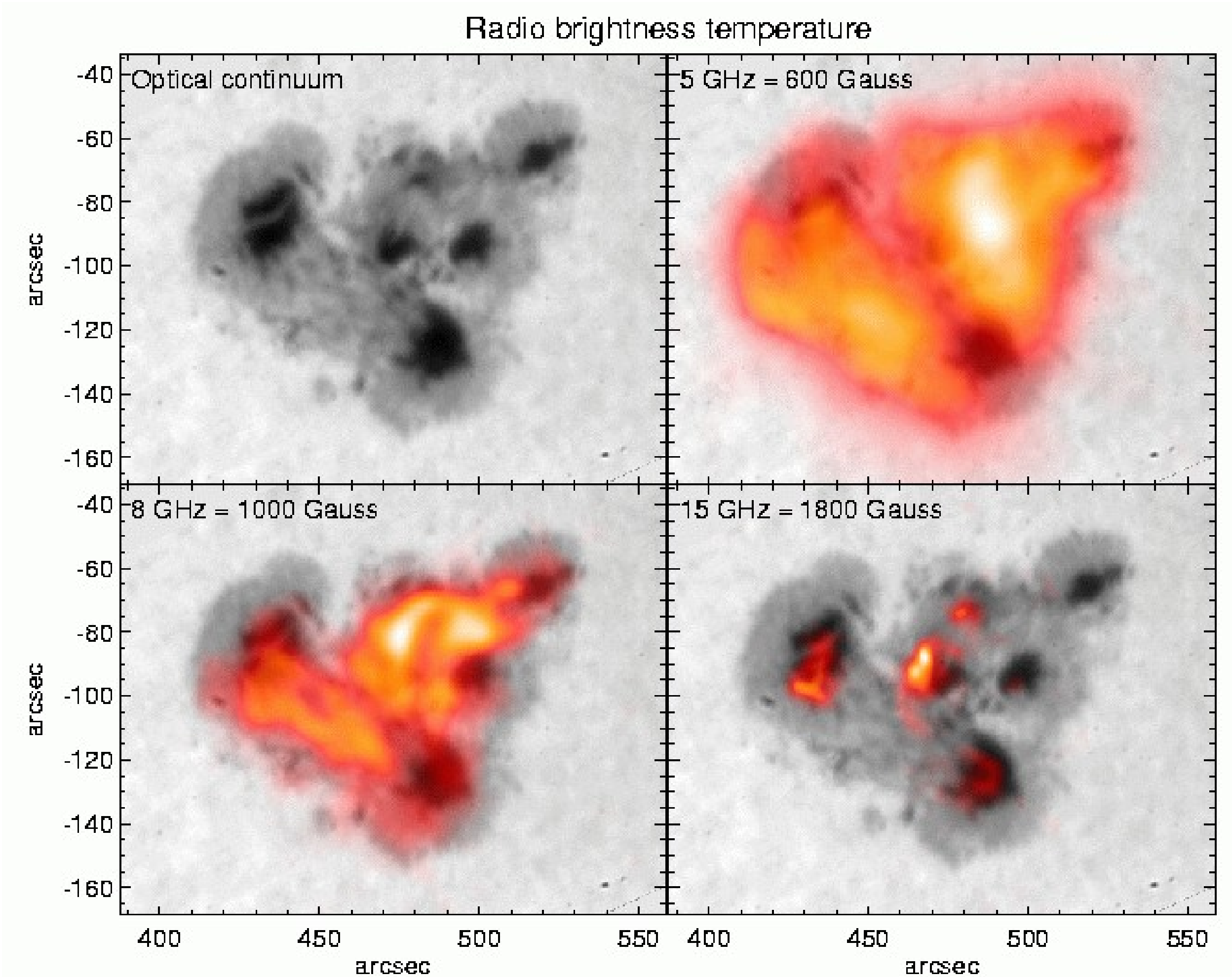
Nuestra Estrella, El Sol

- El Sol en Radio
- Coronal Mass Ejections (CMEs)
- "Space weather"
- Estructura del viento Solar



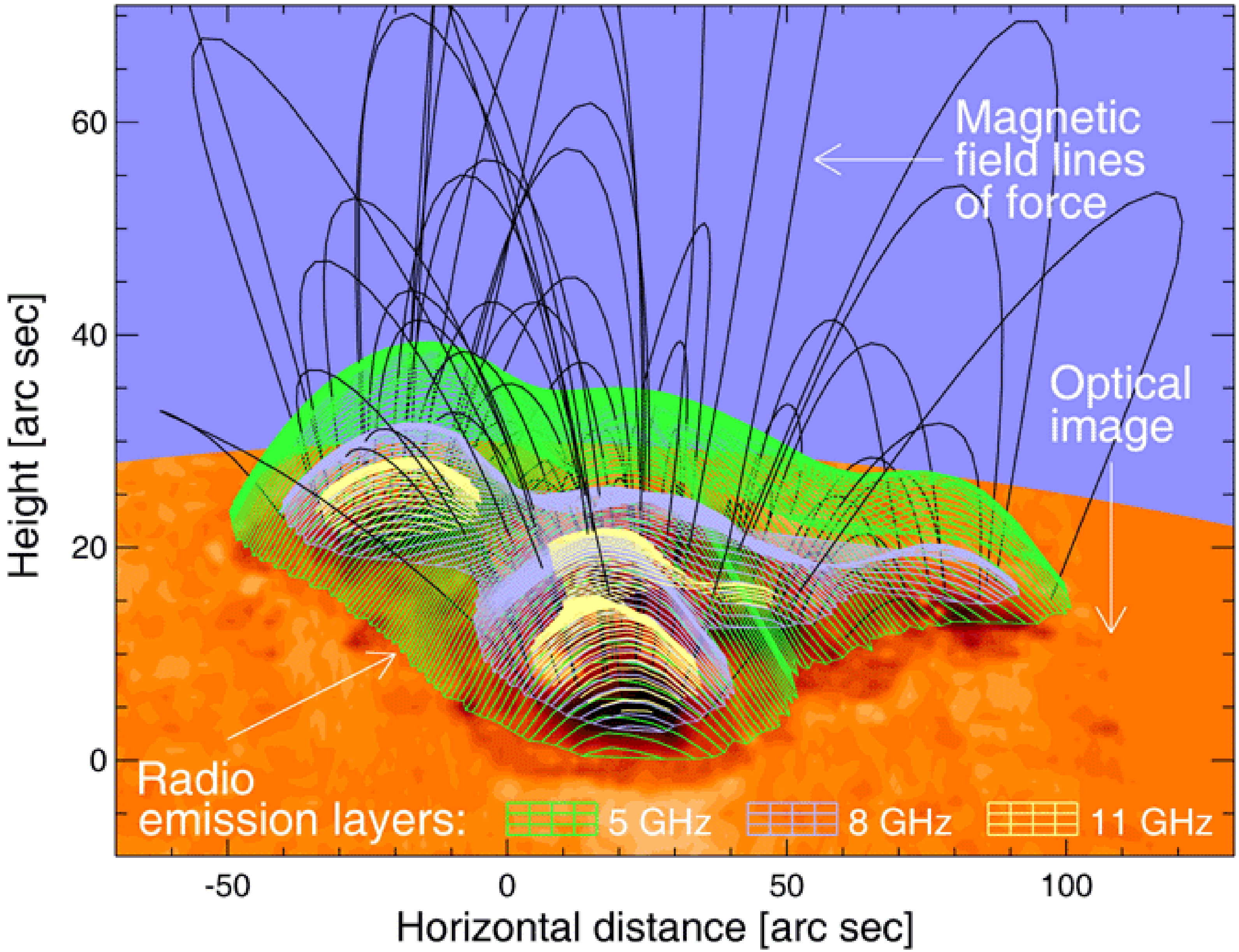
Courtesy Steven White (UMd)
Thermal free-free emission from chromosphere and active regions.
Dark filaments=dense cool material suspended in the corona

Estructura del Campo Magnetico del Sol



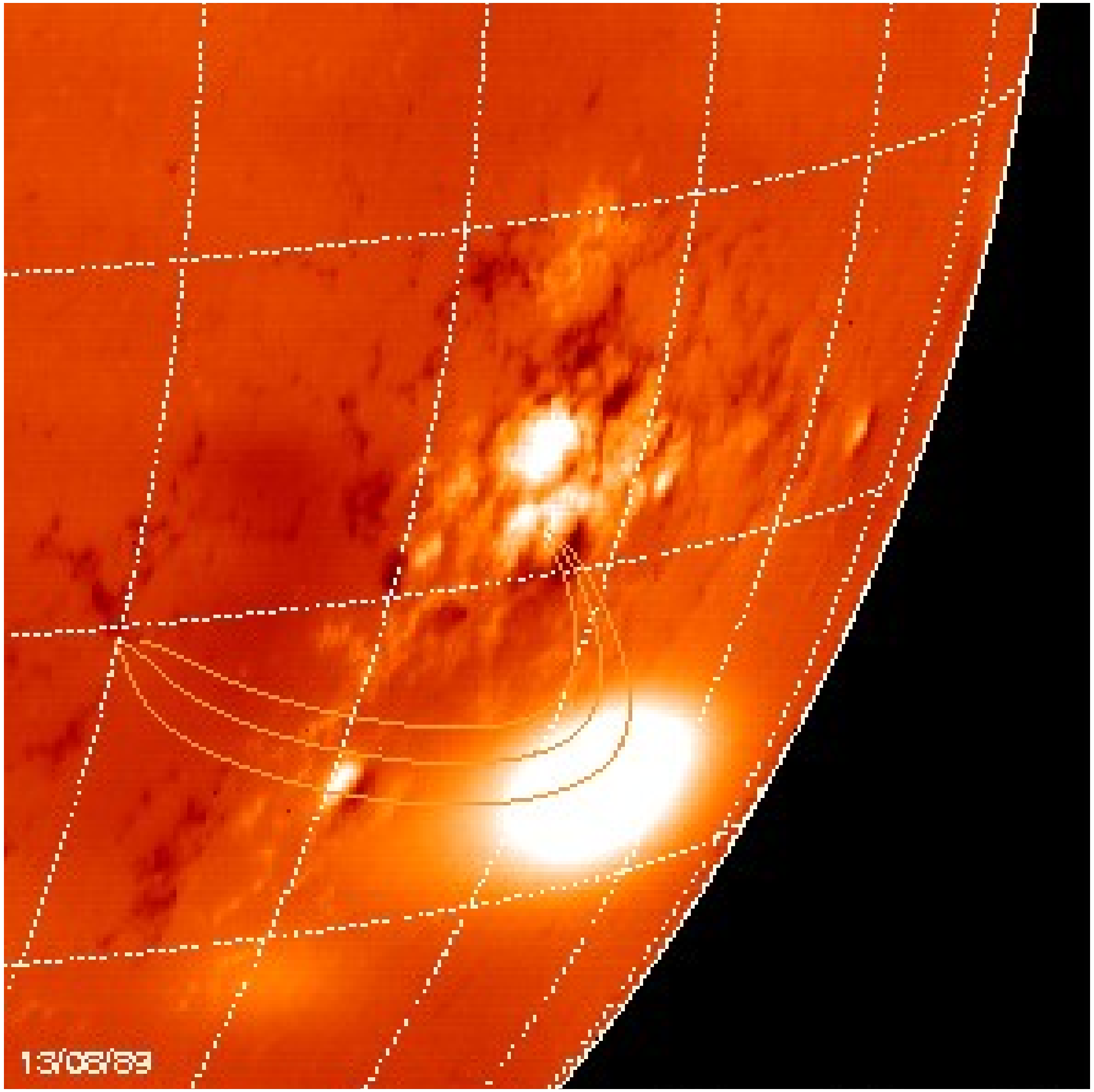
Region activo con `strong shear': imagens en radio mostra alta B y temperaturas muy alta

from Lee et al (1998)


Magnetic field lines of force
Optical image
Radio emission layers:
5 GHz
8 GHz
11 GHz
Height [arc sec]
Horizontal distance [arc sec]
0
20
40
60
-50
0
50
100

Solar Flares

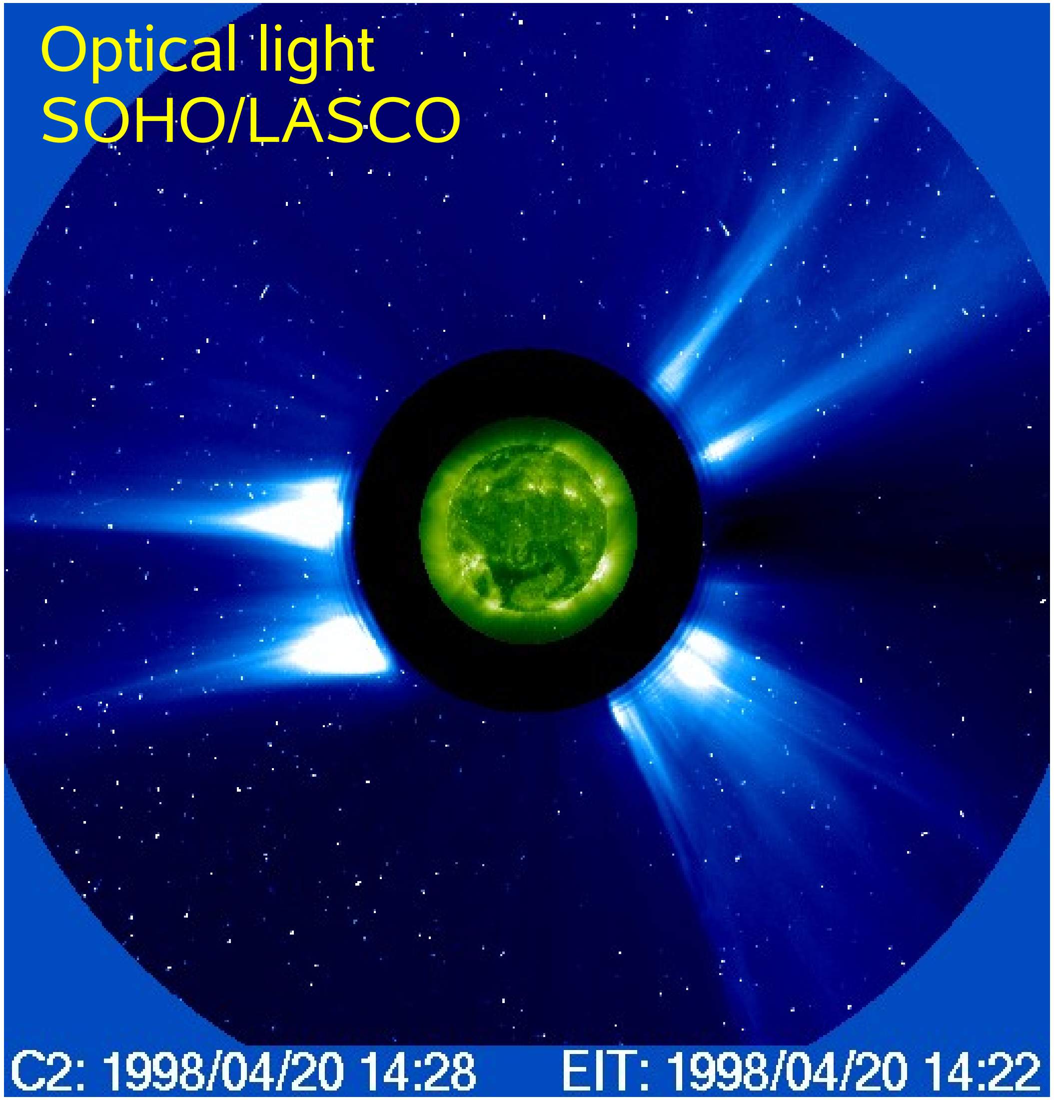
Type U bursts observed by Phoenix/ETH and the VLA.



