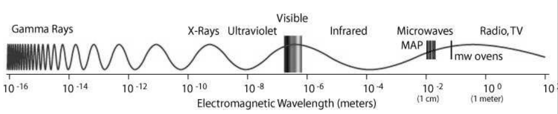
Radio Science
&
Future Interferometers

T. Beasley
CARMA/Caltech
Owens Valley Radio Observatory

Astronomy

- Gather information about universe from
  - Electromagnetic radiation
  - Particles
  - Gravitational radiation…?
- 2-3D imaging – sensitivity, resolution, fidelity
- More Resolution → Interferometry

Electromagnetic spectrum



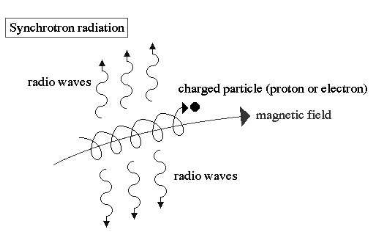
physical properties – temperature, pressure, structure, magnetic fields + physical process→ different emissions

atoms & molecules → unique radio frequencies

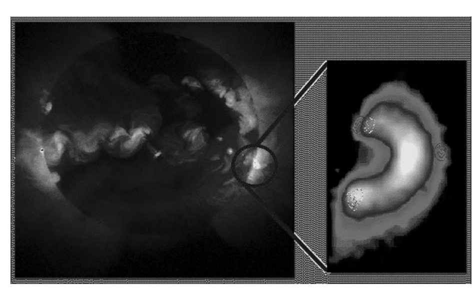
Main Processes - Radio Emission

- Synchrotron radiation - continuum
  - Energetic charged particles accelerating along magnetic field lines
- Thermal emission - continuum
  - Hot → Cool bodies
  - Charged particles interacting in a plasma at T
- Spectral Line emission – spectral line
  - Discrete transitions in atoms and molecules

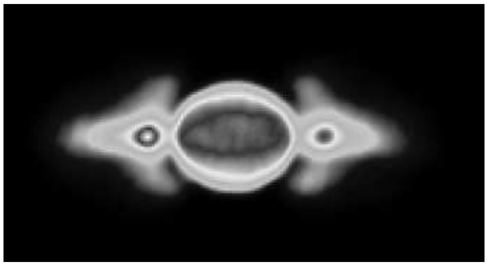
Synchrotron Radiation



- Polarization properties of radiation provides information on magnetic field geometry

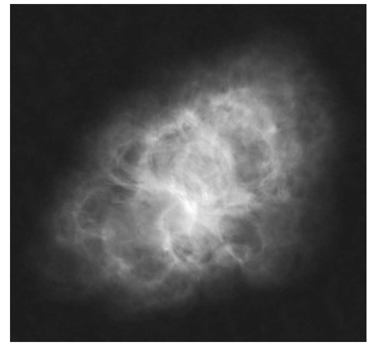


Jupiter - ATCA – 13cm



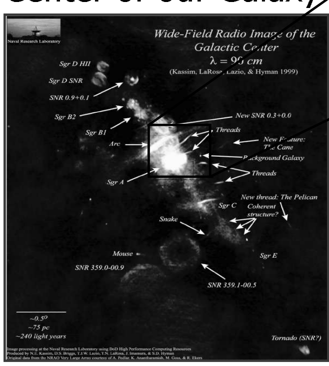
Supernova Remnants - Crab Nebula

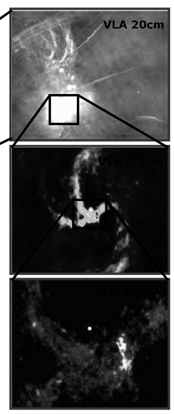
- Remnant of a supernovae from 1054 AD
- Expanding at 1000 km/sec
- Central star left behind a rapidly spinning pulsar
- Wind from pulsar energizes the nebula, causing it to emit in the radio



