Extragalactic Science

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Outline

- Scaling Laws
- Starbursts and Supernovae
- Active Galactic Nuclei
- Astrometry
- High-Redshift Galaxies

Some Angular Scaling Laws

- Nearby starburst galaxies at 3-4 Mpc
  - 1 arcsecond = 15-20 pc
- The Virgo Cluster or AGNs at 15-20 Mpc
  - 1 arcsecond = 75-100 pc; 1 mas = 0.7 pc
- Cygnus A at 225 Mpc
  - 1 arcsecond = 1.1 kpc
- Active galaxies at z=0.5 to 2
  - 1 mas = 5-7 pc
- Star-forming galaxies at z=2
  - 1 arcsecond = 7 kpc

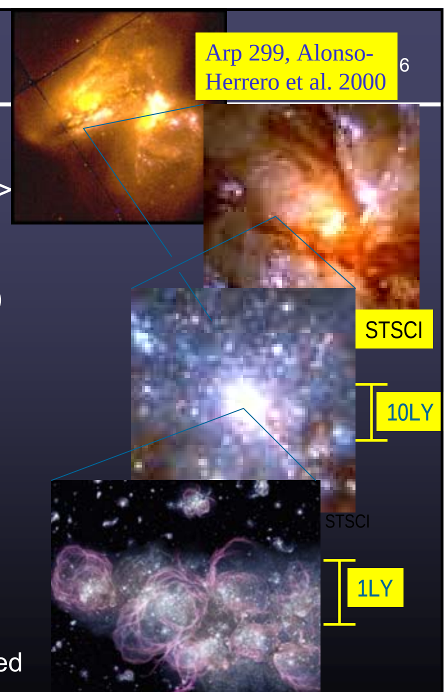
Starbursts and Supernovae

Starburst Galaxies, Supernovae

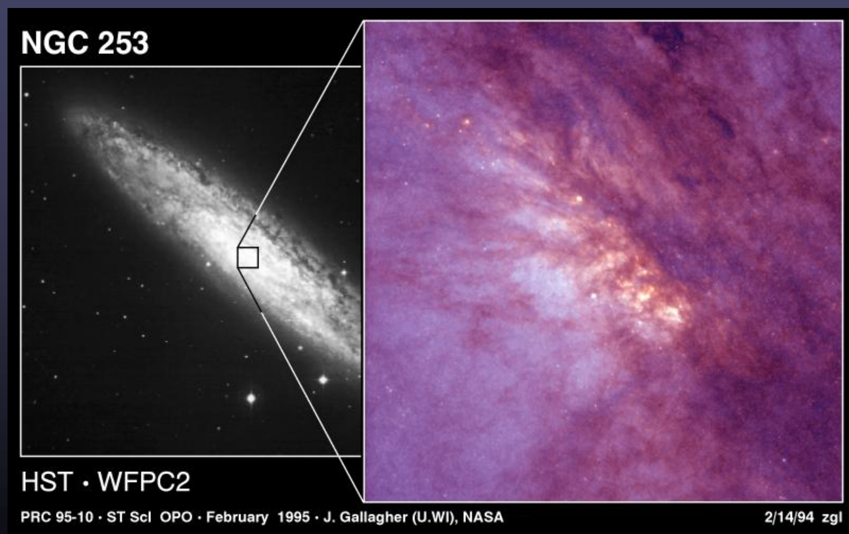
- Starburst galaxies have star-formation intensities of 1-100 M_{Sun} yr^{-1} kpc^{-2}
  – ~1000 times higher than in Milky Way
- Starbursts often are stimulated by galaxy mergers or close passages
- Radio emission is thermal emission from HII regions ("super star clusters") or nonthermal emission from supernova remnants
  – Correlated with Far-Infrared emission
  – Starbursts younger than a few Myr are dominated by thermal radio emission

Star Formation Inside a Starburst

- High mass stars dominate (M > few M_{sun})
  – Ultraviolet (UV)-bright
  – Short lifetimes (few million years)
  – Explode as supernovae
- Stars preferentially form in clusters
  – Young globular clusters?
  – Dense stellar environment
  – Million + stars, in <10LY
- Interstellar Medium is Very Dense
  – Obscures direct view of stars
  – Supernova remnants stay confined

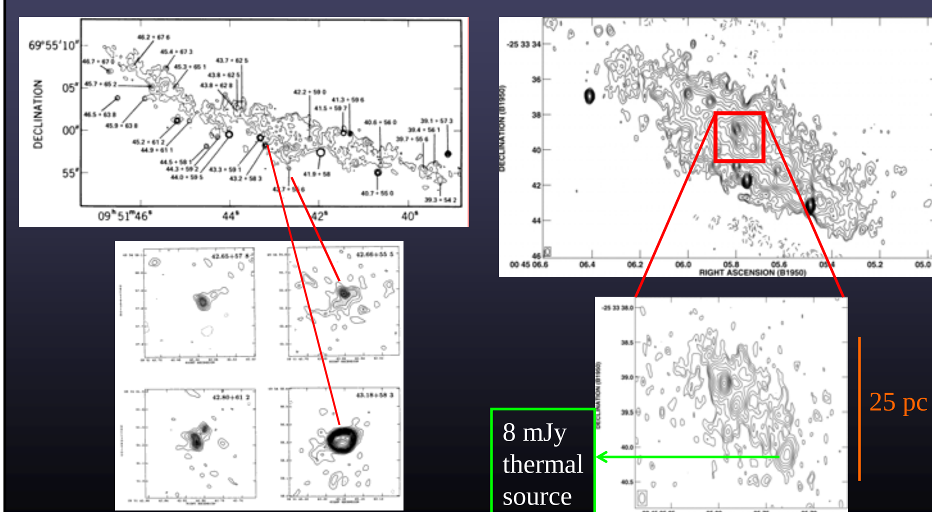


Starburst Galaxy NGC 253, 3 Mpc Distance



Nearby Starbursts

- M82 (Kronberg et al. 1985; Muxlow et al. 1994+)
- NGC 253 (Ulvestad & Antonucci 1997)