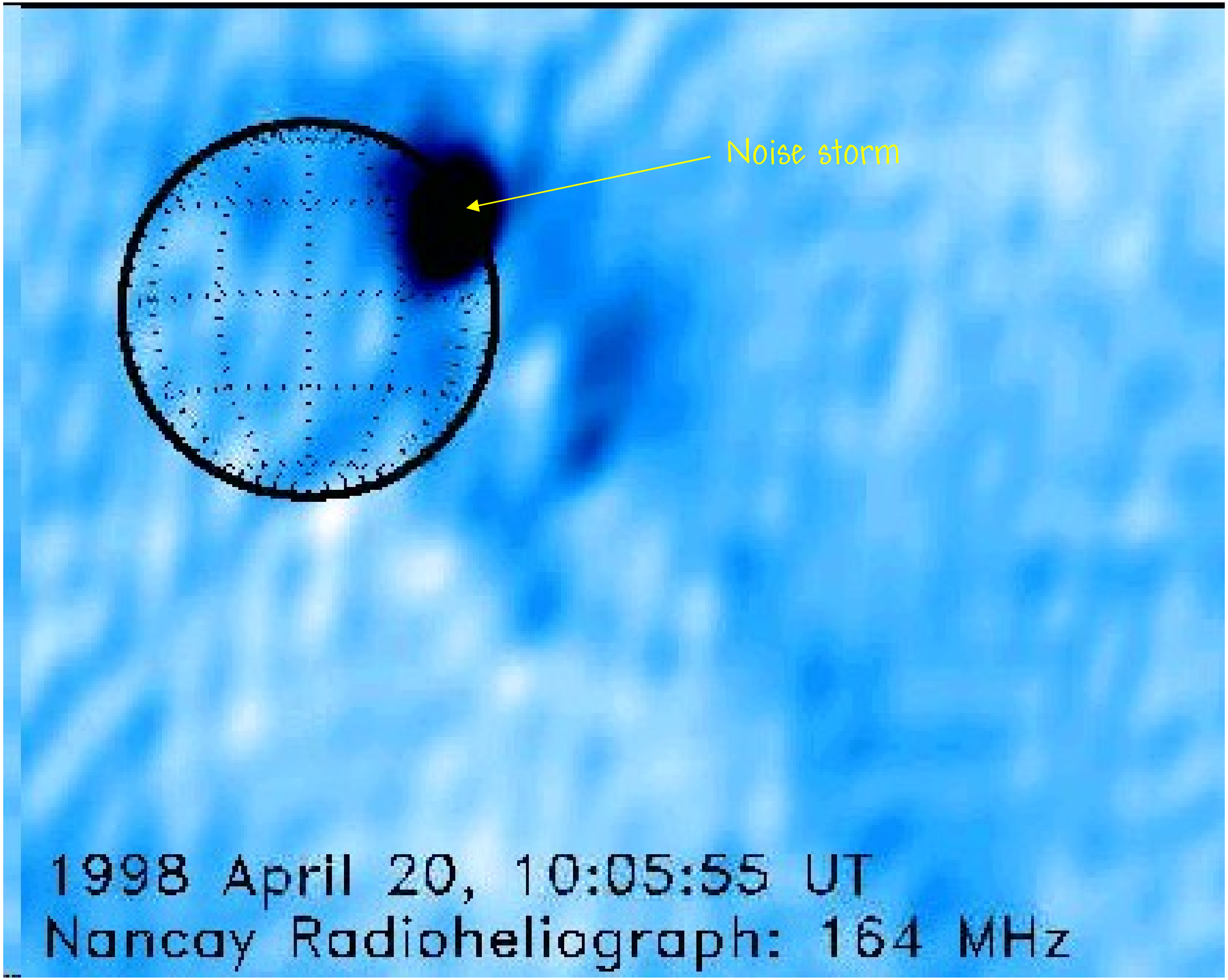
Aschwanden et al. 1992

Coronal Mass Ejections (CMEs)

- Explosiones mas grande en el Sol
- Un gran porcion del Corona Solar esta de-estabilzada y es lanzado con velocidades entre 200-2000 km/s
- particulas con carga accelerado a velocidades circa del velocidad del luz
- Producen efectos de "space weather"
  - interuptir redes de electricidad, inducir corrientes en oil pipelines, disrupt navigacion



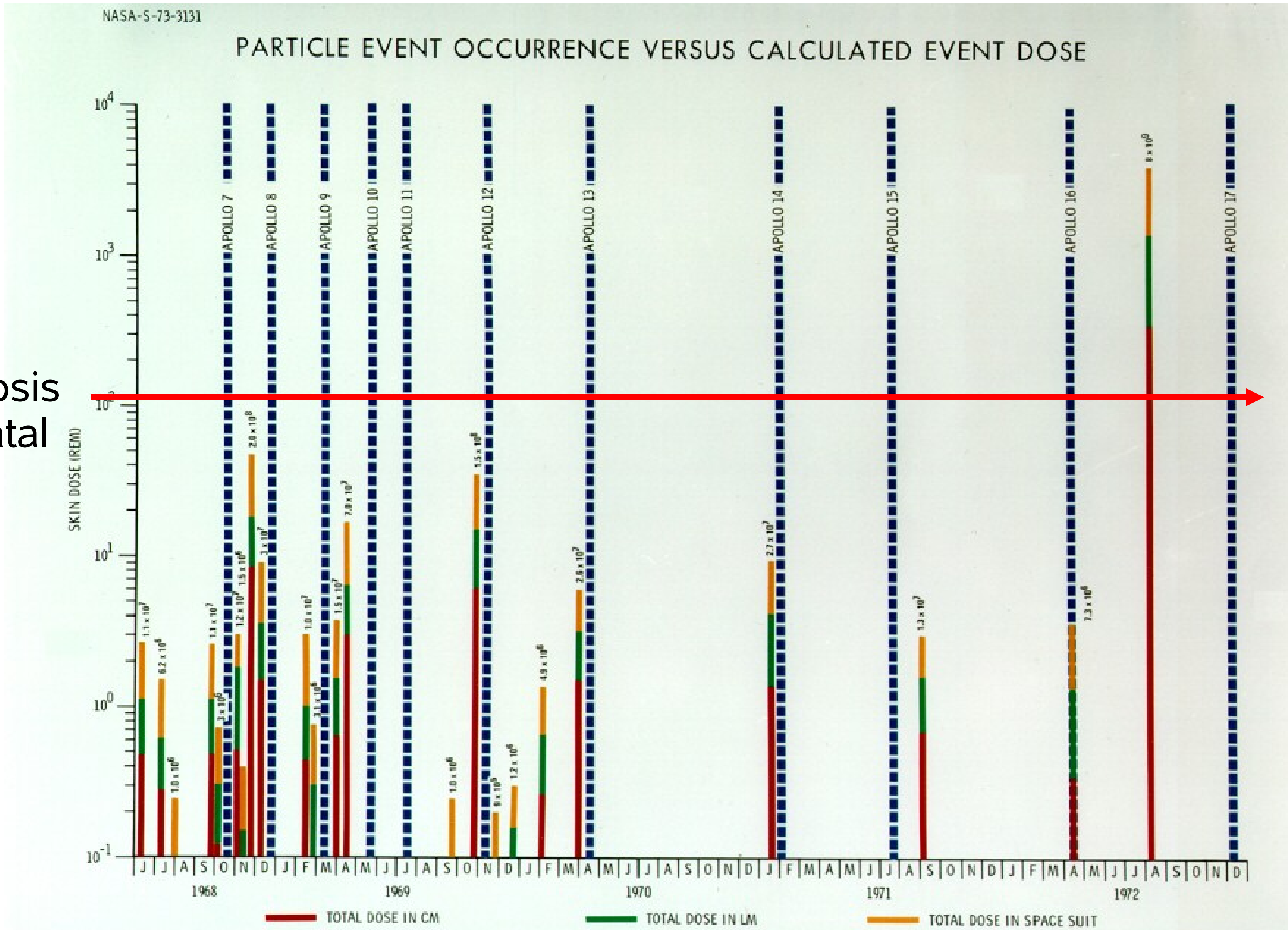
cdaw.gsfc.nasa.gov/CME_list/



Synchrotron Radiation from MeV electrons. B~1 Gauss

Bastian et al. (2001)

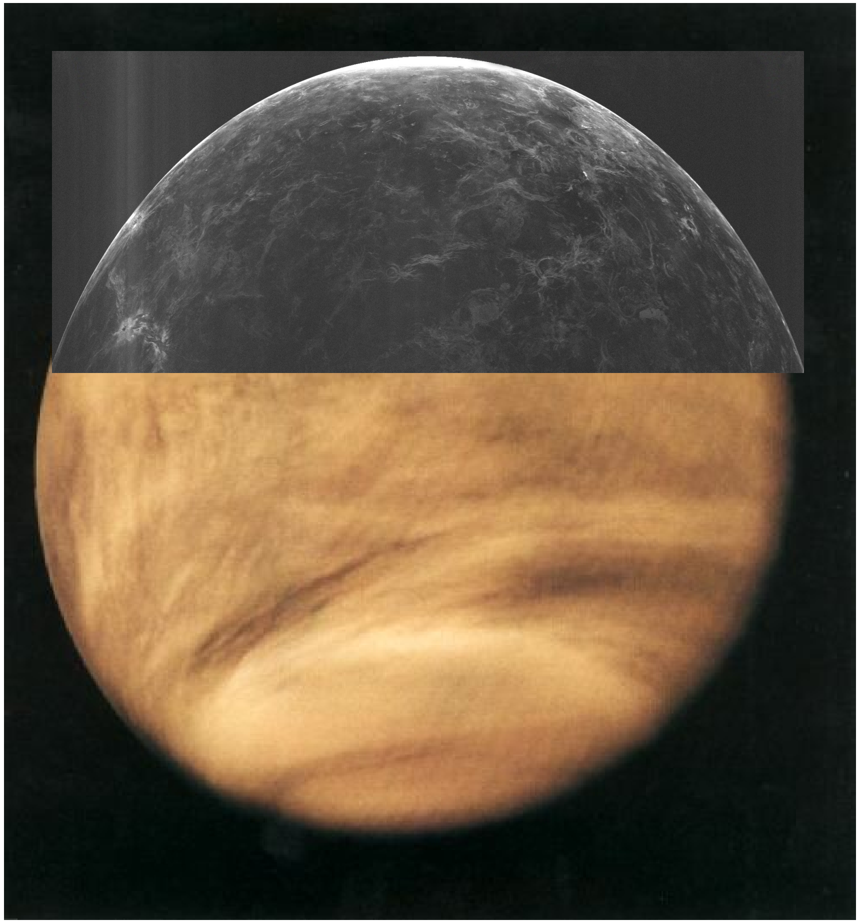
Particulas accelerado durante de Solar Flares y CMEs efectan viajes interplanetarias



Dosis Fatal

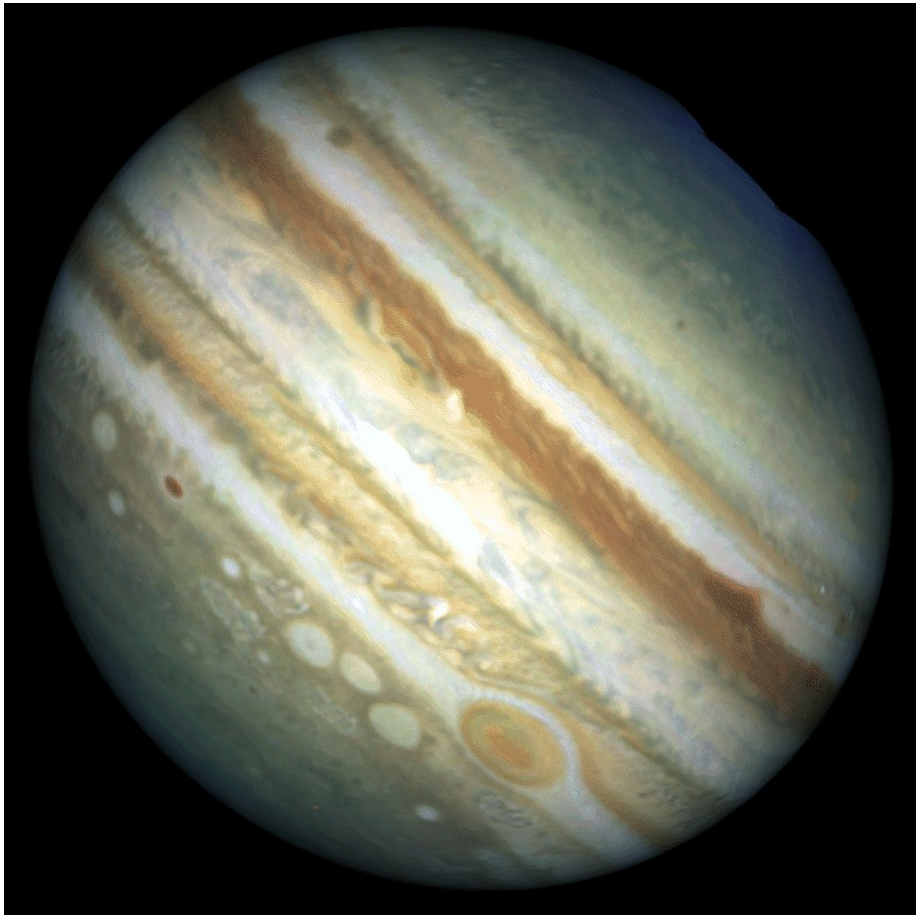
Venus

- Optica/UV imagen de Venus desde Pioneer 10
  - Neblinas, Neblinas y mas Neblinas
- 13 cm Radar imagen de Venus (Arecibo and GBT)
  - Bright=rougher surface
  - Dark=smoother surface



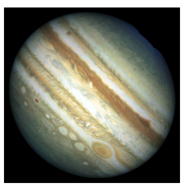
Campbell, Margot, Carter & Campbell

Jupiter

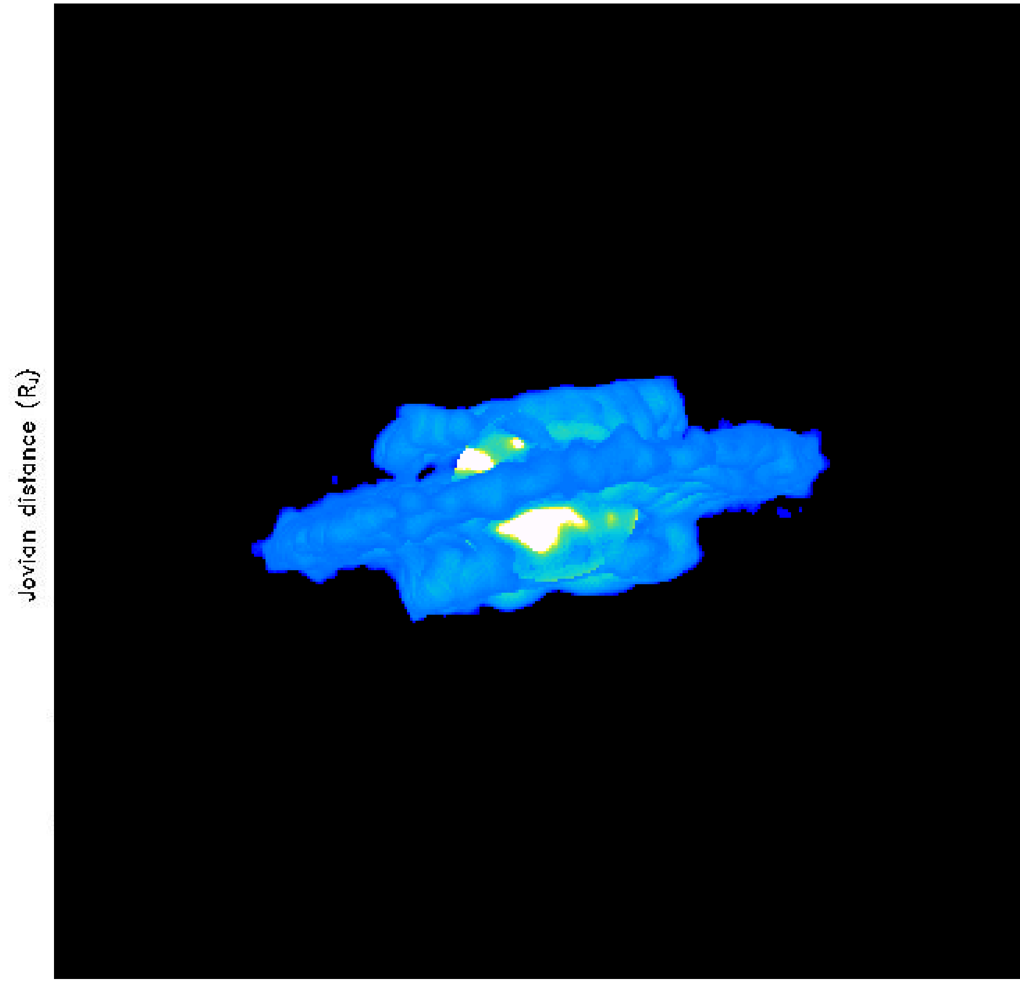


Jupiter - Sincrotron

Particlas cargada y entrapada en el campo magnetico de Jupiter. Similar a la 'Van Allen belt' dela Tierra



A veces Jupiter es mas luminoso del Sol en ondas radios! Puedimos ocupar esta propiedad para buscar planetas extrasolares.