M. Bietenholz www.nrao.edu/imagegallery

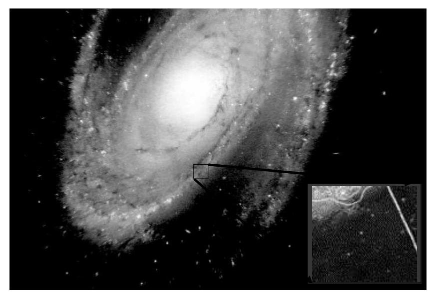
Center of our Galaxy





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

Extragalactic Supernovae

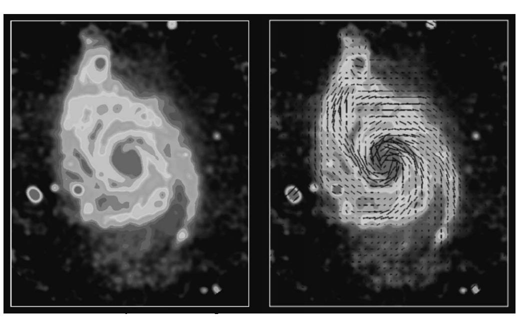


SN 1993J in M81

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

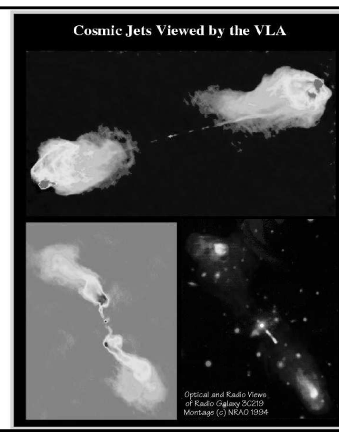


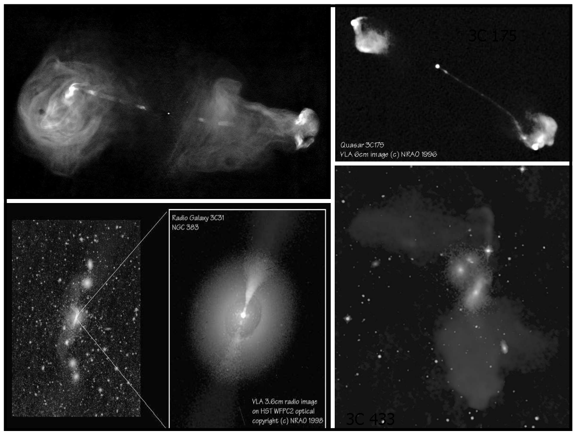
Radio Continuum Lines=Magnetic Field Orientation

Beck, Horellou, Neininger www.nrao.edu/imagegallery

Radio Jets

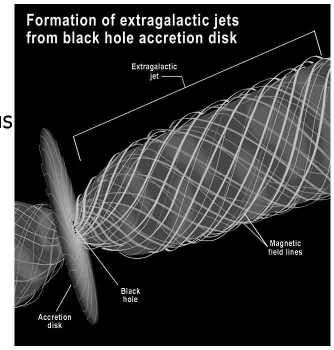
- Cosmic jets are ubiquitous
- They range from extragalactic jets to microquasars in our Galaxy
- Central black hole masses range from 1 to billions of solar masses
- Found in ~10% of quasars or other active galactic nuclei

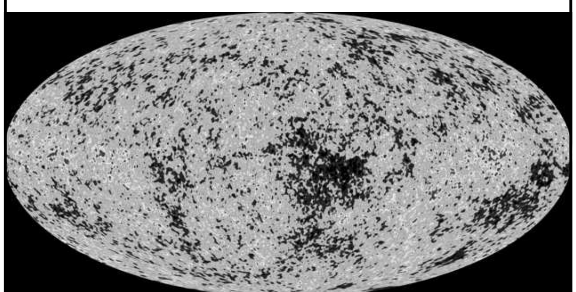




Radio Jets - Theory

- 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

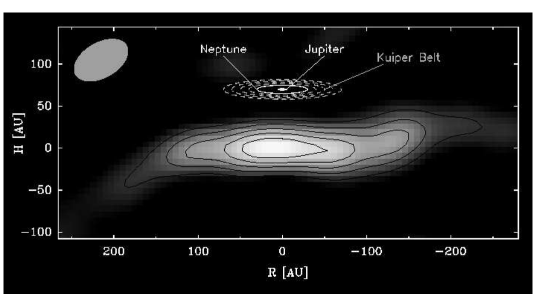




Cosmic Microwave Background - WMAP

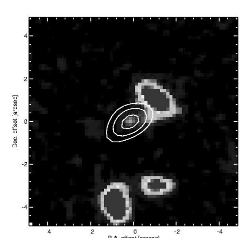
Thermal Emission

- Emission from warm bodies
  - "Blackbody" radiation
  - Bodies with temperatures of ~ 3-30 K emit in the mm & submm bands
- Emission from accelerating charged particles
  - "Bremsstrahlung" or free-free emission from ionized plasmas