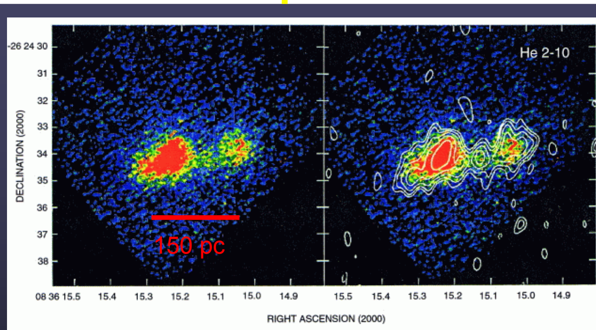


Results from M82, NGC 253

- Little or no source variability
- Steep spectrum sources resolve into SNRs
- Flat-spectrum sources typically H II complexes energized by hot stars
  - At a distance of 2.5 Mpc, 1 mJy of thermal radio flux corresponds to ionizing flux of about 10^{51} photons/s; 10^{49} photons/s = 1 O7 star

    $N(UV)/s = 10^{51}\ (D/2.5\ \mathrm{Mpc})^2\ (S_{5\ \mathrm{GHz}}/1\ \mathrm{mJy})$
  - Strongest NGC 253 thermal source is 8 mJy
    - 750 O7-equivalent stars in a few parsecs

Super Star Clusters



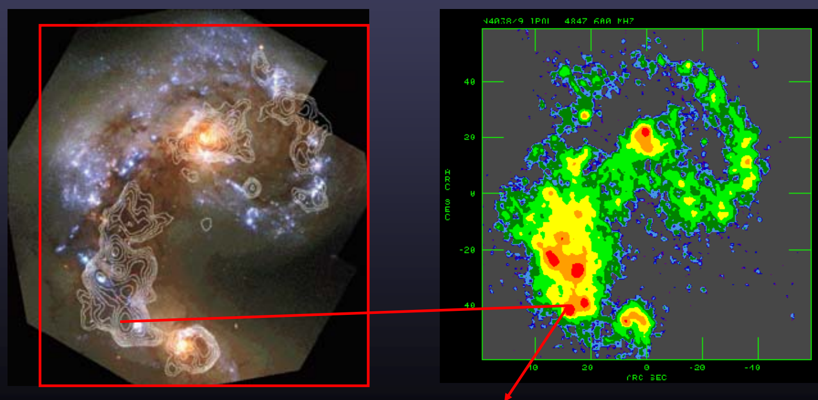
Beck, Turner, & Gorjian 2001

Left: mid-IR image
Right: 2-cm radio contours overlaid (from Kobulnicky & Johnson 1999)

- Often appear in dwarf galaxies
- Can account for most of the host's radio and mid-infrared emission
- Typically heavily obscured, with optically thick thermal emission
- Proto-globular clusters?

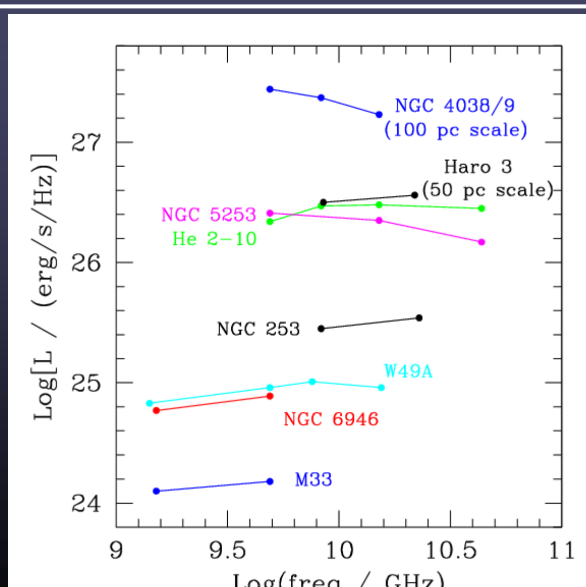
Nearest Merger—The “Antennae”

- WFPC2, with CO overlay (Whitmore et al. 1999; Wilson et al. 2000)
- VLA 5 GHz image (Neff & Ulvestad 2000)