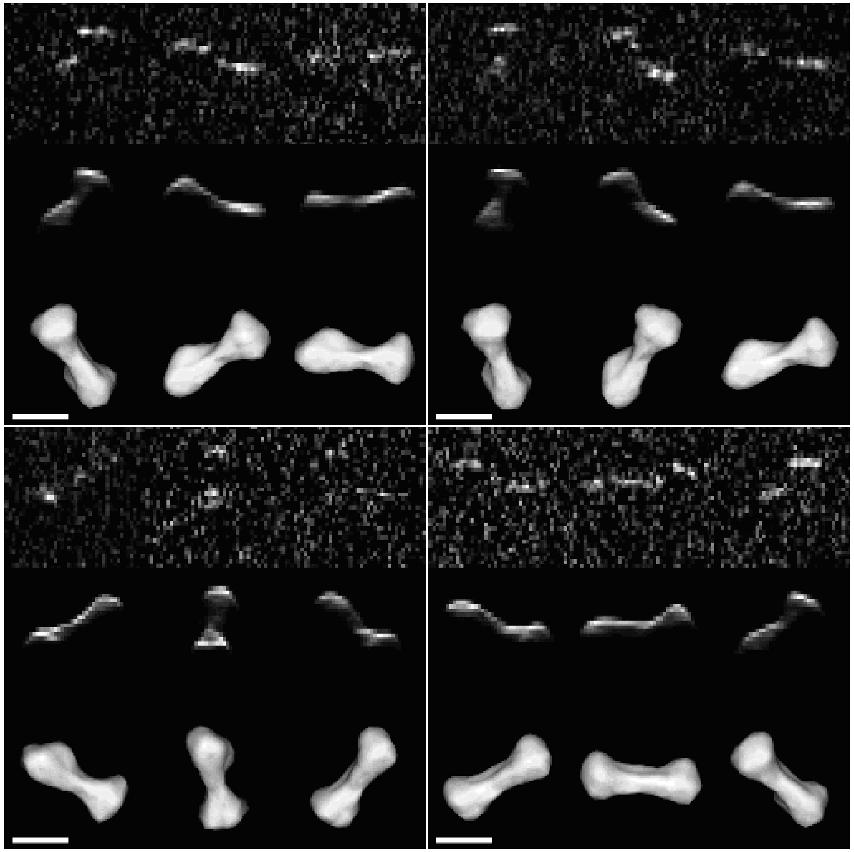
Observations: VLA 20 cm
De Pater, Schulz & Brecht 1997

3-D model: Sault et al. 1997; de Pater & Sault 1998

www.atnf.csiro.au/people/rsault/jupiter/movies/

Doppler Radar Imaging de Asteroides

- S-band (2380 MHz, 12.6 cm) radar imagenes del of main belt Asteroid 216 Kleopatra con Arecibo
- 217 km x 94 km x 81 km
- “dog-bone” estructura talvez un resulto de una collision de dos asteroides



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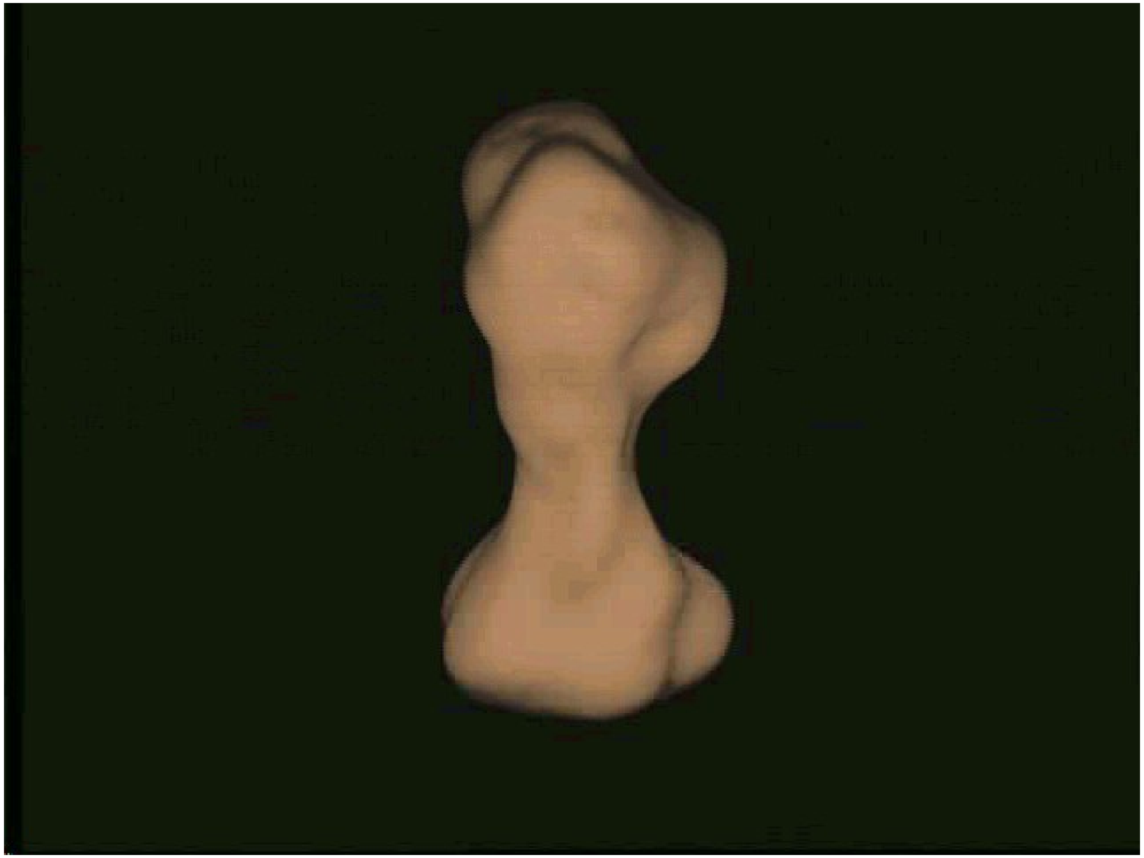


Computer reconstruction by Ostro et al. 2000, Science, 288, 836

echo.jpl.nasa.gov

Formacion de un Estrella

- Un estrella naciendo (protostar) tiene un sobre de gas y polvo
- Radio y far-infrared son los unicos radiaciones que pueden salir
- Neblinas tiene muchos moleculares (tracers) (CO, NH_3, y otros) que emiten ondas mm

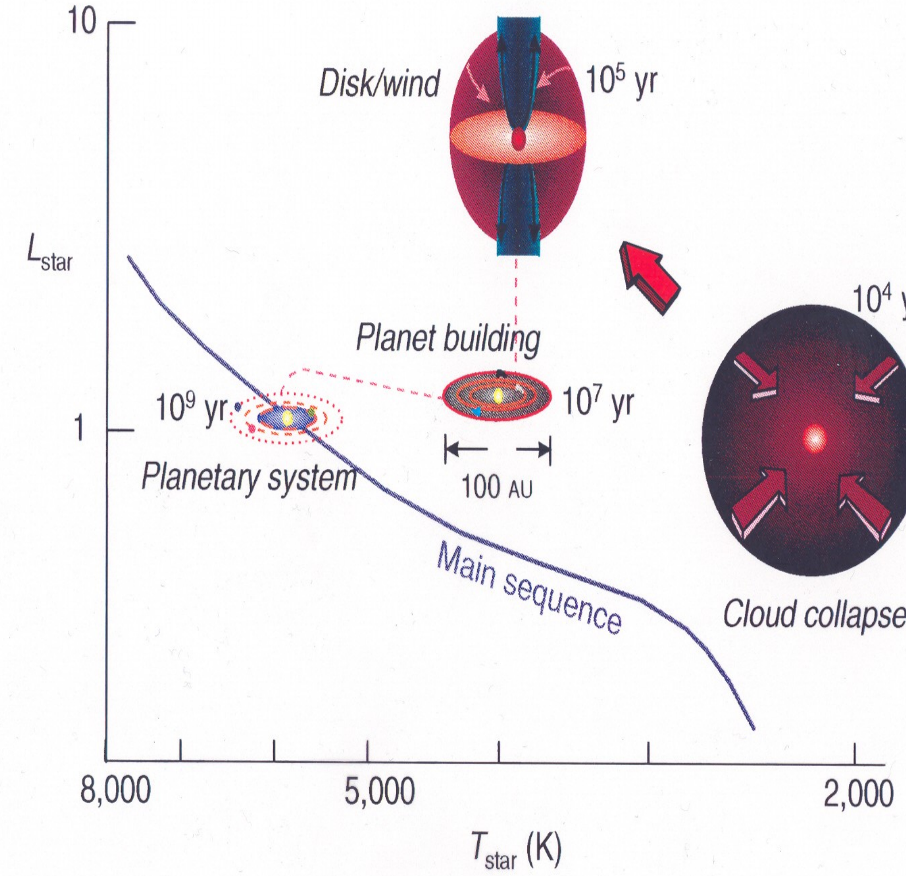
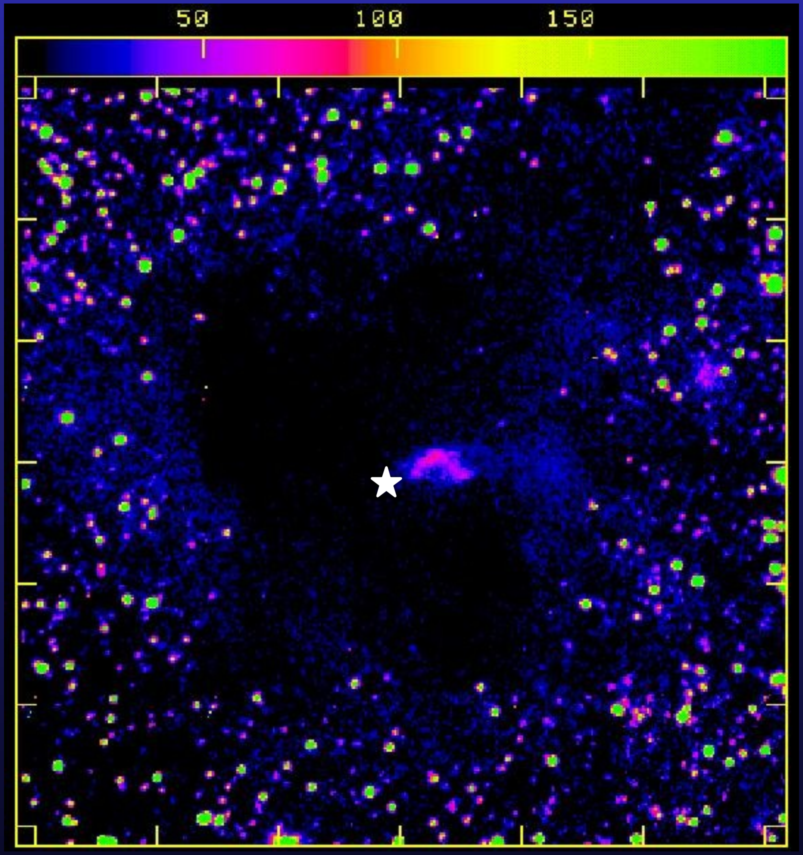


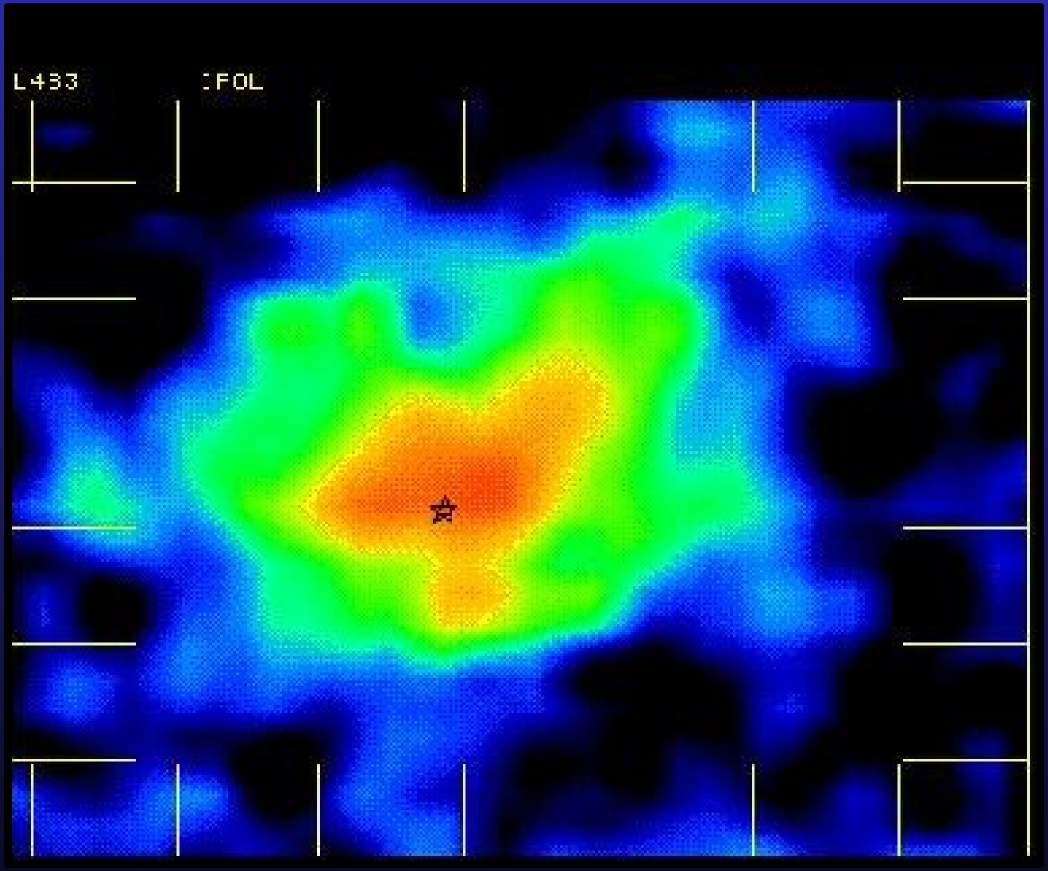
Fig. 2, Beckwith & Sargent, *Nature*, **383**, 139-144.

Neblinas oscuras con formacion de Estrellas

L483 Molecular Cloud



Near-infrared (1.2 microns)



NRAO 12-m CO(1-0)

El gas es mas luminoso donde acrecion al protoestrella warms la neblina.

A. Wootten & G. Fuller
www.nrao.edu/imagegallery

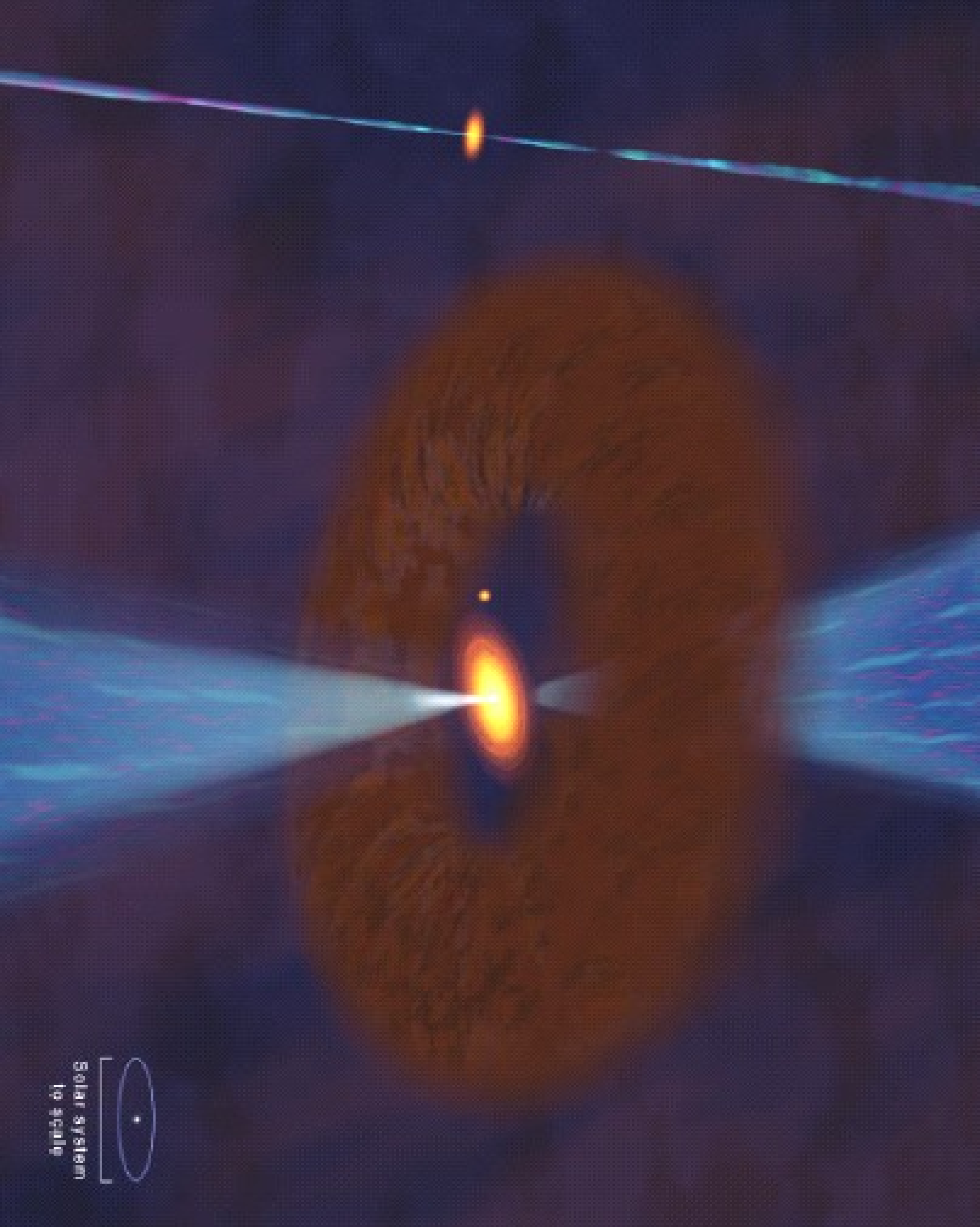
Proto-stellar Outflows

"9 point" radio map of bipolar molecular outflow from the S106 protostar

Blue=Towards us

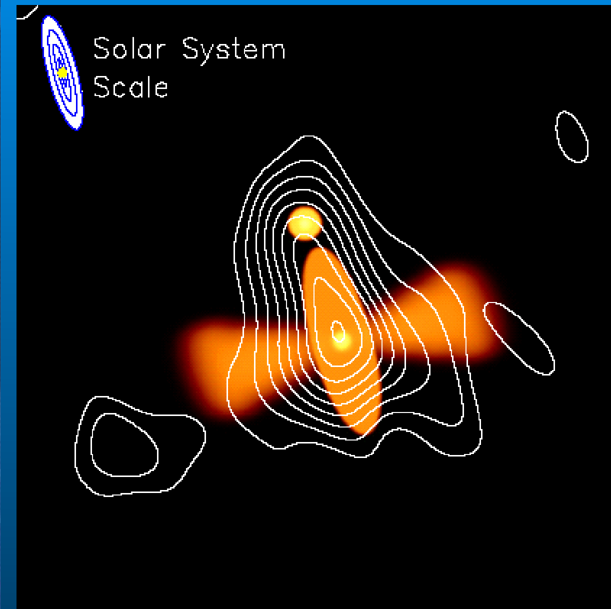
Red=Away from us

S106, IR Subaru Telescope, Japan



Credit: B. Starosta, NRAO/AUI/NSF

Accretion Disk



tours: observations

or: model of accretion disk,
tral star, outflow, & companion
ostar:

$_{sun}$ protostar

M$_{sun}$ disk

Outflow with 40° opening angle.