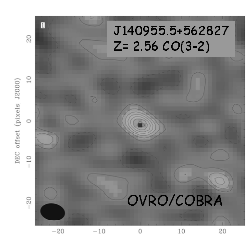


1.3-mm dust continuum : CB26 circumstellar disk : 0.1 Msun

Star Formation at high redshifts OVRO/COBRA dust & gas detections



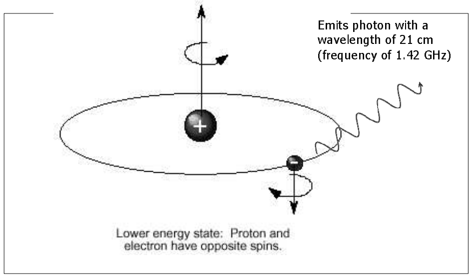
Frayer et al. 2000



Hainline & Scoville 2003

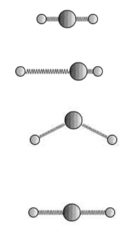
Spectral Line emission

- Hyperfine transition of neutral Hydrogen



Spectral Line emission

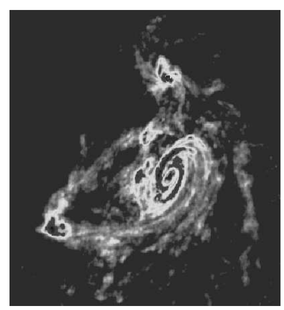
- molecular rotational and vibrational modes – many in mm/submm
- Commonly observed molecules in space:
  - Carbon Monoxide (CO)
  - Water (H_2O), OH, HCN, HCO^+, CS
  - Ammonia (NH_3), Formaldehyde (H_2CO)
- Less common molecules:
  - Sugar, Alcohol, Antifreeze (Ethylene Glycol), glycine? (amino acid)
- SL: Doppler shifts + line profiles indicate kinematics and/or physics of sources



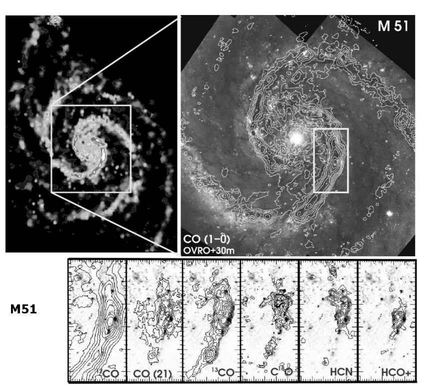
Neutral Hydrogen in Galaxies

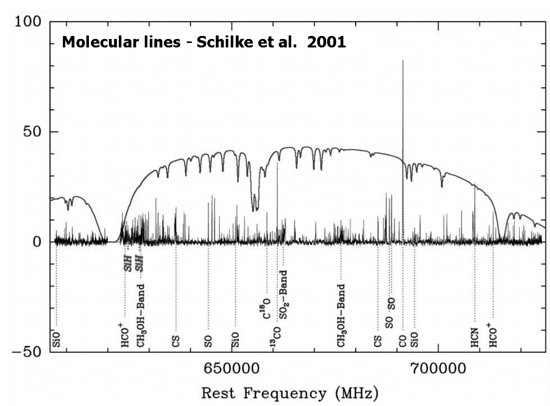
- B/W=optical image of NGC 6946 from Digital Sky Survey
- Blue=Westerbork Synthesis Radio Telescope 21 cm image of Neutral Hydrogen
- Neutral Hydrogen is the raw fuel for all star formation
- Hydrogen usually much more extended than stars