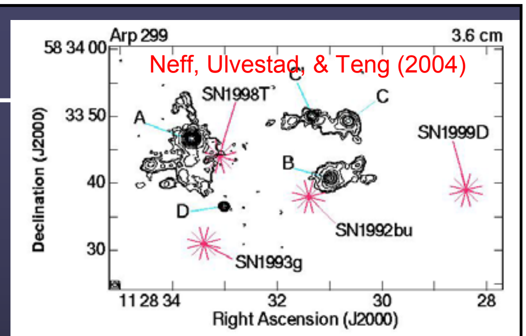
5 mJy 30,000 O7-equivalent stars

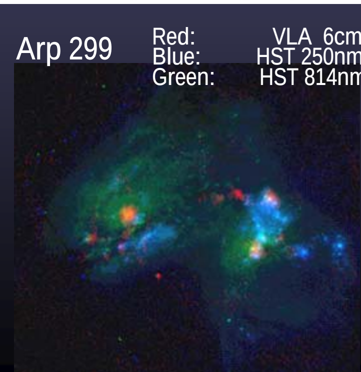
SSC and Related Radio Sources



Arp 299 Radio Emission

- No radio emission at optical SN positions
- Four Strong Radio Peaks
  - A and B: galaxy nuclei
  - C and C': overlap region
- Alonso-Herrero et al. IR/opt. (2000)
  - Assume starbursts Gaussian in time, 5 Myr wide, peak 5 Myr after start
  - A: 7 Myr post-peak, 0.6 SN/yr
    - 700 million solar masses in young stars
    - 140 solar masses/yr in star formation
  - B1: 5 Myr post-peak, 0.1 SN/yr





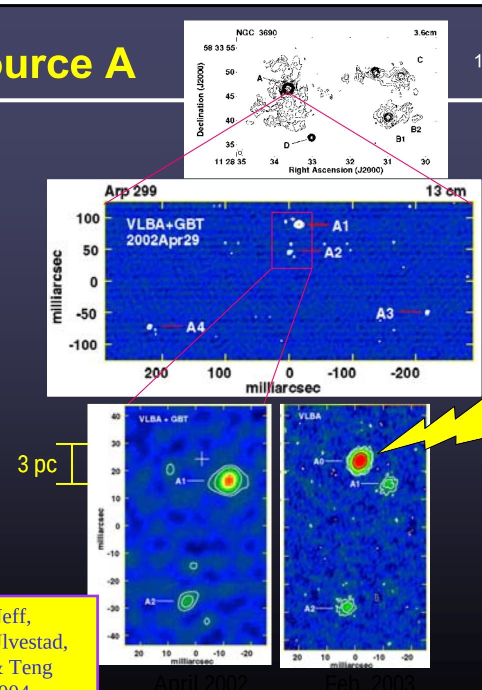
Arp 299: Inside Source A

VLBA+GBT

A "nest" of four young SNe, within 100 pc

and

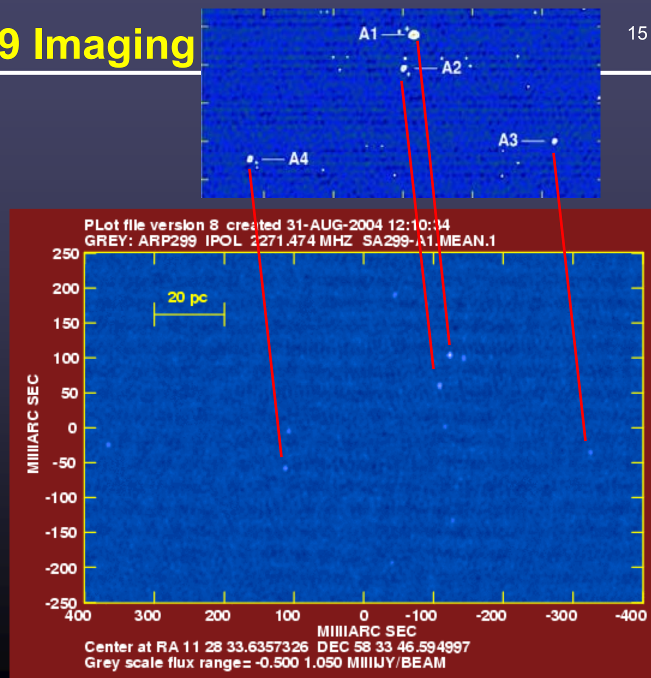
A young supernova, only 2 pc from one of the other sources
- ➢Tracing super-star clusters?



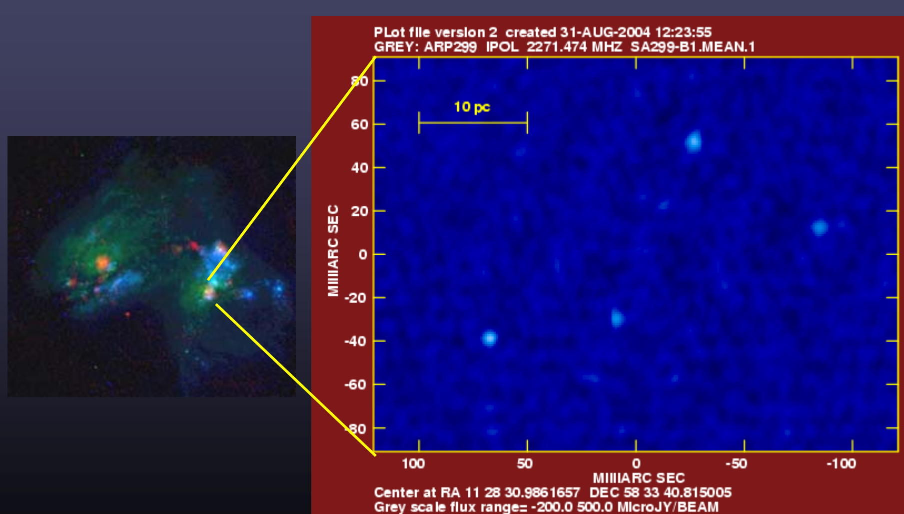
Neff, Ulvestad, & Teng 2004

More Arp 299 Imaging

- More VLBA + GBT imaging
- 2.3, 8.4 GHz from 2003 through 2005
- Total of 15 SNe at 2 and 8 GHz