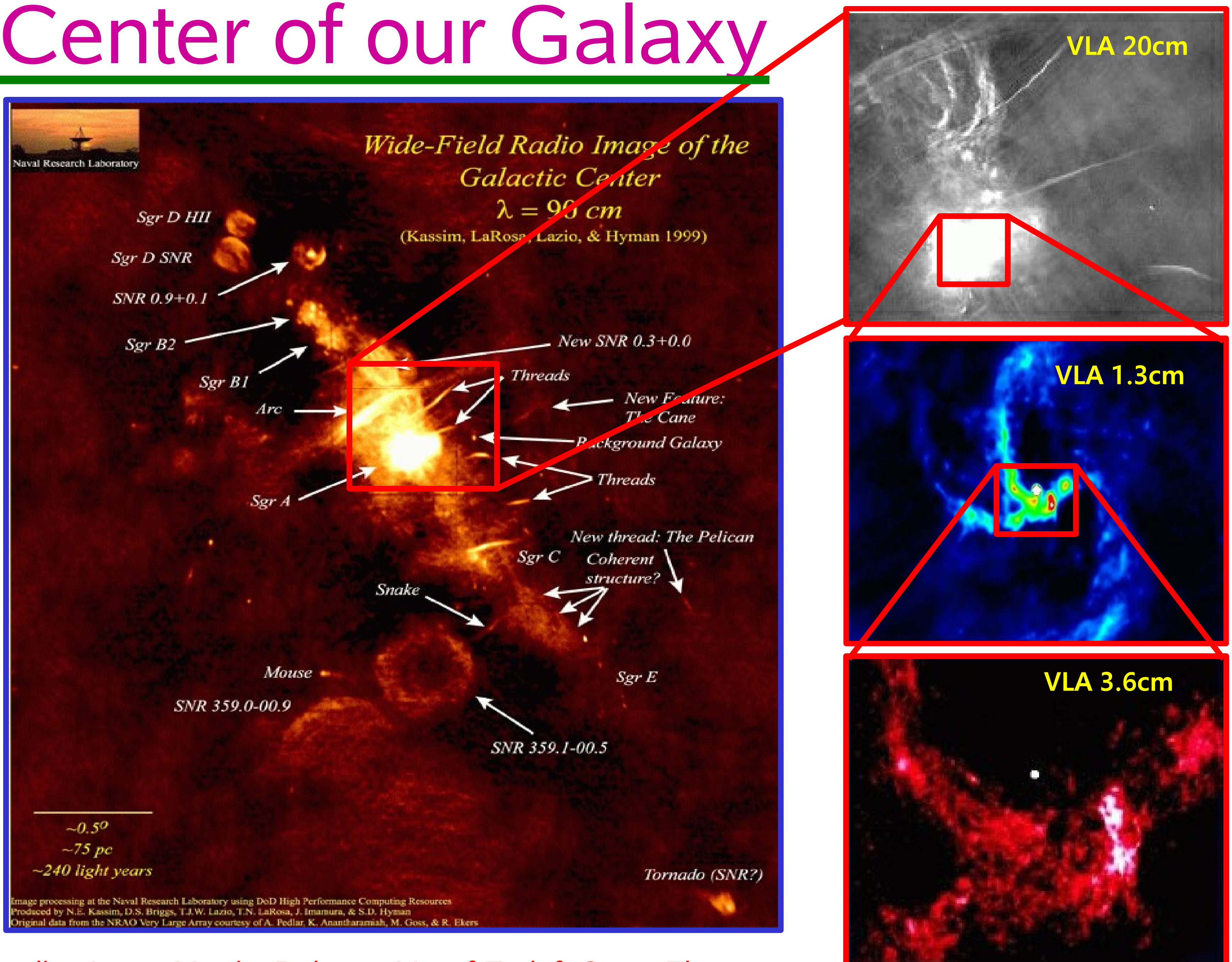
- Remnant of a massive star that exploded ~300 years ago
- VLA image at 1.4, 5, and 8.4 GHz
- Synchrotron emission from tangled magnetic fields

Rudnick et al., Image by T. Rector www.nrao.edu/imagegallery

- Remnant of a supernovae from 1054 AD
- Expanding at 1000 km/sec
- Central star left behind a rapidly spinning pulsar
- Wind from pulsar energizes the nebula, causing it to emit in the radio

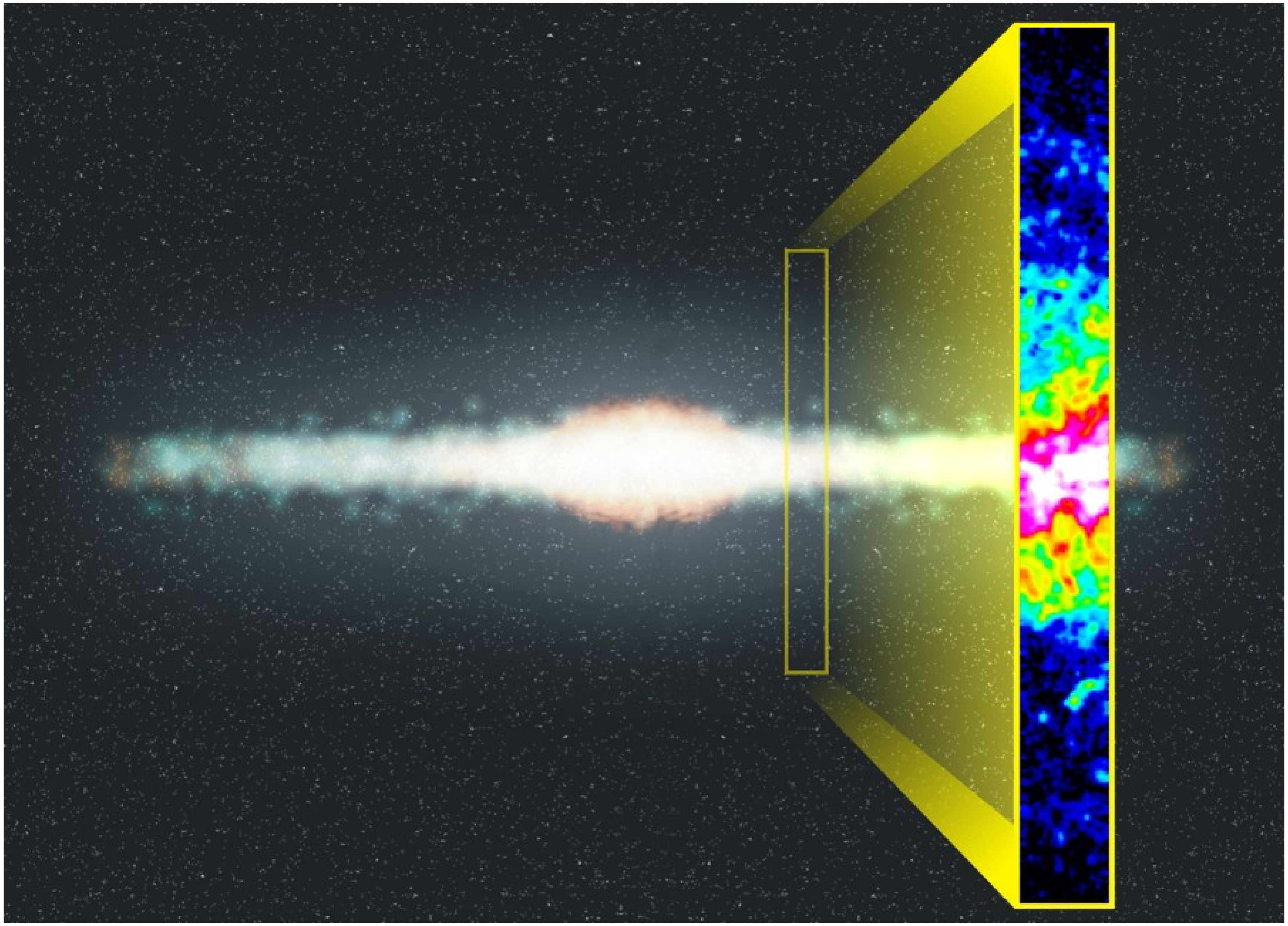
M. Bietenholz
www.nrao.edu/imagegallery

Center of our Galaxy



Credits: Lang, Morris, Roberts, Yusef-Zadef, Goss, Zhao

Same Space -- Different Light



Extragalactic Supernovae

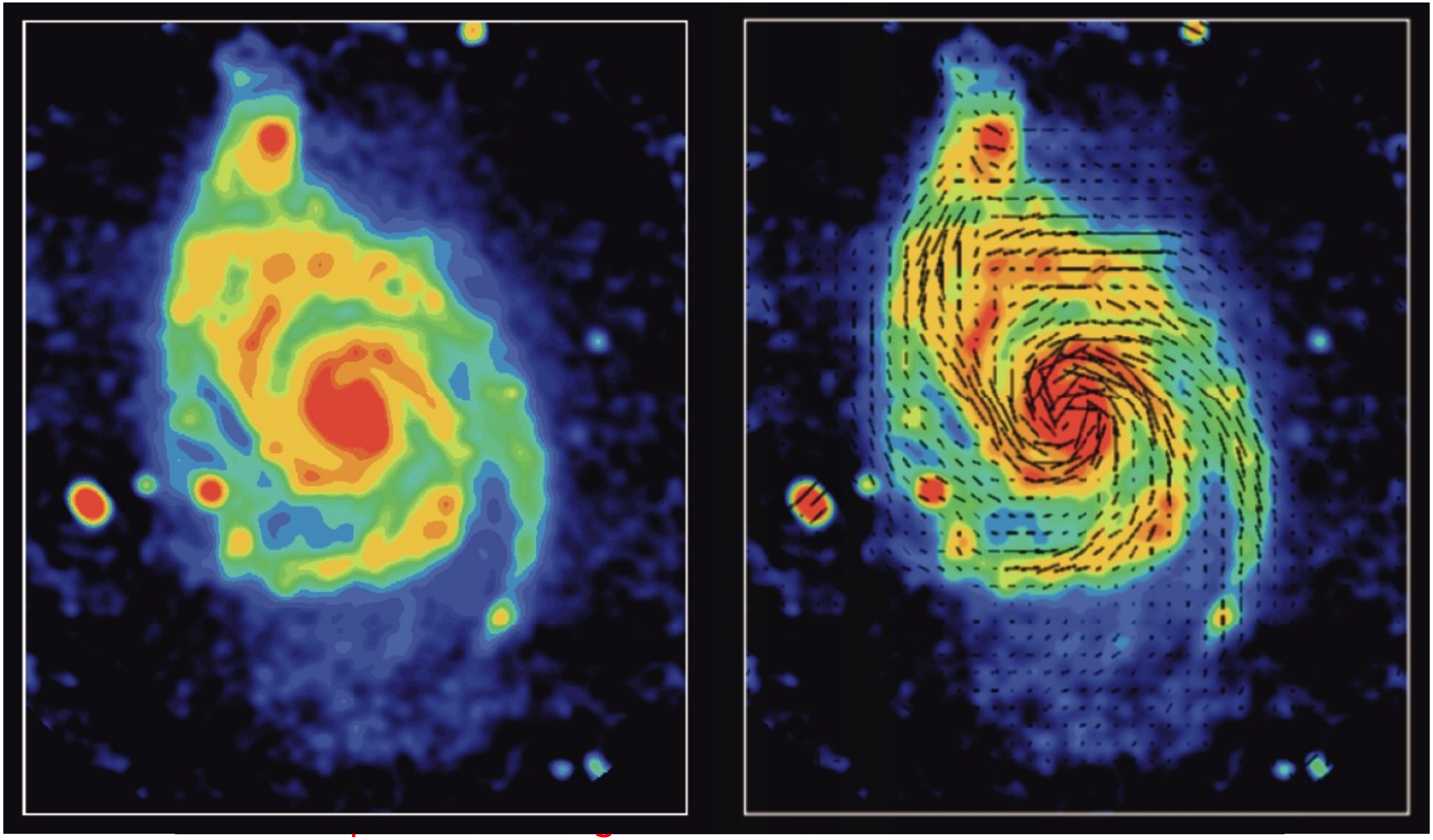
SN 1993J in M81

VLBA Observation from
May 17, 1993 – Feb 25 2000

Bartel, Bietenholz, Rupen et al.

aries.phys.yorku.ca/~bartel/SNmovie.html

Magnetic Field Orientation in Galaxies



Radio Continuum

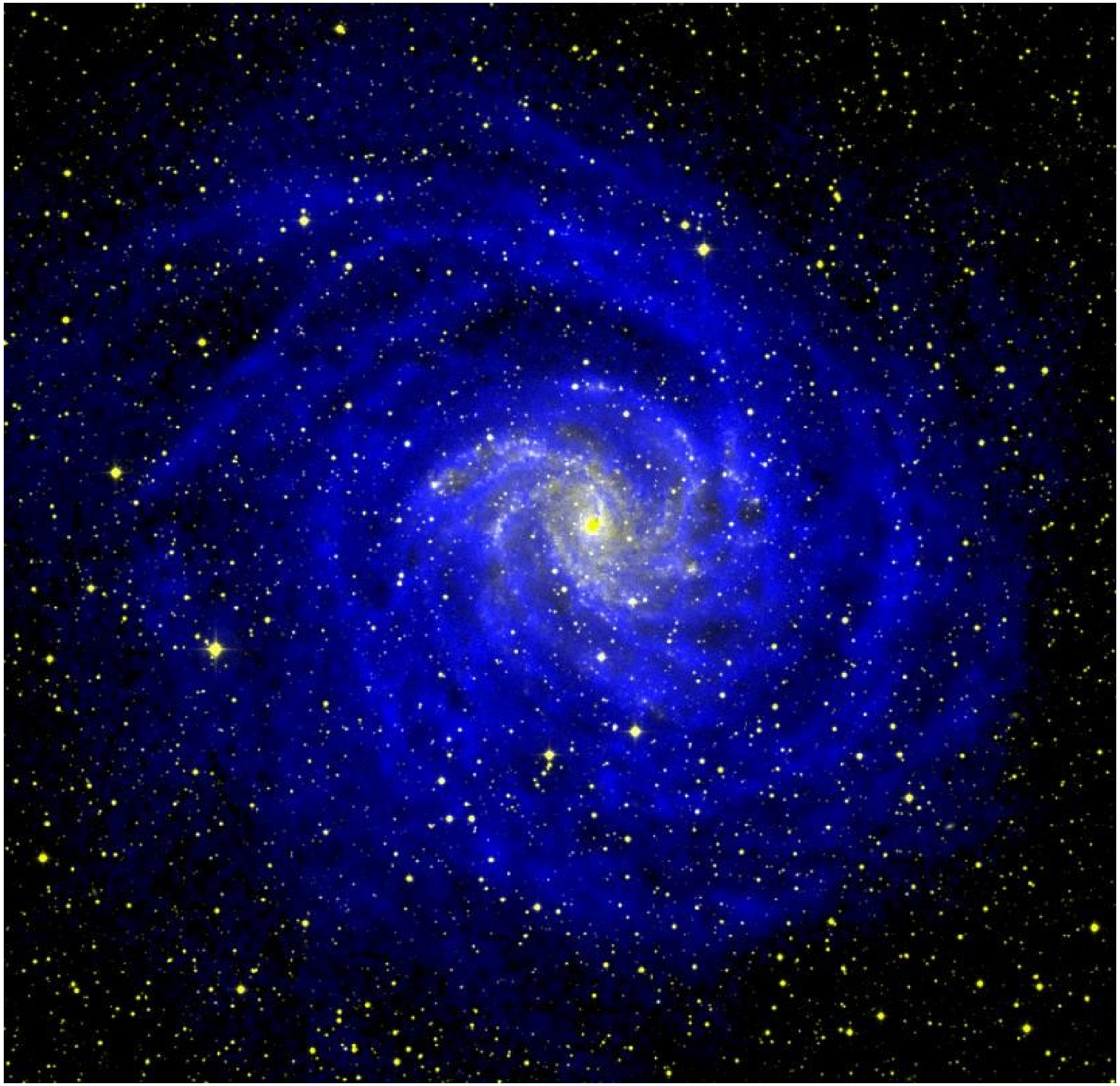
Lines=Magnetic Field Orientation

Beck, Horellou, Neininger

www.nrao.edu/imagegallery

Neutral Hydrogen in Galaxies

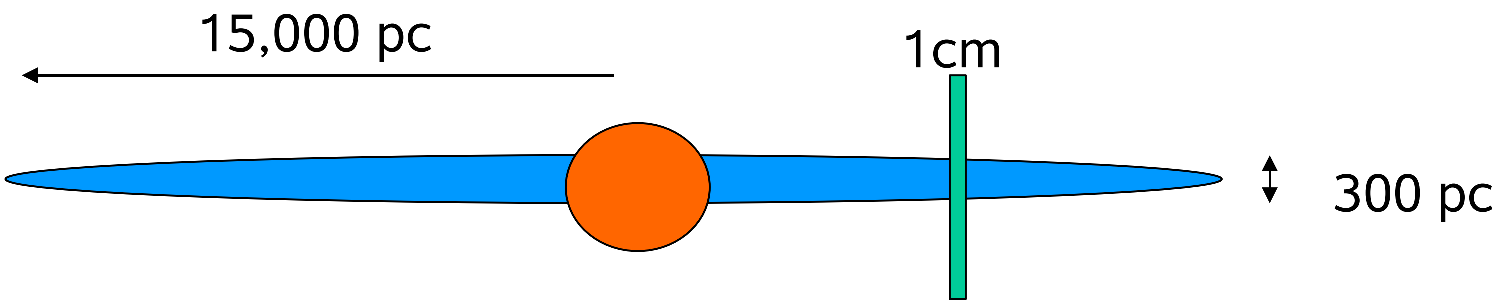
- B/W=optical image of NGC 6946 from Digital Sky Survey
- Blue=Westerbork Synthesis Radio Telescope 21 cm image of Neutral Hydrogen
- Neutral Hydrogen is the raw fuel for all star formation
- Hydrogen usually much more extended than stars



Why can we see 21cm line of neutral Hydrogen?