21 cm Spectral Line Observations



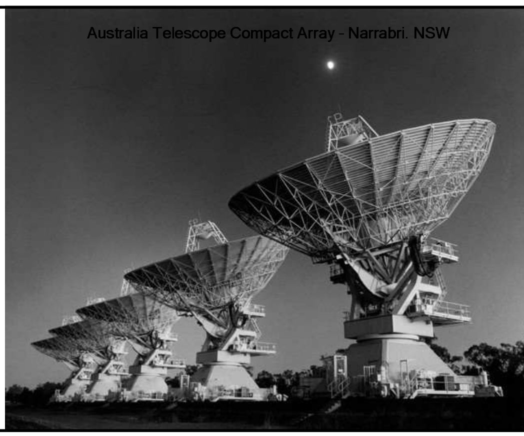
VLA 12-pointing mosaic Yun et al. 1994

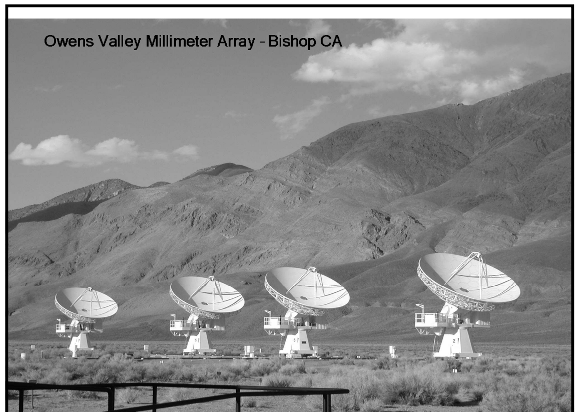


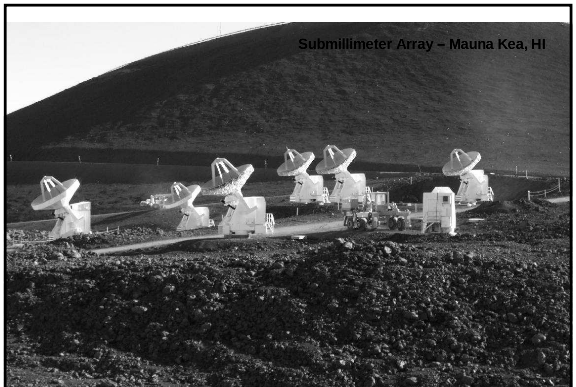


Astronomy

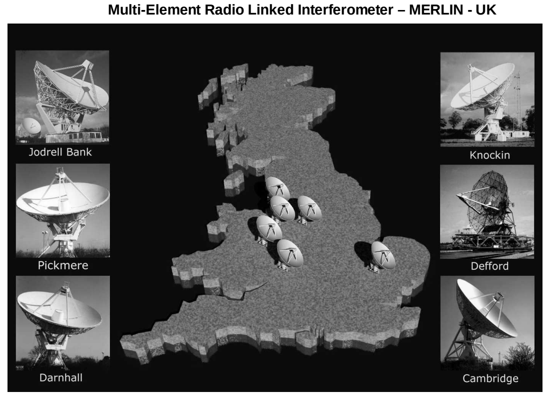
- Information via
  - Electromagnetic radiation
  - Particles
- Approach: 2D imaging. Parameters of interest → sensitivity, resolution, fidelity, spectroscopy
- More Angular Resolution → Interferometry



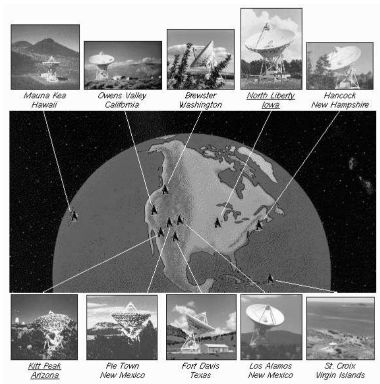




Multi-Element Radio Linked Interferometer – MERLIN - UK



VLBA



Future Radio Interferometers

- Underway/funded
  - EVLA (cm/mm)
  - ATA (cm)
  - SZA (cm/mm)
  - CARMA/SZA (mm)
  - ALMA (mm/submm)
- Proposed
  - LWA/LOFAR (m)
  - FASR (m/cm)
  - SKA (m/cm)

Expanded VLA - EVLA

- VLA – 27 x 25m reflectors, Y array arms up to 22 km long
- Built in 1970s, dedicated 1980
- Limited upgrading since original construction

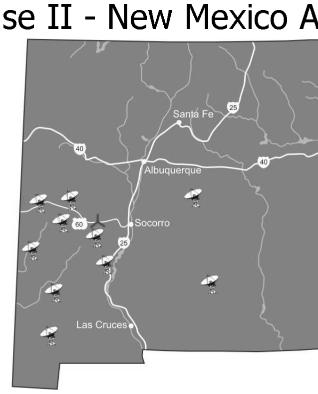
EVLA Goals

- Use modern technology to obtain an order of magnitude improvement in most VLA observational capabilities
  - Continuous frequency coverage 1-50 GHz
  - 8 receiver bands, new LO system
  - Up to 16 GHz bandwidth per antenna
  - New IF system (8 x 2GHz), fiber optic digital transmission
  - New wideband, high spectral resolution correlator
  - New monitor/control and data processing systems
- Maintain VLA science during the decade-long upgrade

EVLA Performance

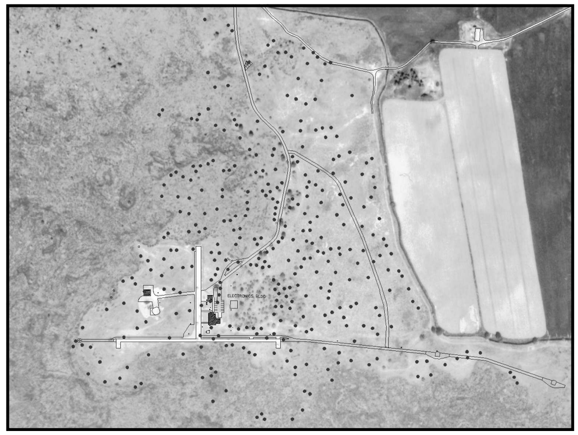
	VLA	Phase 1	Phase 2
Point source sensitivity	10 μJy	0.8 μJy	0.6 μJy
No. baseband pairs	2	4	4
Maximum bandwidth in each pol'n	0.1 GHz	8 GHz	8 GHz
No. frequency channels, full BW	16	16384	16384
Max. frequency channels	512	16384 [262144]	16384 [262144]
Max frequency resolution	381 Hz	~1 Hz	~1 Hz
(Log) Frequency coverage 0.3-50 GHz	25%	75%	100%
No. baselines	351	351	666
Spatial resolution @ 5 GHz	0.4″	0.4″	0.04″