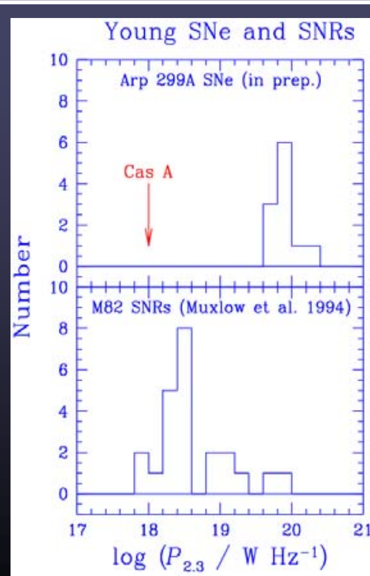


Inside Source B1, 2nd Nucleus



Beginning of a Luminosity Function

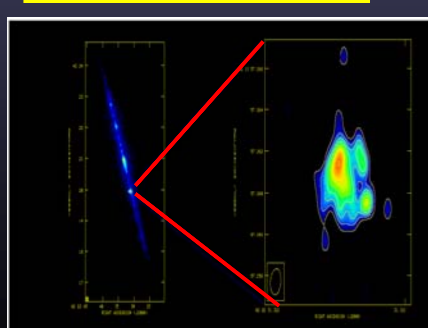
- Arp 299-A SN rate is believed to be about 6 times M82.
  - Accounting for incompleteness, looks okay within a factor of two