- A single Hydrogen atom will emit a single 21cm photon once every 11 Myr
- Typical Density in Interstellar Medium ~ 0.1 atom per cubic cm
  - Compare to density of sugar cube: 2×10^{21} molecules per cubic cm
  - Density of best vacuum: 1 Million atoms per cubic cm
- But…Galaxies are big
  - HI layer ~300 parsecs (pc) thick
    1pc=3.08×10^{18} cm
  - Radius of "typical" spiral galaxy ~ 15,000 pc

Why can we see 21cm line of neutral Hydrogen?



- Number of hydrogen atoms in column 1cm across and 300 pc thick:

  Number = density times volume

  = 0.1 atoms/cm^{-3} x 300 pc x 3.08x10^{18} cm/pc x 1cm^{2}

  ~ 1x10^{20} atoms (100 billion billion)

Why can we see 21cm line of neutral Hydrogen?

- Number of these atoms that are emitting a 21cm photon each second:

  = Number of atoms times rate of emission

  = $1x10^{20}$ x $3x10^{-15}$ atoms/sec

  = 300,000 atoms each second each $1cm^2$ area

- Number of atoms in typical galaxy emitting each second

  = number per unit area times total area

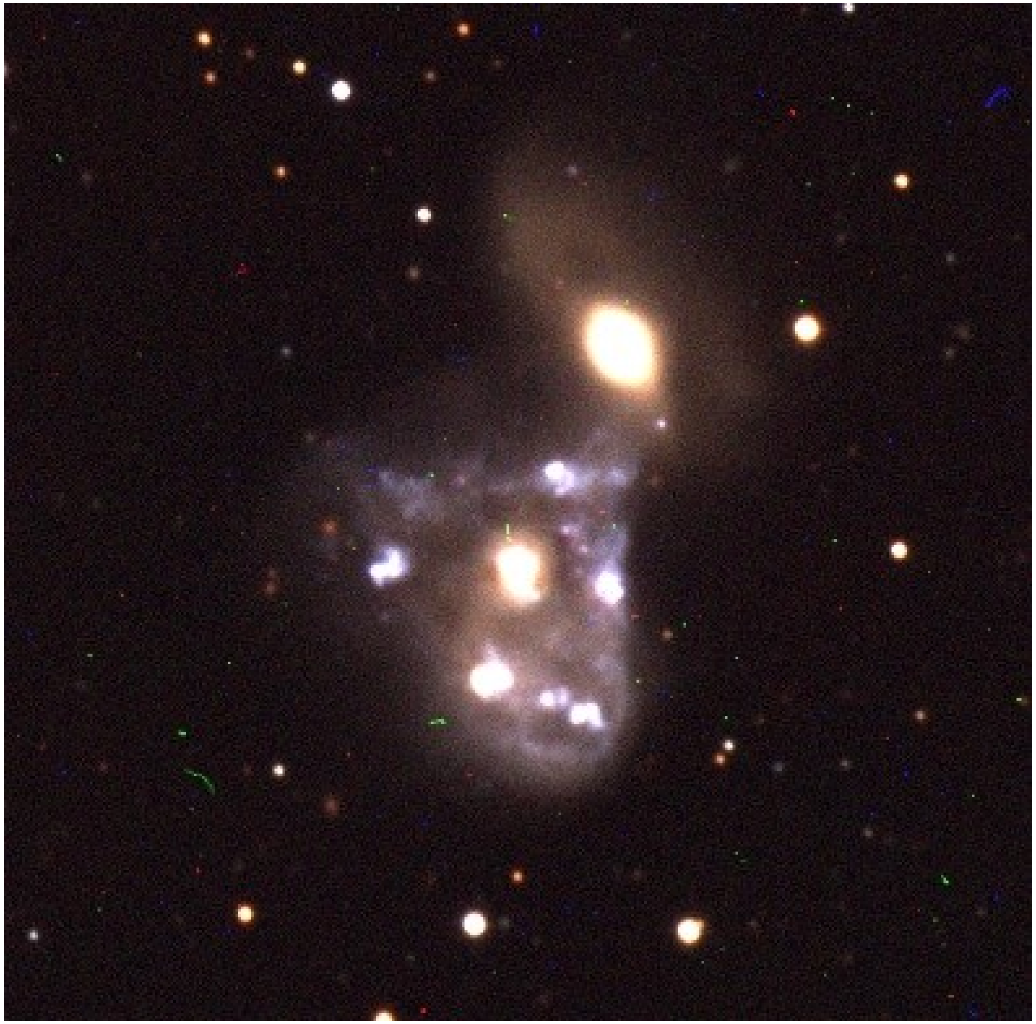
  = 300,000 atoms/cm^2 x (π r^2)

  = 300,000 x 3.1415 x (15,000 pc * $3.08x10^{18}$ cm/pc)^2

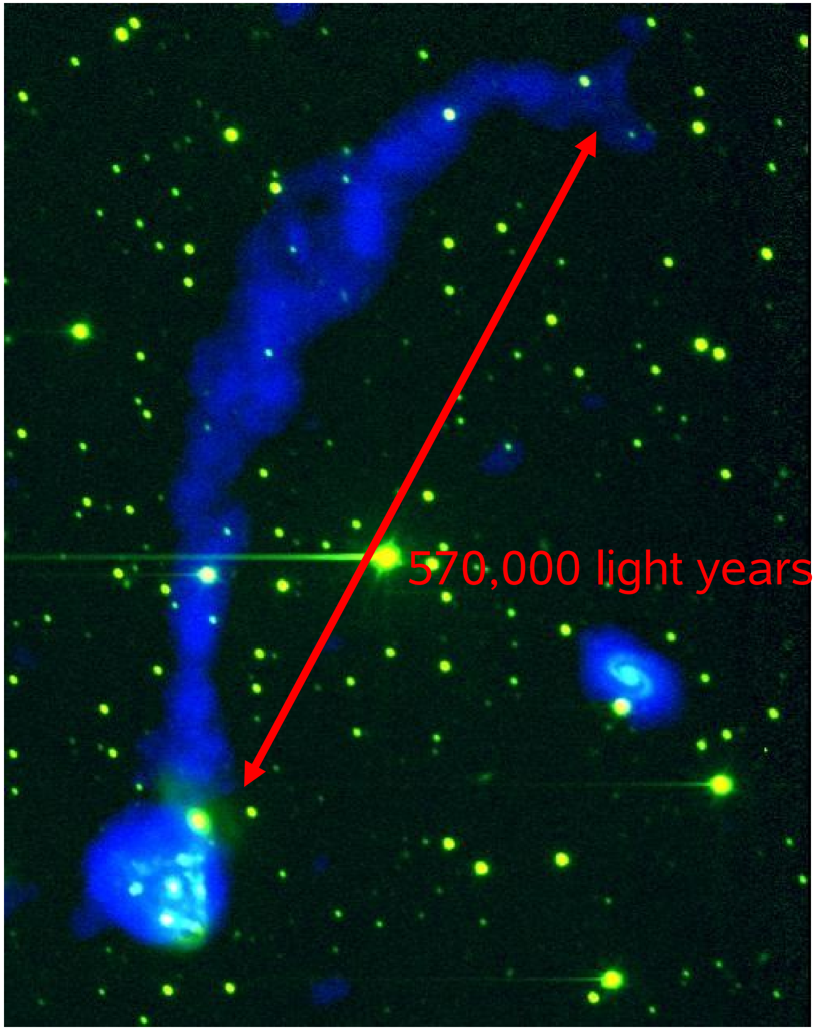
  ~ $2x10^{51}$ atoms each second

21 cm Spectral Line Observations

Often find things you'd never guess from optical light



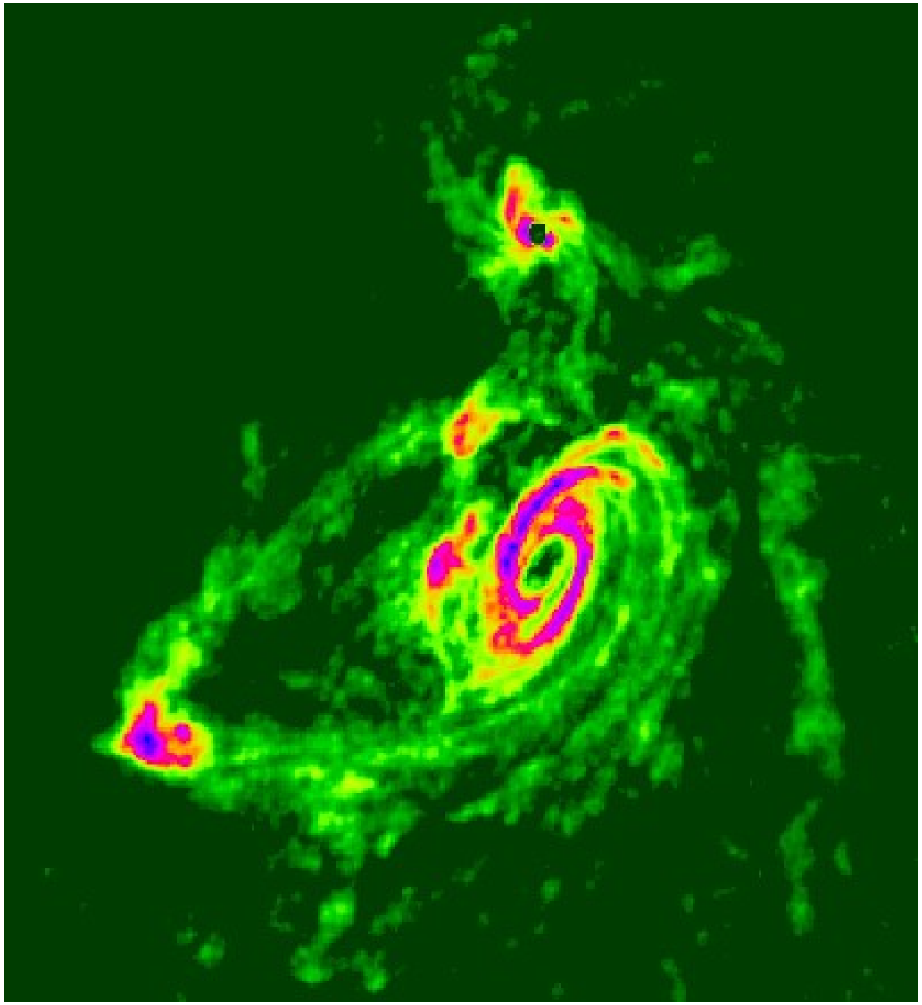
Optical Image of Ring Galaxy Arp 143



VLA 21cm observation Appleton et al. 1987

21 cm Spectral Line Observations

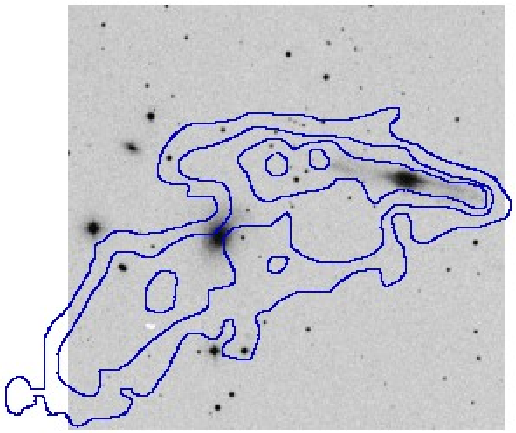
Often find things you'd never guess from optical light



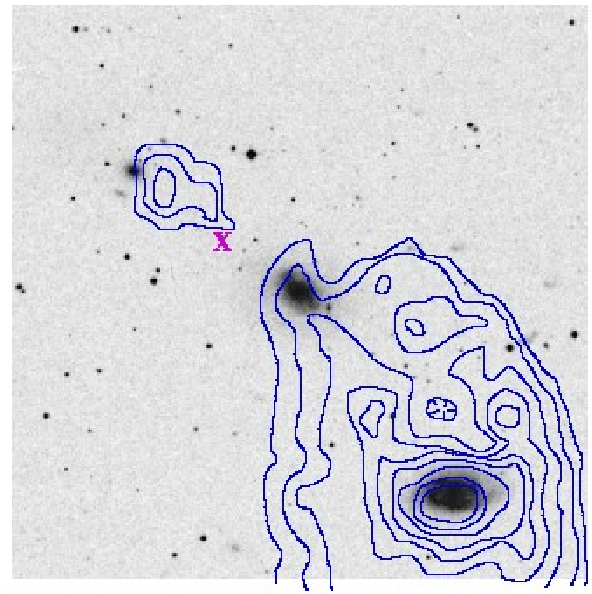
VLA 12-pointing mosaic Yun et al. 1994

21 cm Spectral Line Observations

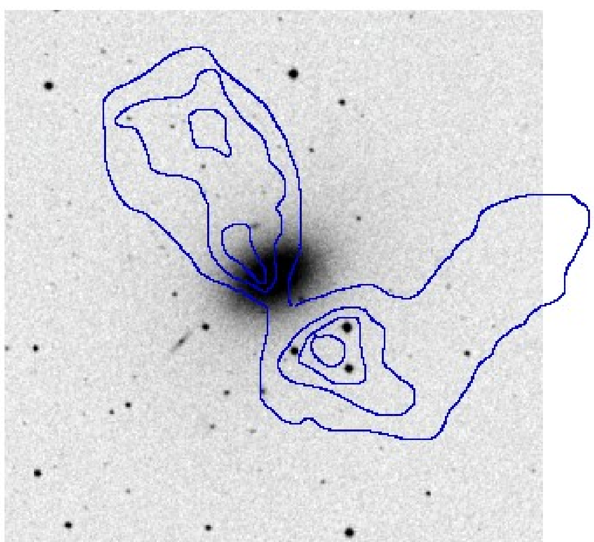
Often find things you'd never guess from optical light



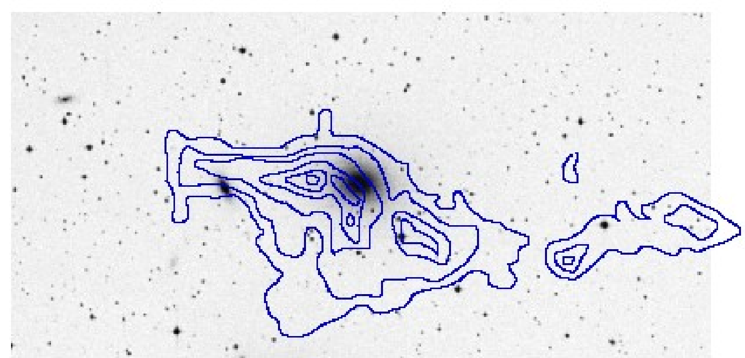
NGC 678+680, Sb+Epec, van Moorsel 1988



NGC 2964+2968+2970, Sb+I0+E1 with extragalactic SNe
van Gorkom & Tyson, in prep



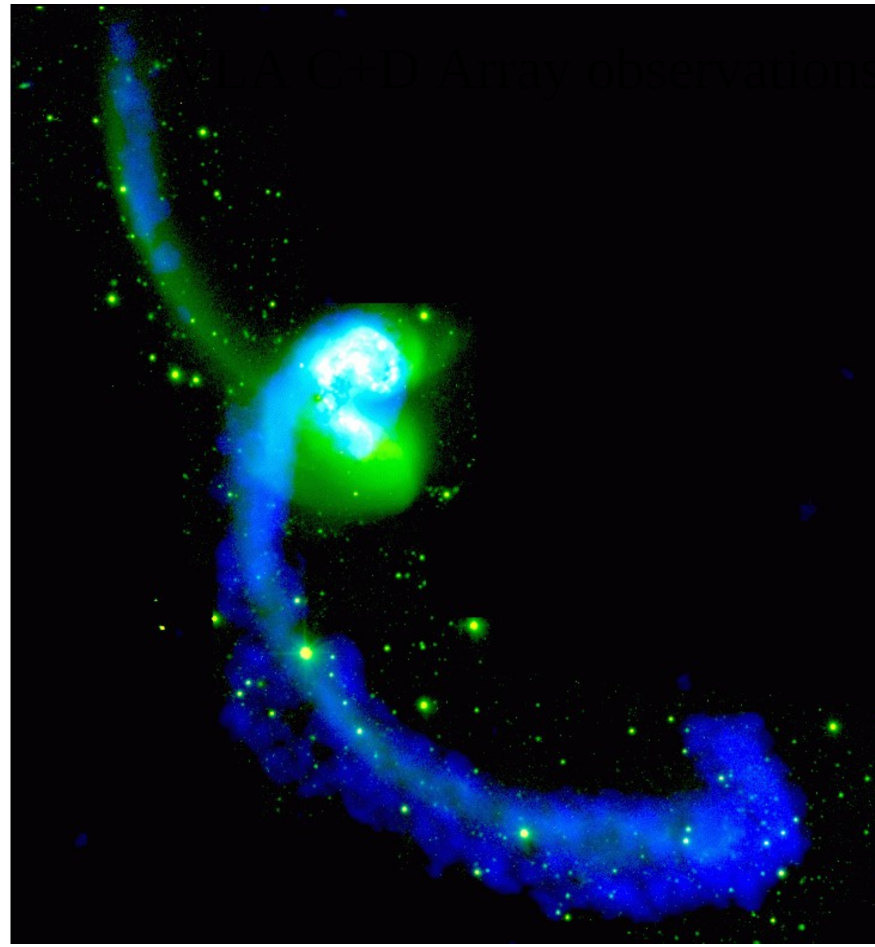
NGC 1052, E4, Sy2, van Gorkom et al. 1986