Phase II - New Mexico Array

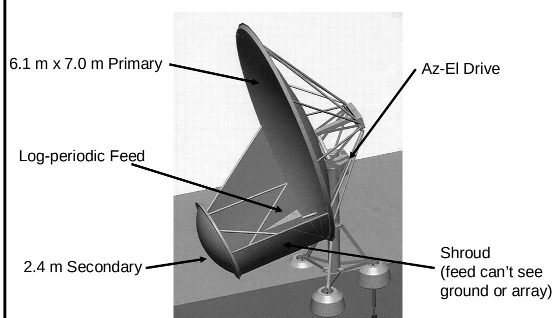


The Allen Telescope Array

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



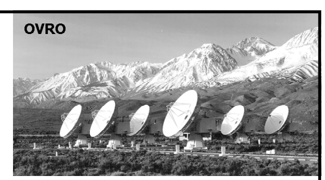
Offset Gregorian Antenna



ATA Science

- SETI
  - 100,000 FGK stars
  - Galactic plane survey (2nd generation DSP)
- HI
  - All sky HI, z < 0.03, Milky Way at 100 s
  - Large area to z ~ 0.1 or more
  - Zeeman measurements – magnetic field
- Temporal Variables
  - Pulsar Timing Array
  - Pulsar survey follow-ups
  - Extreme Scattering Events
  - Transients (e.g. gamma ray bursts)

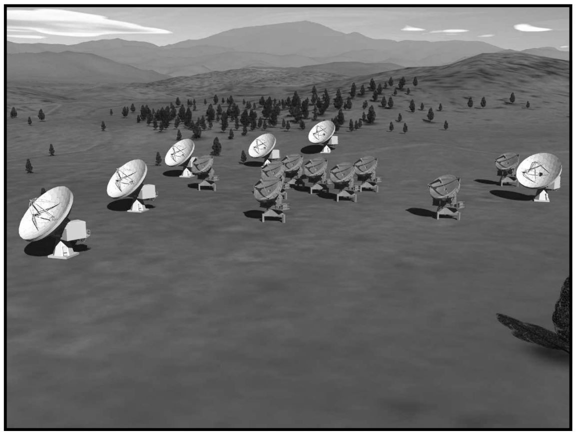
Caltech
Six 10.4 m dishes



CARMA

Berkeley – Illinois – Maryland
Nine 6.1 m dishes

Chicago
Eight 3.5 m dishes



key features

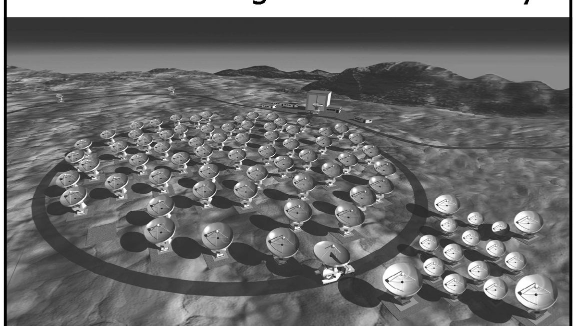
- Heterogeneous array (850 m²) at new 2200m site
  - six 10.4m antennas - OVRO
  - nine 6.1m antennas - BIMA
  - eight 3.5m antennas - SZA
- Frequency: 22-30GHz, 70-118 GHz, 220-270 GHz
- Arrays: four configs: 100m – 2000m + SZA
- Imaging over wide range of angular scales:
  CARMA: 0.15-30”, SZA: 30-180”
- More antennas ⇒ High-fidelity imaging + snapshot
- Mosaicing (point-click + OTF)

Millimeter science

- Studies of circumstellar/protoplanetary disks, stellar outflows, stellar winds from evolved stars
- Examine SF environments of nearby & distant galaxies
- Explore Solar System: Sun, planets, comets, KBOs
- Probe astrochemistry of ISM, IPM
- Image distant universe: CO/SF in high-redshift galaxies
- Cosmology experiments – SZ, CMB polarization