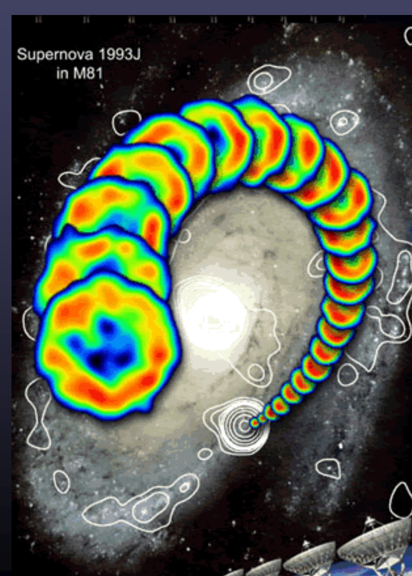


VLBI Imaging of Nearby Supernovae

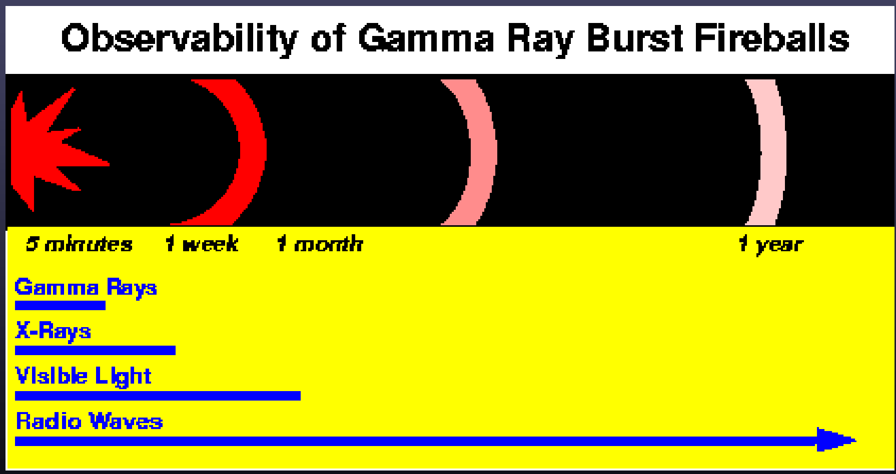
- 1993J in M81
- 1986J in NGC 891

Bietenholz, Bartel, & Rupen



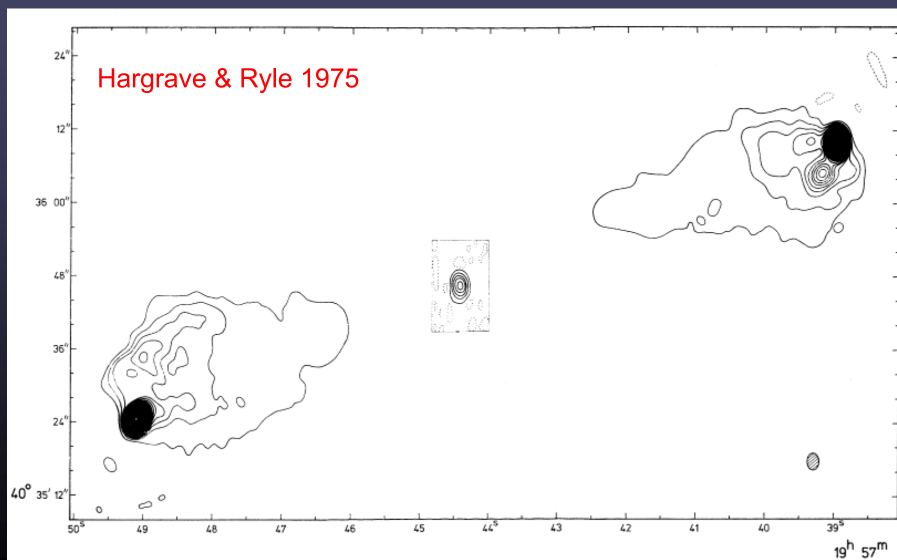


Cataclysmic Explosions in Distant Galaxies

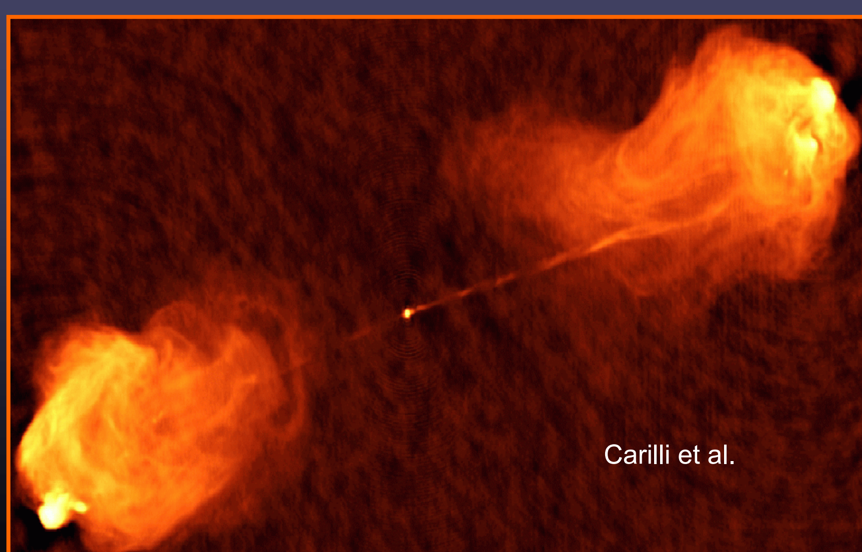


Active Galactic Nuclei

Radio Galaxy Cygnus A: Pre-VLA



Cygnus A Imaged by the VLA

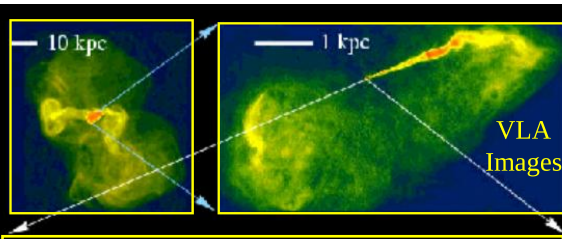


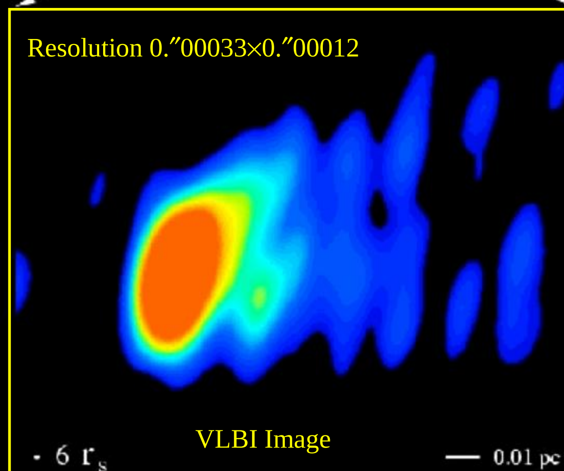
M87

Base of Jet

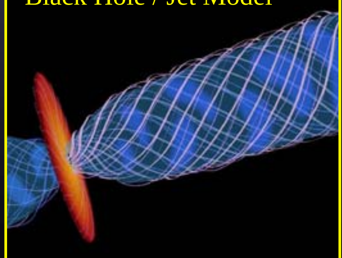
43 GHz Global VLBI

Junor, Biretta, & Livio
Nature, 401, 891



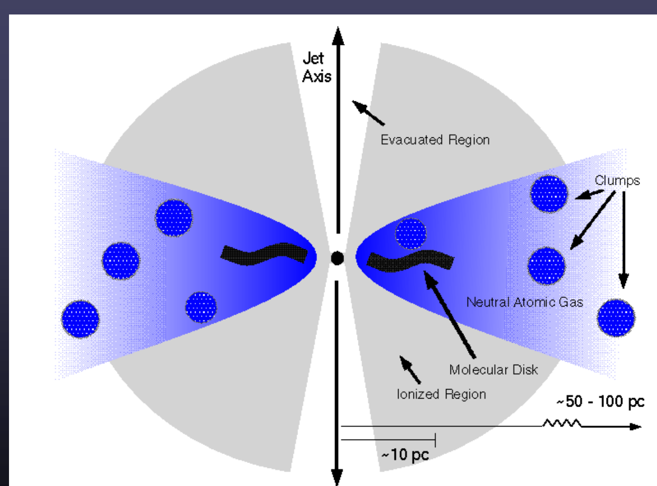


Black Hole / Jet Model



AGN Unification (Antonucci ARAA 1993)

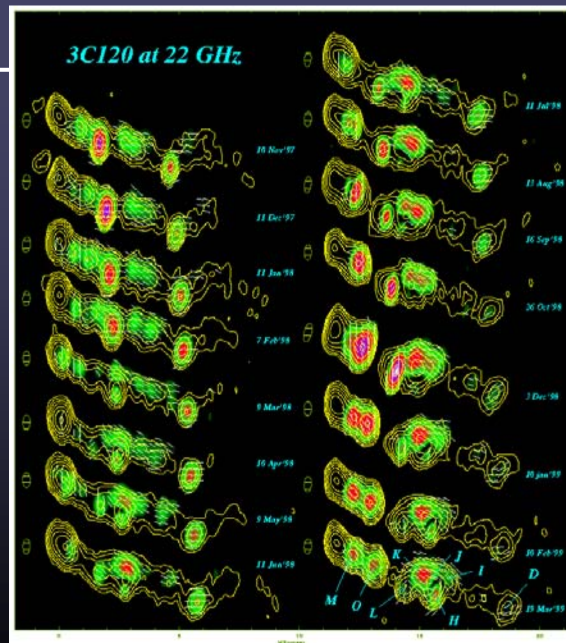
- Broad-line AGN (Type 1) if seen down the jet axis
- Narrow-Line AGN (Type 2) if seen from the side