NGC 5903, E2, Appleton, Pedlar & Wilkinson 1990

Spectral Line Observations also provide velocity information

CTIO 0.9m Optical image

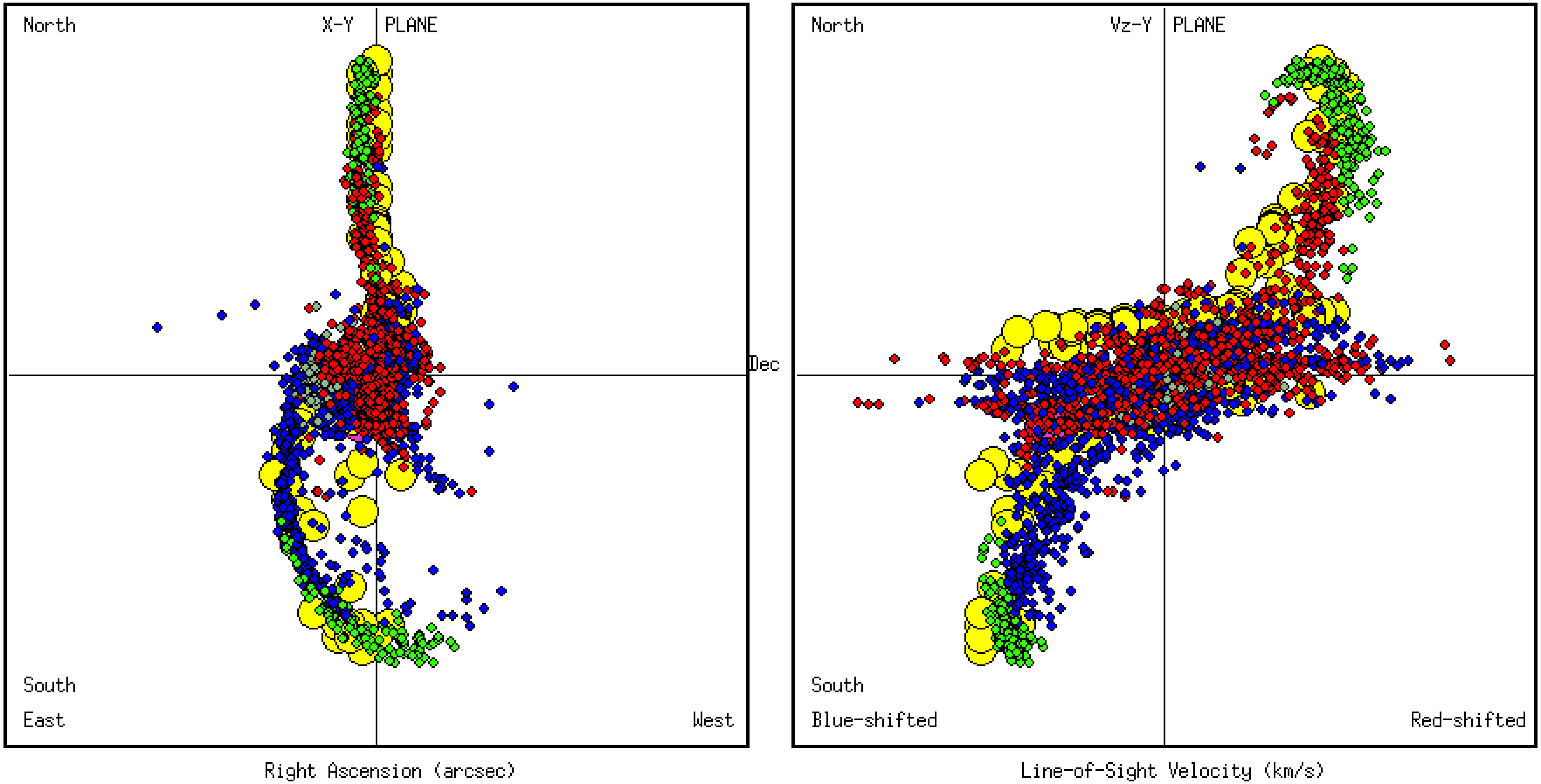


Optical image (green) + VLA 21cm (blue)

Hibbard, van der Hulst, Barnes & Rich, 2001, AJ, 122, 2969

Rotating “Velocity cube” of neutral hydrogen

Spectral Line Observations also provide velocity information

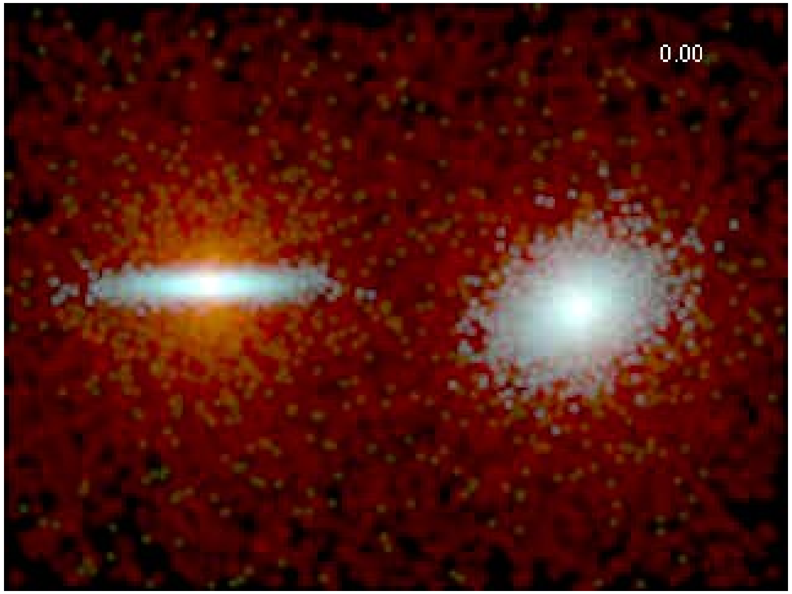


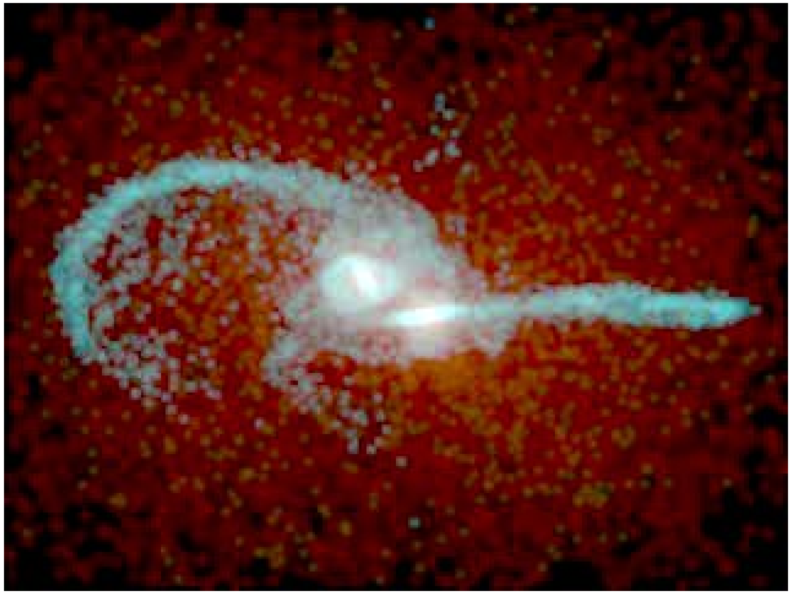
Spatial and Velocity information help motivate physical models

N-body simulation of NGC 4676 “The Mice” Hibbard & Barnes, in preparation

N-body simulation of NGC 4676 “The Mice”
Hibbard & Barnes, in preparation

N-body simulations provide past/future evolution and 3-D geometry





Information from Radio compliments that from other wavelengths

Information from Radio compliments that from other wavelengths

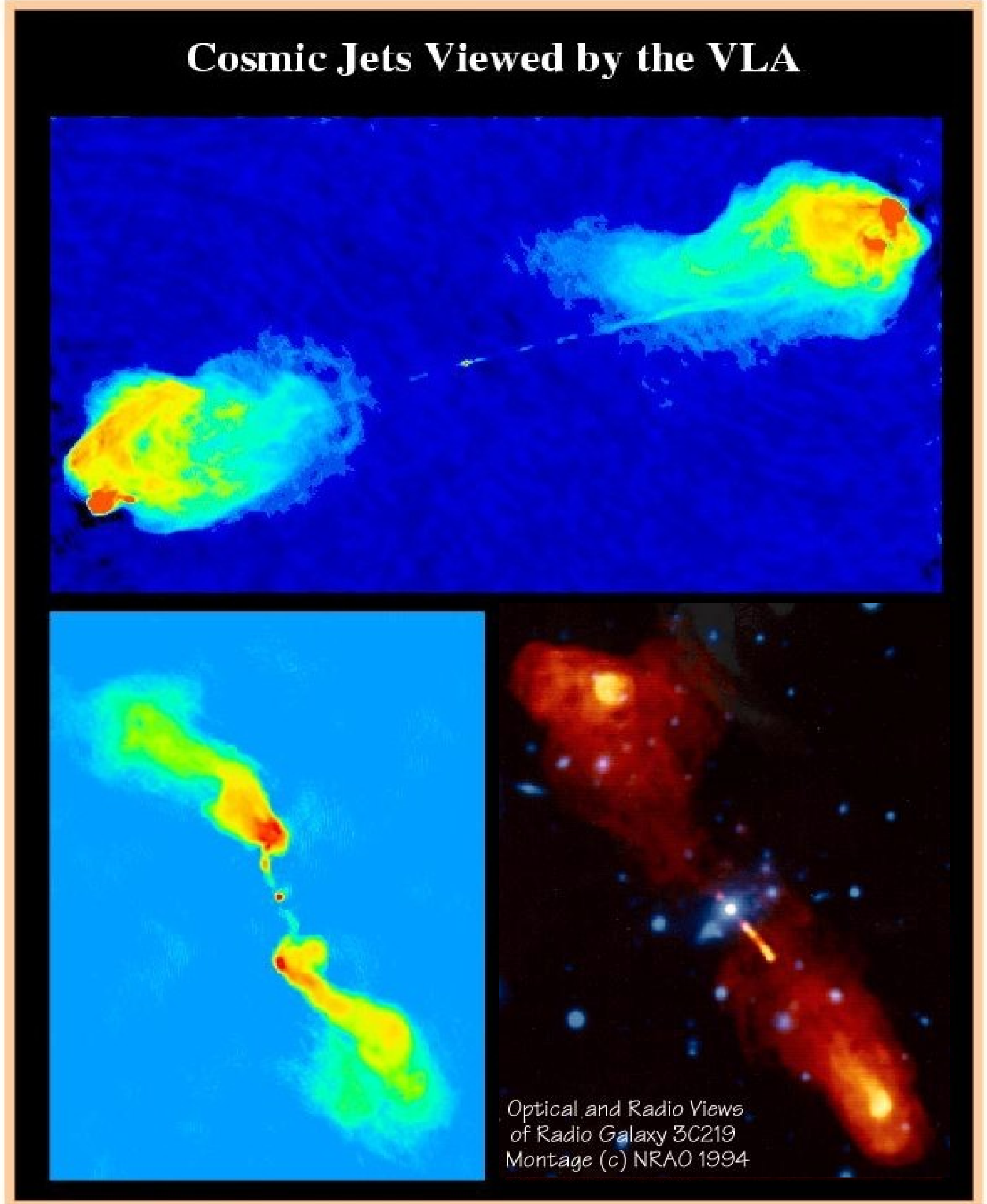
X-ray: Karovska et al.
Optical: DSS
Radio Continuum: NVSS
21cm: Schiminovich et al.

CHANDRA X-RAY | DSS OPTICAL | NRAO RADIO CONTINUUM | NRAO RADIO (21-CM)

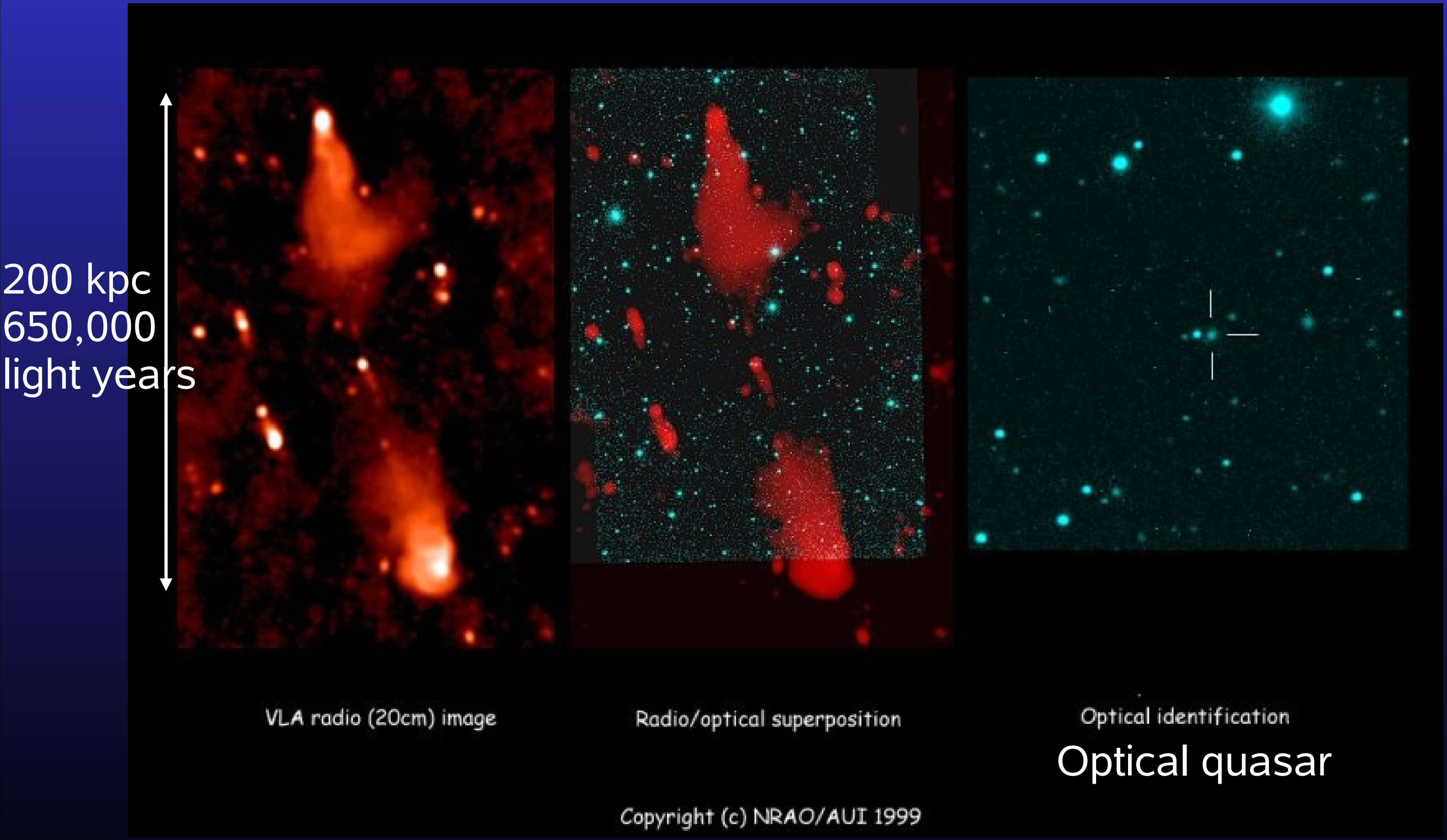
Chandra.harvard.edu

Radio Jets

- Cosmic jets are ubiquitous
- They range from extragalactic jets to microquasars in our Galaxy
- Central black hole masses range from 1 to billions of solar masses
- Found in ~10% of quasars or other active galactic nuclei