ALMA
ATACAMA LARGE MILLIMETER ARRAY

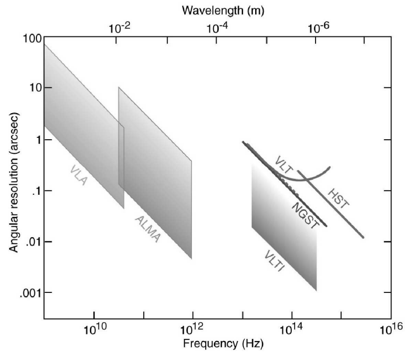
Atacama Large Millimeter Array

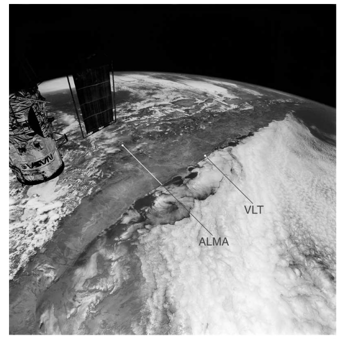


Most Compact configuration. Baseline extendible up to 14 km

ALMA

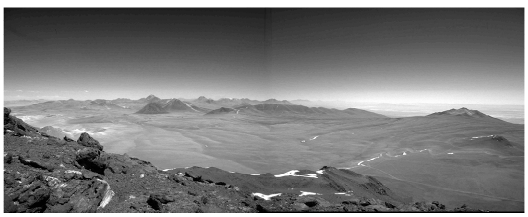
Antennas	64 x 12 m
Collecting area	>7000 m^2
Resolution	0”.02 λ_{mm}
Receivers	10 bands: 0.3 – 7 mm (36 - 850 GHz)
Correlator	2016 baselines
Bandwidth	16 GHz/baseline
Spectral channels	4096 per IF (8 x 2 GHz)





View of Northern Chile (NASA Space Shuttle)

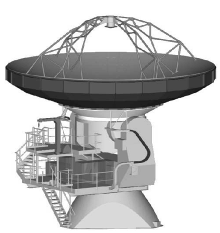
ESO PR Photo 24b/99 (8 June 1999) © ESO - ESA - Claude Nicollier

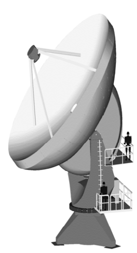


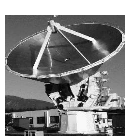
ALMA
TACAMA LARGE MILLIMETER ARRA

ALMA Science

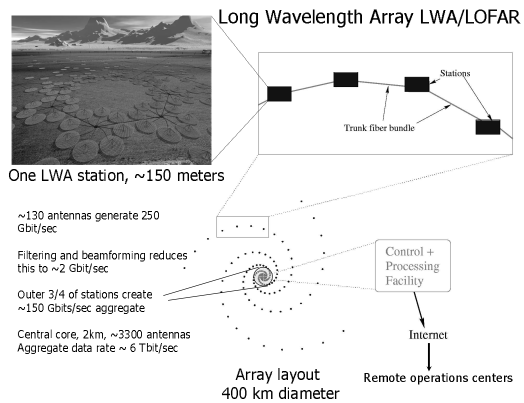
- Formation of galaxies and clusters
- Formation of stars
- Formation of planets
- Creation of the elements
  - Old stellar atmospheres
  - Supernova ejecta
- Low temperature thermal science
  - Planetary composition and weather
  - Structure of Interstellar gas and dust
  - Astrochemistry and the origins of life







Long Wavelength Array LWA/LOFAR



Low Frequency Science Targets

- **Redshifted HI from the Epoch of Reionization**
- High-z starbursts
- Galaxy clusters and the IGM
- Cosmic ray distribution, and airshower radio bursts
- **Steep spectrum and fossil radio galaxies**
- Supernova remnants and ISM energy budget
- Interstellar recombination lines
- Nearby pulsars, ghost nebulae
- Extrasolar gas giant planetary radio emission
- Stellar flares
- **Interstellar medium propagation effects**
- Transients, GRB and LIGO event counterparts, buffering
- Solar radio studies
- **CME detection, mapping by IPS, scattering**
- Extremely high resolution ionospheric tomography
- Passive Ionospheric Radar

Frequency Agile Solar Radiotelescope (FASR)

- Of order 100 antennas (5000 baselines)
- Better than 1" imaging at 1s time resolution
- Full frequency coverage 0.1-30 GHz
- Designed Specifically for Solar Imaging
  - Full Sun (to at least 12 GHz)
  - Designed for solar spatial scales
  - Designed for solar brightness variability

Square Kilometer Array - SKA

Next generation "discovery" telescope in the meter to centimeter wavelength region with

- 100 x sensitivity of EVLA
- large instantaneous field of view
- new modes of operation (multiple simultaneous users - multibeaming)

→ extremely powerful survey telescope with the capability to follow up individual objects with high angular and time resolution

SKA Design Goals

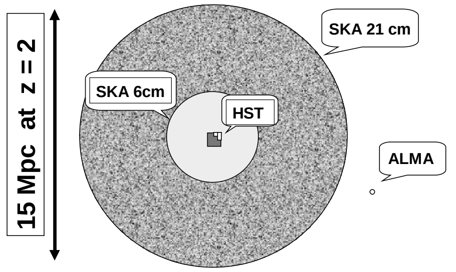
Sensitivity	$A_{eff}/T_{sys} = 2 \times 10^4$ m^2/K
Surface brightness sensitivity	1K at 0.1 arcsec (continuum)
Frequency range	0.15 – 22 GHz
Redshift coverage	z<8.5 (HI); z>4.2 (CO (1→0))
Imaging field of view	1 deg^2 at 1.4 GHz
Multi-beam capability	N_{beams}>100
Angular resolution	<0.015 arcsec at 1.4 GHz
Number of spatial pixels	>10^8
Instantaneous bandwidth	0.5 + frequency/5 GHz
Number of spectral channels	>10^4
Image dynamic range	10^6
Polarisation purity	40 dB