Peck, Taylor, & Conway 1999

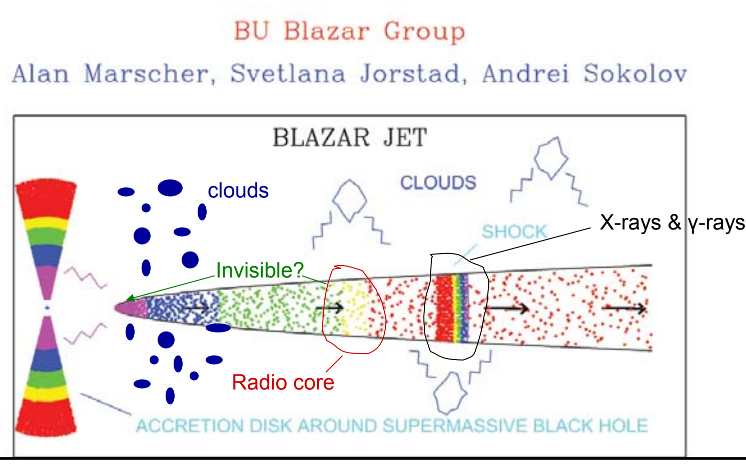
3C120

- Apparent superluminal motion
- Tracing evolution of a jet from a supermassive black hole
- Components "hit" gas clouds
  - Brighten and deflect



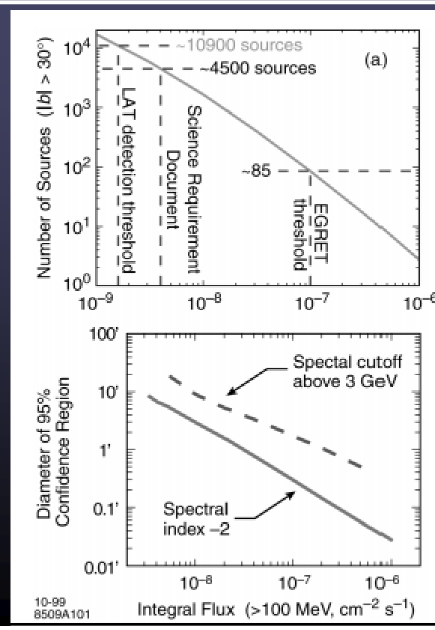
Gomez et al. 2000

Where Most X-rays & γ-rays Are Emitted



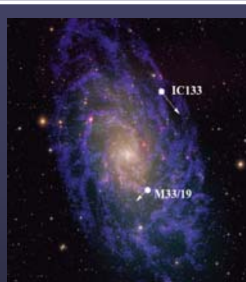
GLAST LAT Source Count Predictions

- GLAST gamma-ray satellite due for launch in late 2007
- LAT will detect several thousand sources with 1-10 arcmin position errors
- Density of flat-spectrum radio sources above 30 mJy is 1-2 per square degree
  - VLA identification
  - VLBA imaging of flares

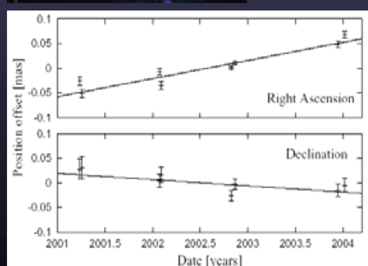


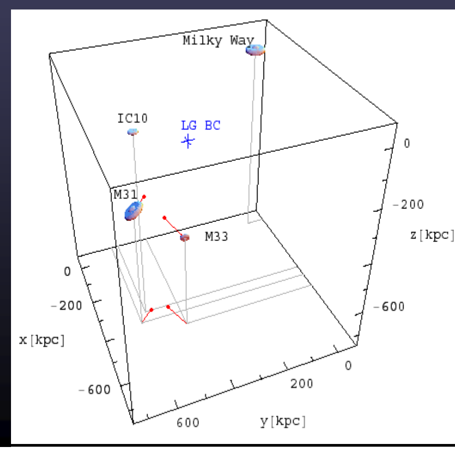
Astrometry

Local Group Motion-M33



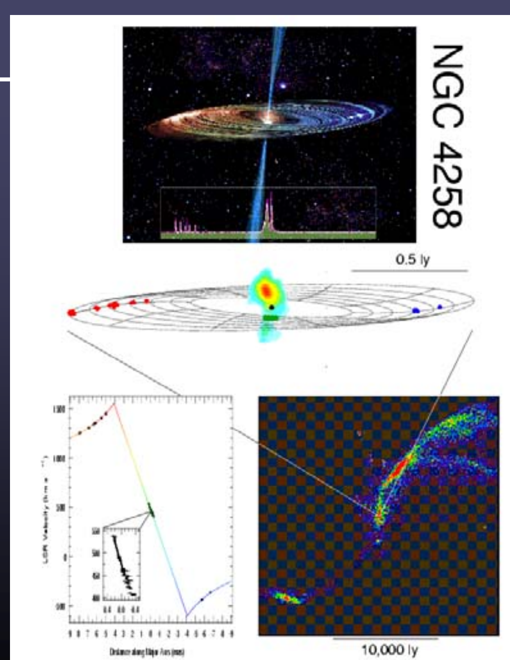
- VLBA astrometry of H_2O in M33
- Angular rotation + proper motion
- Mass + dark-matter halos in Local Group