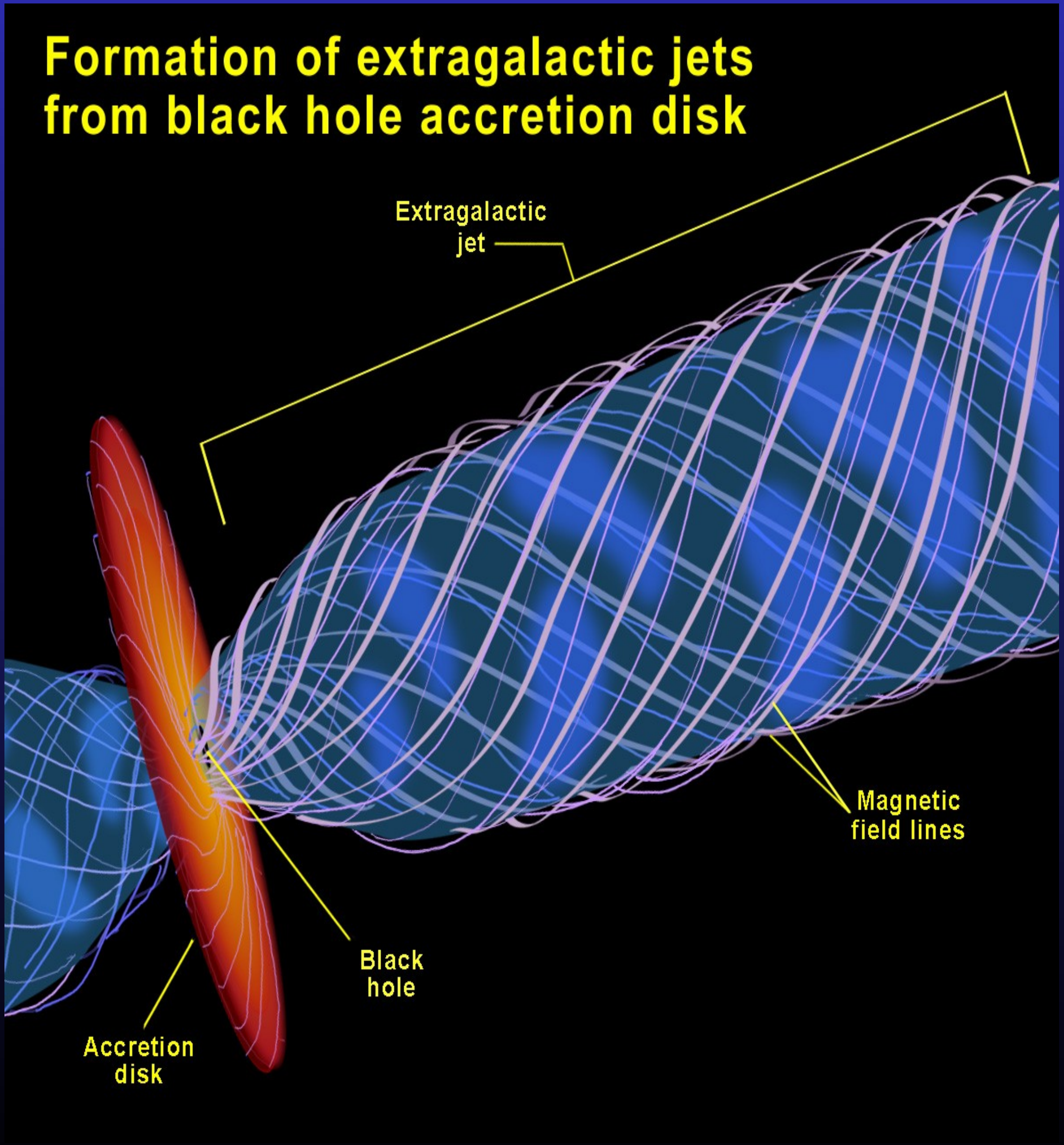
Radio Jets



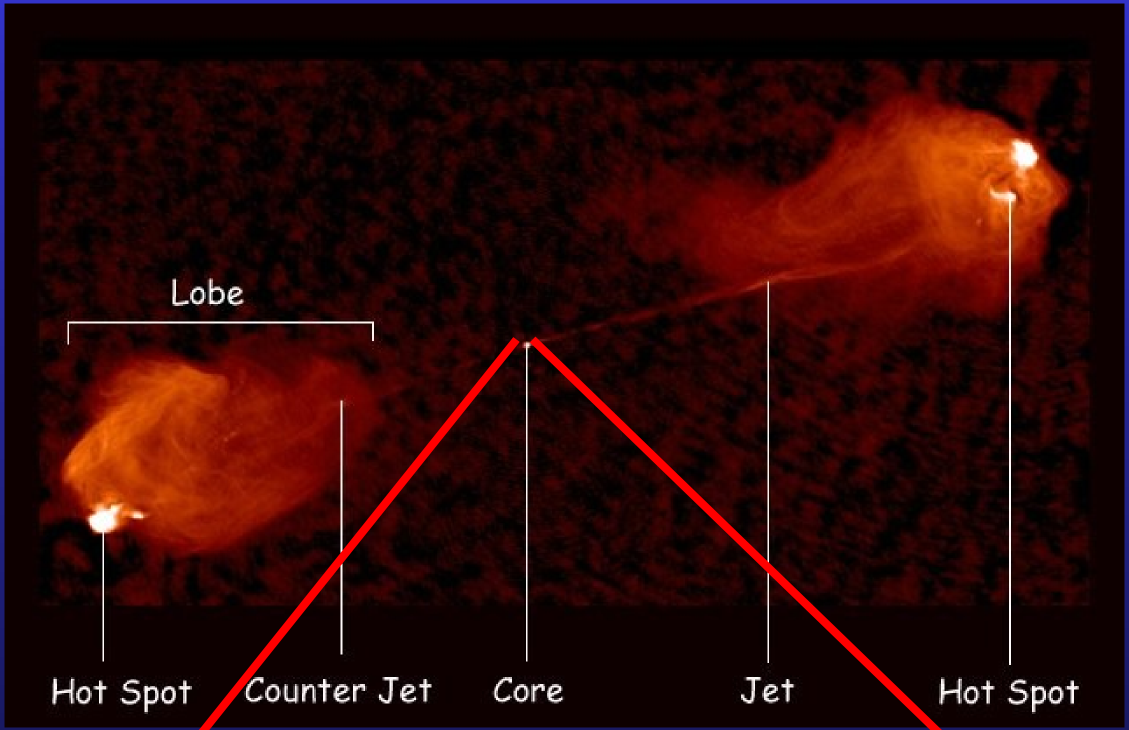
An exclusively radio phenomena

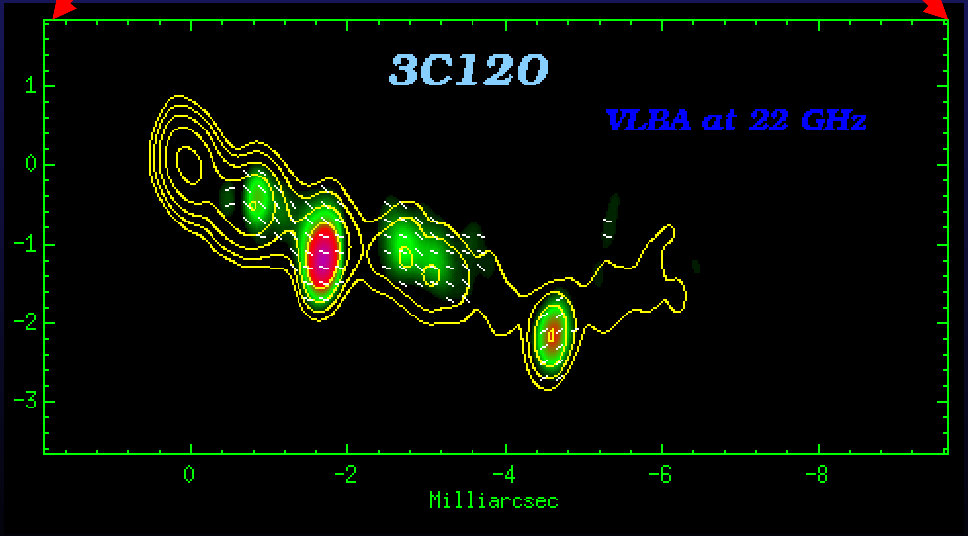
Jet Mechanism:

- Accretion of gas onto a massive central black hole releases tremendous amounts of energy
- Magnetic field collimates outflow and accelerates particles to close to the speed of light

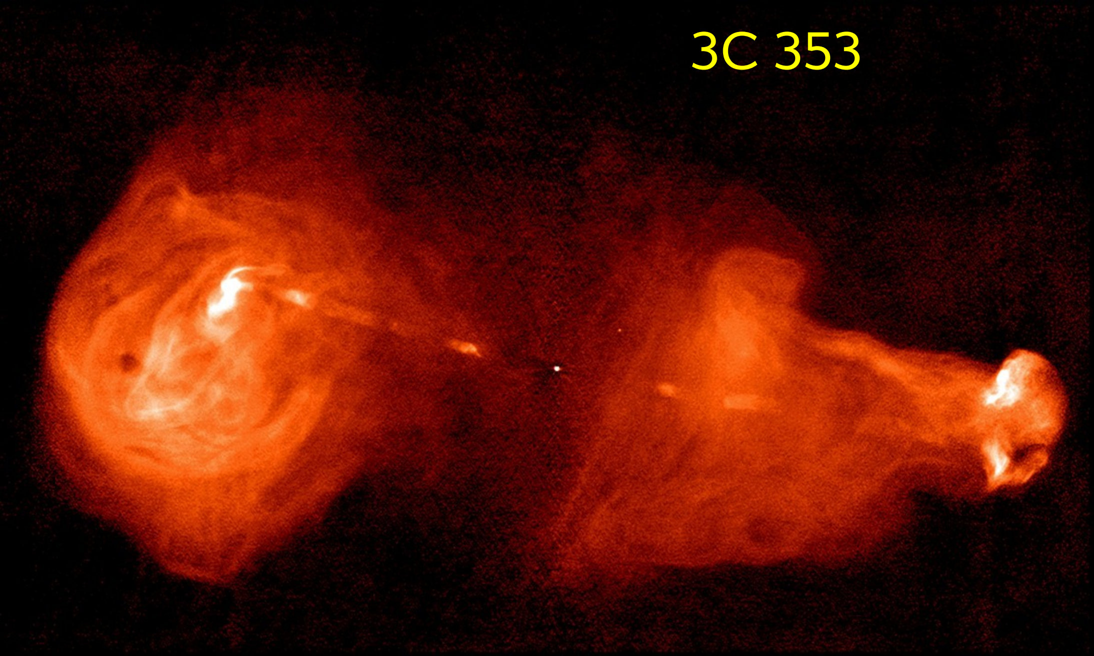


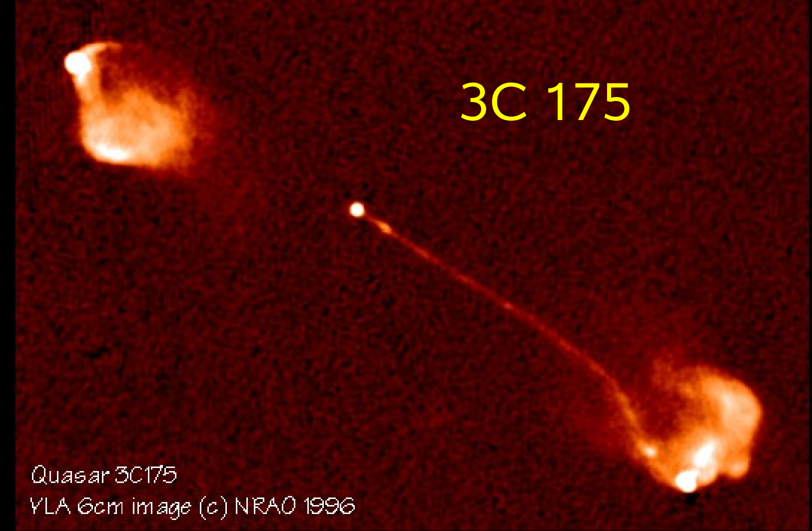
VLBA Time-Elapsed Observations of the Innermost Regions of a Jet

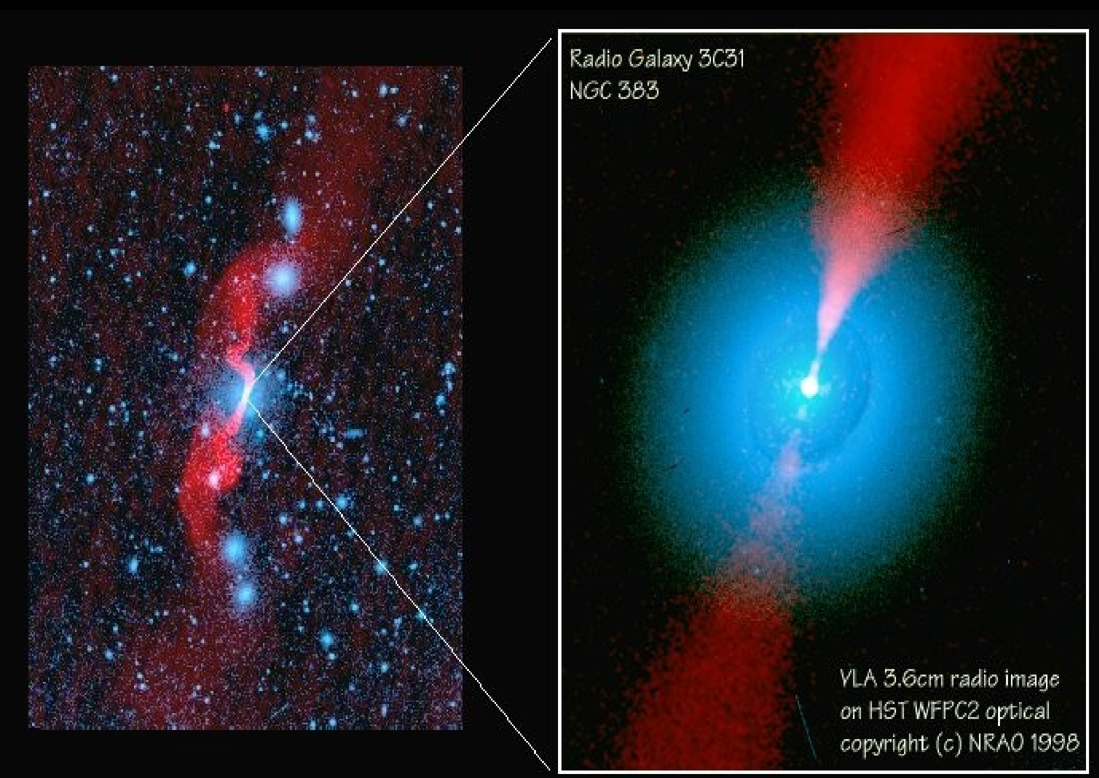


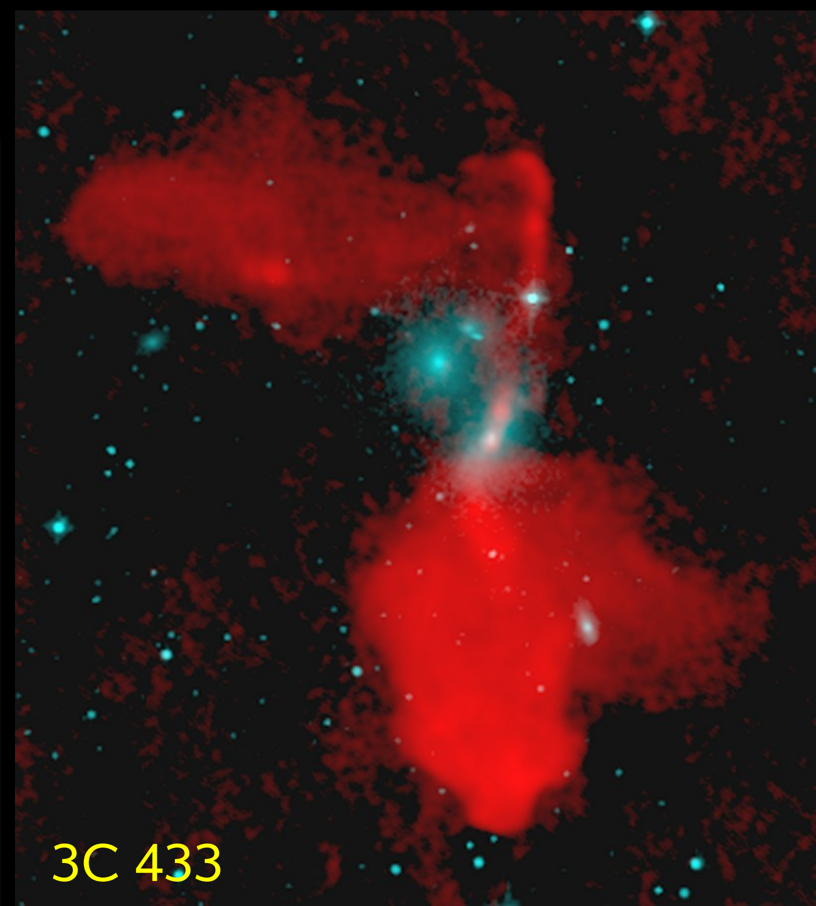


AGN Artistic Simulation by Steffen & Gomez


3C 353

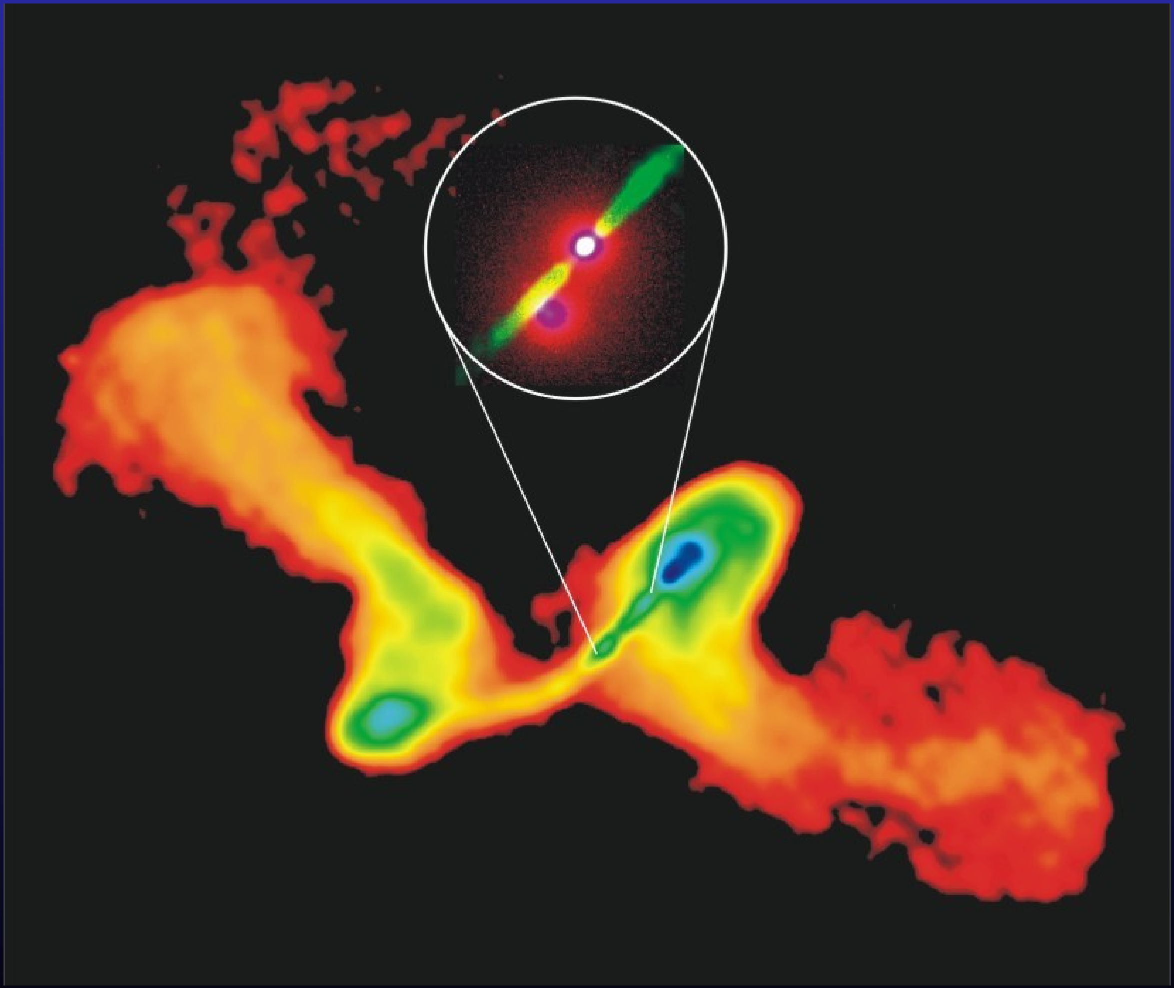

3C 175
Quasar 3C175
VLA 6cm image (c) NRAO 1996


Radio Galaxy 3C31
NGC 383
VLA 3.6cm radio image
on HST WFPC2 optical
copyright (c) NRAO 1998