SKA scientific drivers

- **Dark Ages and Epoch of Re-ionization**
  - **ionization of neutral IGM**
  - **properties of first luminous objects**
- **Large Scale Structure in the Universe**
  - **dark energy as function of redshift**
- Evolution of galaxies
  - genesis of black holes
  - star formation rate
- Probing Gravity through pulsars
  - black hole binary as probe of strong gravity
  - low-frequency gravity wave background
- Origin and evolution of Cosmic Magnetic Fields
  - large scales, primordial fields
  - small scales, turbulence & dynamos
- Transient universe
- Protoplanetary disks

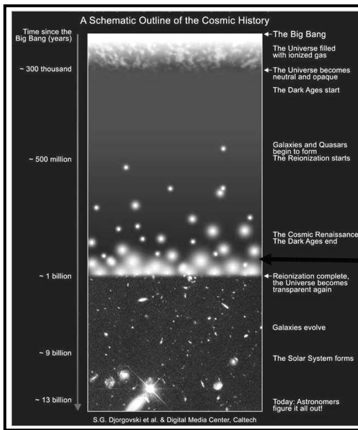
1 deg^2 (minimum) field-of-view

for surveys and transient events



Dark energy

- Alters distance measures in cosmology incl. evolution of Hubble parameter with time and growth of structure
- Power spectrum of the clustering of galaxies (angular/redshift) likely to contain a signature of acoustic oscillations at time of recombination
- Use scale of acoustic oscillations as a cosmological standard ruler to measure equation of state of dark energy at intermediate redshift and possibly its evolution. $1<z<2$ optimal.
- SKA: In 360 hours and a 4 deg^2 FOV (@1.4) SKA will detect ~2x10^6 HI galaxies. It can then cover 'whole' sky in ~5 years with 8 simultaneous FOVs.



History of IGM

Epoch of Reionization (EoR)

- **Bench-mark in cosmic structure formation indicating the first luminous structures**
- **Search for HI spectral signature…… tough….**

Achieving the SKA

- Reduce overall cost per m^2 of collecting area by a factor ~10 cf. current arrays

  while…

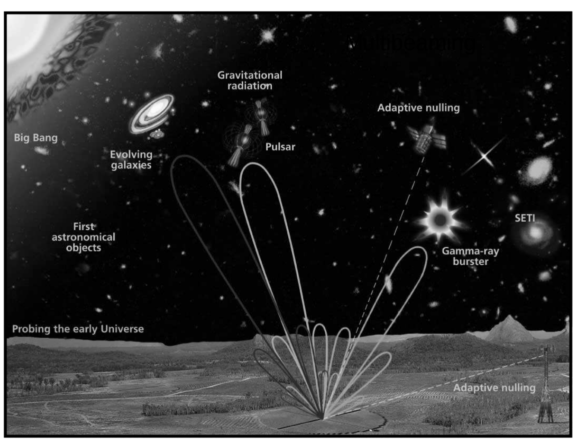
- Maximising flexibility of design

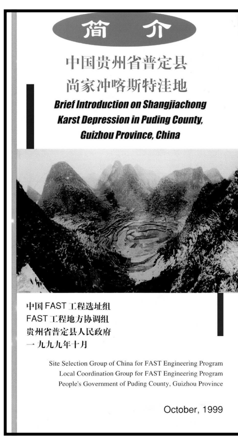
  And…

- Minimising maintenance/running costs

→Take advantage of massive industrial R&D in fibre optics and electronics industries ("Moore's Law" to ~2015) for transport and handling of data

→ Develop innovative, cost effective, new concepts for collectors





简 介

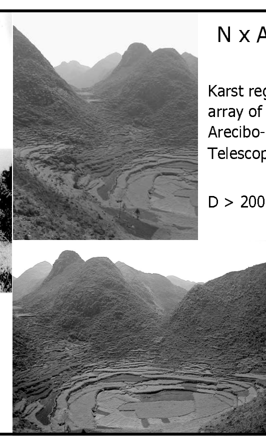
中国贵州省普定县
尚家冲喀斯特洼地

Brief Introduction on Shangjiachong Karst Depression in Puding County, Guizhou Province, China

中国FAST工程选址组
FAST工程地方协调组
贵州省普定县人民政府
一九九九年十月

Site Selection Group of China for FAST Engineering Program
Local Coordination Group for FAST Engineering Program
People's Government of Puding County, Guizhou Province