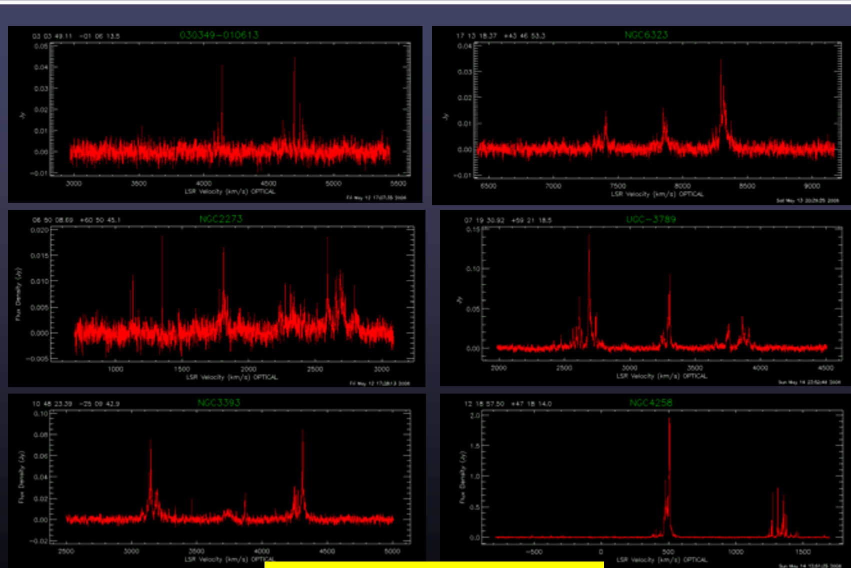


NGC 4258

- Water megamaser emission associated with nuclear torus
- Direct measurement of BH mass in galaxy at 7.4 Mpc
- Calibration anchor for distance scale of the Universe



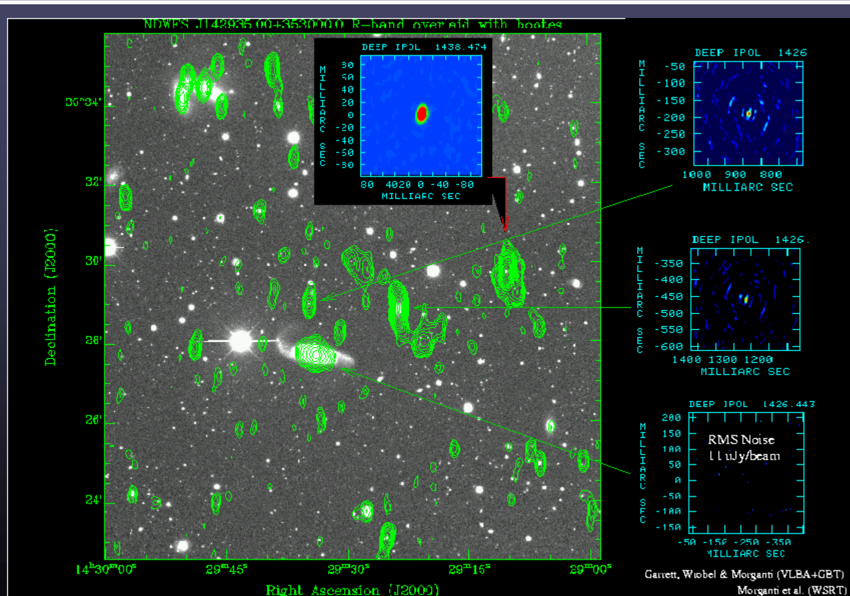
GBT Spectra of Maser Disks

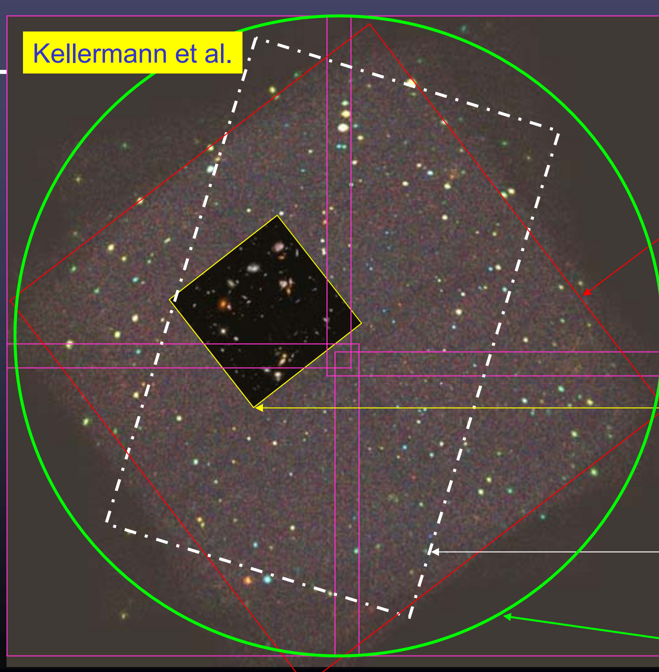


Braatz et al., in preparation

High-Redshift Galaxies

NOAO Deep Field: AGNs or Starbursts?