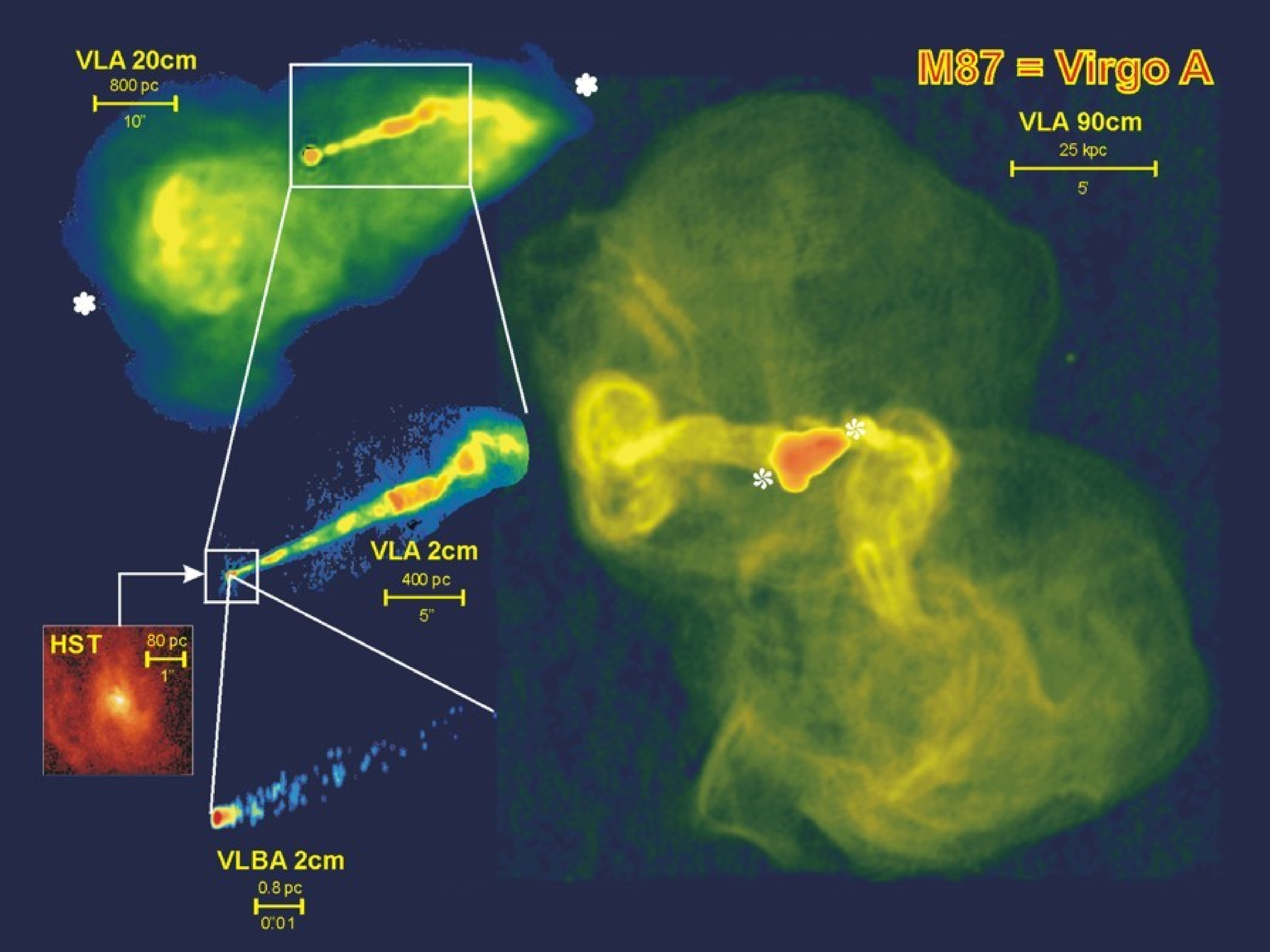

3C 433

NGC 326: "Smoking Gun" of Colliding Black Holes

- Inset HST optical image shows two nuclei, presumably the result of two galaxies merging
- "X-shaped radio jets show radi axis has flipped
- It is thought that only another black hole can realign a black hole jet



Merritt & Ekers www.nrao.edu/imagegallery

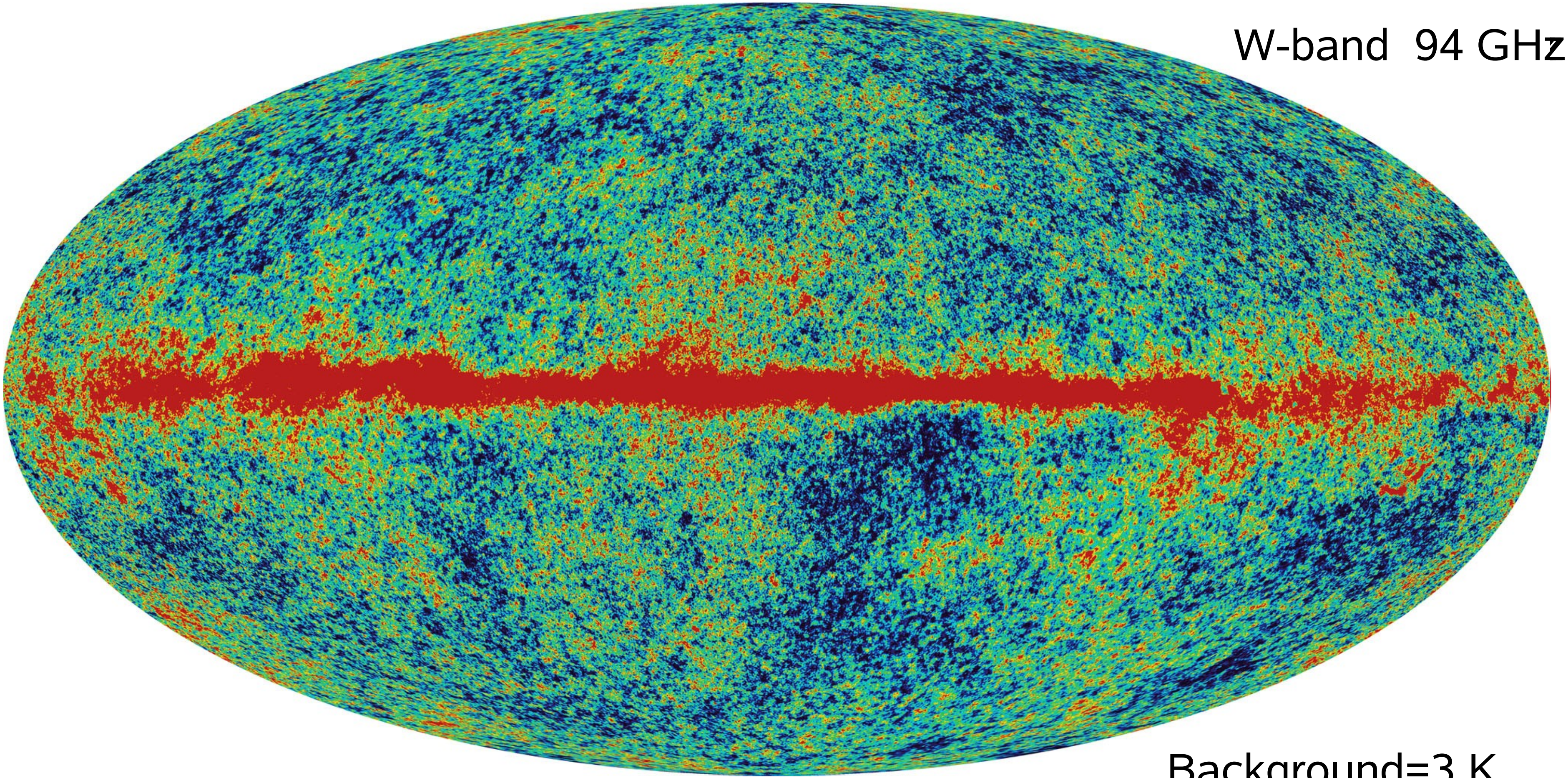


M87 = Virgo A
VLA 20cm
800 pc
10"
VLA 90cm
25 kpc
5'
VLA 2cm
400 pc
5"
HST
80 pc
1"
VLBA 2cm
0.8 pc
0."01

Wilkinson Microwave Anisotropy Probe (WMAP)

map.gsfc.nasa.gov

W-band 94 GHz



Background=3 K
blackbody radiation

Shepherding in the era of "Precision Cosmology"

So What's Next for Radio Astronomy?

- 2003-2013:
  - EVLA: making the VLA ten times better
  - ALMA: VLA for the sub-millimeter
  - ATA: SETI lives on
- 2008-2030+
  - FASR: solar array
  - LOFAR: low frequency array
  - SKA: collecting area of 75 VLA's

The VLA Expansion Project:
21st Century Astrophysics with the VLA

EVLA - The Expanded Very Large Array

Built on the infrastructure of the current VLA, including its 27 antennas of 25-meter diameter, the EVLA will incorporate state-of-the-art electronics to replace present equipment dating to the 1970s and may include approximately eight new stations as distant as 250 kilometers from the current array. These features will improve the scientific capabilities of the instrument by a factor of 10 in all key observational parameters.

EVLA - Improved Capabilities

Sensitivity:
Continuum sensitivity improvement by up to a factor of 5 (below 10 GHz) to more than 20 (between 10 and 50 GHz).

Frequency Accessibility:
Operation at any frequency between 1.0 and 50 GHz, and potentially to as low as 300 MHz.

Spectral Capabilities:
As many as 262,144 frequency channels will provide flexible, variable resolutions between 1 MHz and 1 Hz.

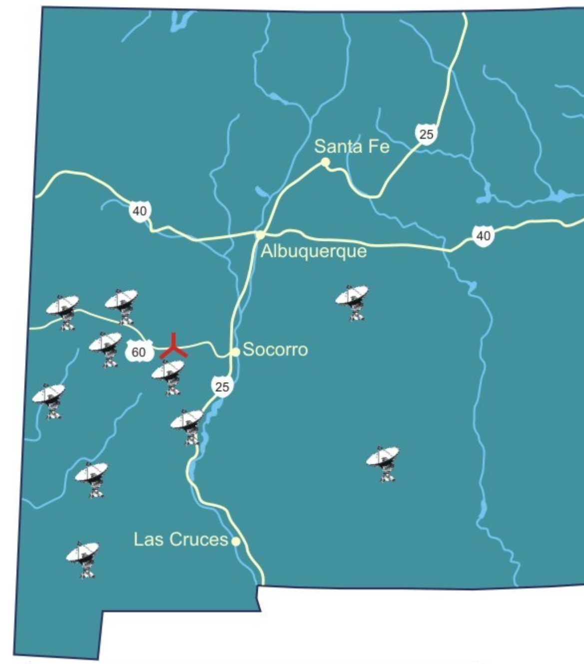
Spatial Resolution:
Maximum resolution ranging from 0.004 arcsec at 50 GHz to 0.2 arcsec at 1 GHz, complementing the higher resolution of the VLBA.

Implementing the EVLA

The VLA Expansion Project will combine modern technologies with the sound design of the existing VLA to produce a tenfold increase in scientific capabilities for much less than the inflation-adjusted cost of the VLA. The project consists of two phases, with the second phase projected to start midway through implementation of the first phase. The design and development effort for Phase I has now formally begun. A proposal for the Phase II part of the project is currently under development.

Phase I - The Ultrasensitive Array

The Phase I EVLA consists of : wideband receiver systems, a state-of-the-art, flexible correlator, a fiber-optic data transmission system, all new digital electronics, a new powerful on-line control system, and the 27 exisiting VLA antennas.



Phase II - The New Mexico Array

In Phase II of the EVLA construction, approximately 8 new stations at distances of up to 300 km from the VLA will be brought on-line. The new antennas and some inner VLBA antennas will be connected to the VLA by fiber-optics links.

Atacama Large Millimeter Array

A project of the National Science Foundation and the National Research Foundation of Canada through the North Americar Project for Radio Astronomy via its partners, Associated Universities, Inc. operating the National Radio Astronomy Observatory, and the Herzberg Institute of Astronomy and the European Southern Observatory and its partners The Centre ational de la Recherche Scientifique (CNRS), France; Max Planck Gesellschaft (MPG), Germany; The Netherlands Foundation esearch in Astronomy, (NFRA); Nederlandse Onderzoekschool Voor Astronomie, (NOVA); The United Kingdom Particle Physics and Astronomy Research Council, (PPARC);The Swedish Natural Science Research Council, (NFR); and the Ministry de Ciencia y Tecnologia and Instituto Geografico Nacional (IGN,)(Spain)

EuB

- ALMA will be an array of 64 precision engineered antennas deployed in the Atacama desert in the high Andes in Chile. Configurable array, like the VLA, to provide a zoom-lens capability.
- Most of the energy in the Universe lies at submillimeter/millimeter wavelengths yet we cannot image the sources of this energy with reasonable detail. ALMA will reach the sensitivity of current submm telescopes in seconds, with resolutions reaching 10mas.
- ALMA has been endorsed as the highest priority project for the next decade by the astronomical communities of the United States, Canada, the United Kingdom, France, the Netherlands and Japan (the latter as LMSA). Planned completion in 2012.

Al Wootten, ALMA/US Project Scientist

The Allen Telescope Array

- First telescope designed specifically for the Search for Extra-Terrestrial Intelligence (SETI)
- Array of 350 commercial satellite dishes, 6m in diameter. More collecting area than the GBT
- Will speed SETI targeted searching by 100x
  - Will target from 100,000 to 1 million nearby stars
  - Will scan 100 million radio channels
- Start-up scheduled for 2005

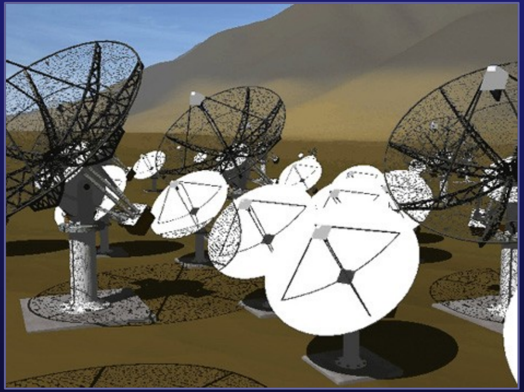
www.seti-inst.edu/seti/our_projects

Proposed Radio Instruments:

2008: Low-Frequency Array (LOFAR)

A low-frequency (10-240 MHz) multi-beam-forming array composed of ~100 antenna "stations" each containing ~100 individual antenna, spread over an area of ~400 km. Will open a new window on the Universe

www.lofar.org



2009: Frequency Agile Solar Radiotelescope (FASR)

A multi-frequency (~0.1 - 30 GHz) imaging array composed of ~100 antennas for imaging the Sun with high spectral, spatial, and temporal resolution.

www.ovsa.njit.edu/fasr/

2030?: Square Kilometer Array (SKA)

A multi-frequency (~0.1 - 3 GHz?) imaging array with a collecting area of 1 square kilometer.

www.skatelescope.org

Conclusions

- Radio astronomical imaging is a relatively young, but rapidly advancing field which will explode in the next decade
- You don’t have to have a well-funded P.R. machine to churn out fascinating science