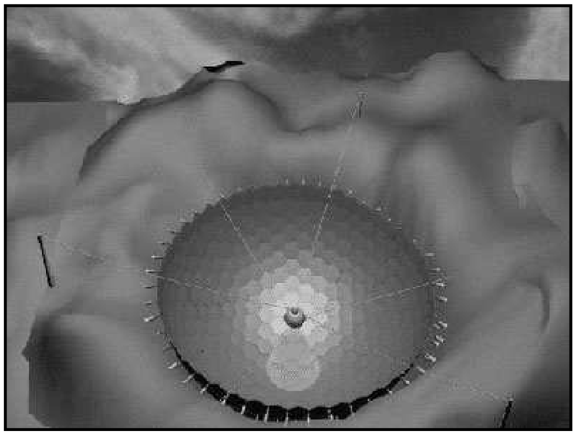
October, 1999



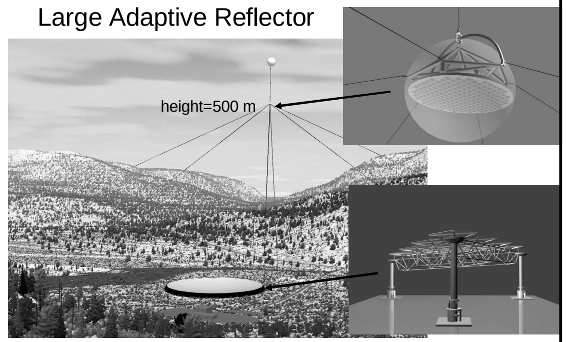
N x Arecibo

Karst region for array of large Arecibo-like Telescopes

D > 200 m



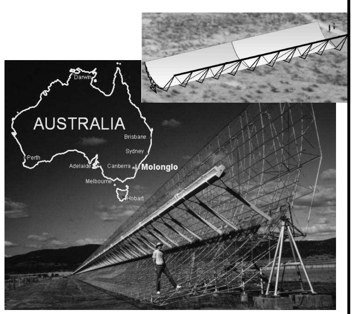
Large Adaptive Reflector



- 150-200m diameter stations
- large F/D
- focal platform supported by aerostat
- almost flat panels
- 150 MHz to 22 GHz
- DRAO, U Calgary

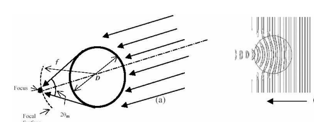
Cylindrical reflector

- 111x15 m elements
- 600 elements
- 100 MHz - >9 GHz
- multifielding possible



Luneberg lenses

- 7 m spheres
- in patches 180 m in diameter
- 300 patches
- CSIRO/ATNF

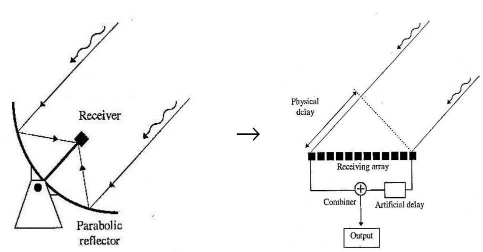


Large N small D: the Allen Telescope Array

- SETI Institute
- UC Berkeley
- 100m equivalent
- 350 x 6.1 m parabolas
- 0.5-11 GHz (simultaneously)
- 2.5^{o} FOV at 1.4 GHz
- 4 simultaneous beams
- 206 antennas in 2005

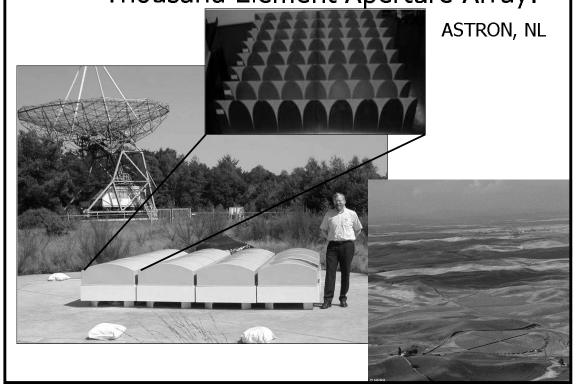
Phased array concept

Basic idea: replace mechanical pointing & beam forming by electronic means



Thousand Element Aperture Array:

ASTRON, NL



SKA

- Initial site analyses submitted by Australia, China, South Africa, and USA in May 2003
- Initial site analysis by Brazil in preparation
- RFI and tropospheric stability testing at candidate sites in 2004-5
- Technology decision – 2007/2008
- Construction – 2012+

Summary

- Future: Radio astronomy ↔ Interferometry
- Current arrays going strong, new arrays under development (mm)
- Importance of any field can grow rapidly, multiple routes to knowledge valuable…
- Challenges – cheap collecting area, data transport & processing, public outreach, international collaboration (imho)
- Understanding of techniques, limitations, possibilities important – summer school

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