Chandra Deep Field South

942 ks exposure
361 X-ray sources
5×10^{-17} ergs/sec

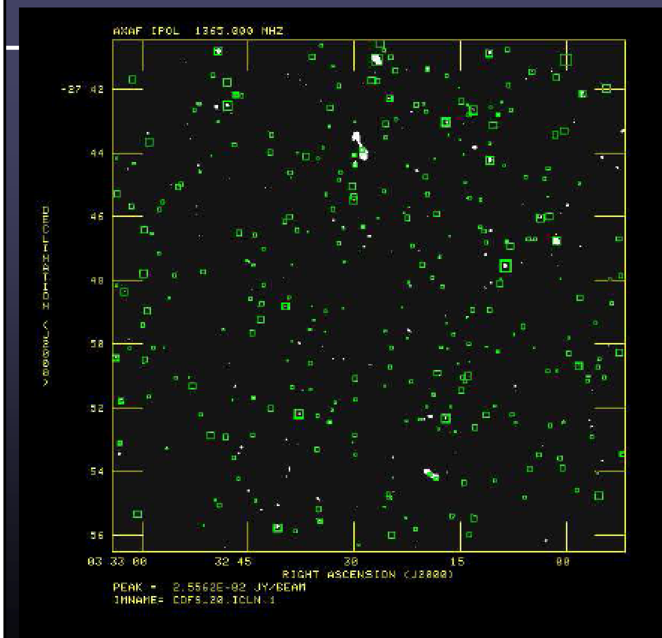
Extended CDFS
250 ks per field

Hubble UDF
976 ks exposure
B, V, I, z
10,000 galaxies
I < 29

GOODS ACS
B, V, i, z
I < 28

VLA 20 cm

VLA Observations of CDFS



6 and 20 cm 35

θ = 3.5 arcsec

σ = 8-11 μJy

266 Radio sources

198 Sources in Complete sample
S_{20} > 40 microJy
Within CDFS

57 in CDFS X-ray list
74 additional in ECDFS

Extragalactic "Blank Field" VLA Programs 36

- VLA is the telescope of choice for deep radio integrations of various extragalactic fields
- Made a special proposal call for current VLA cycle, for 40-200 hr proposals

AM857	A Deep & Unbiased Probe of Star Formation in the GOODS Northern Field	VLA A	2006	77 hr	G. Morrison
AO201	The SWIRE Deep Field at 90cm: A Steep Spectrum MicroJy Radio Population?	VLA A,C	2006	66 hr	F. Owen
AS859	Follow-up of the COSMOS 1.4 GHz Imaging Survey: Identification of Dusty Massive Starforming Systems	VLA A	2006	60 hr	E. Schinnerer
AY164	An In-depth Investigation of the Nature of the Faint 24 Micron Spitzer Sources and 1100 Micron AzTEC Sources in the FLS Verification Strip	VLA A,B	2006	96 hr	M. Yun

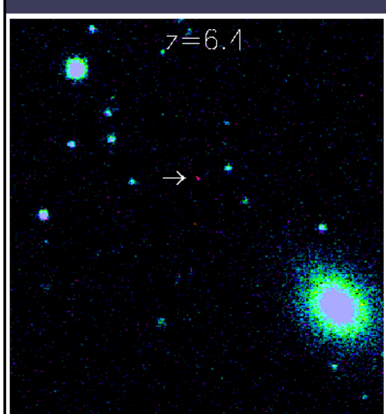
VLA Low-frequency Sky Survey

- 74 MHz VLA survey of sky north of -30 deg.
- Newly discovered steep-spectrum radio sources may yield some very distant radio galaxies

Perley et al., in prep.

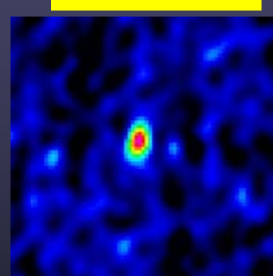
The Most Distant Quasar

- Optical Image



SDSS Discovery Image of J1148+5251: Quasar is Red Dot Pointed Out by Arrow

Walter et al. 2003

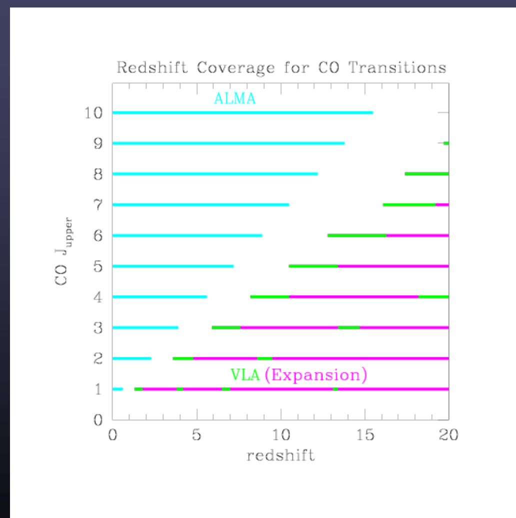


- VLA image of CO from the first known star formation
  - Redshifted to 46 GHz

- Artist's conception of disk of molecules and dust

EVLA and ALMA

- Continuous frequency coverage from 1 GHz to 50 GHz
- Detect CO at almost any redshift
- Study excitation of star-forming gas in distant galaxies



Scaling Arp 220 to High Redshift