GOODS in FIR and Radio

Urmas Haud

FIR and Radio

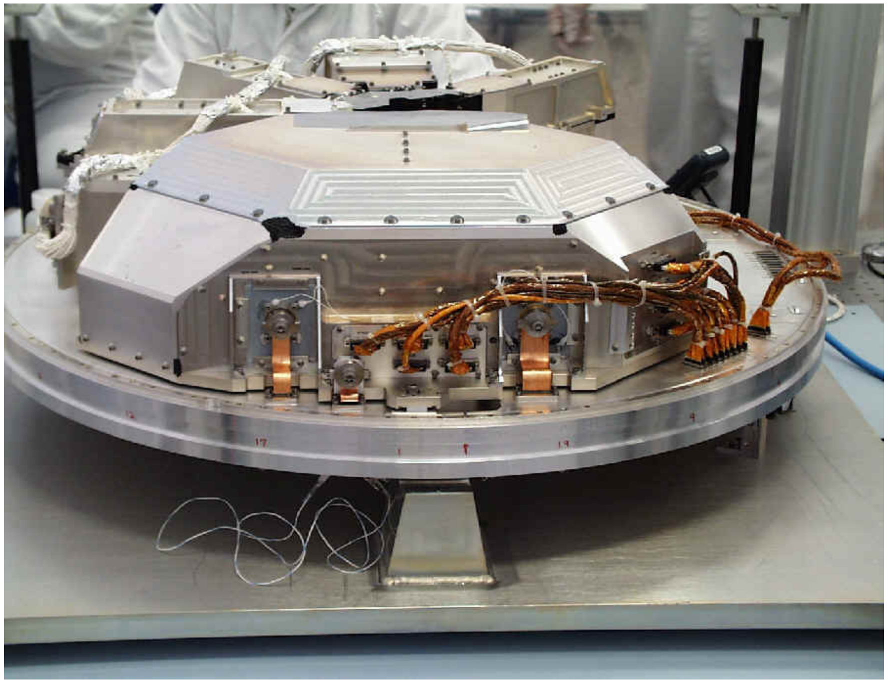
- $\lambda \geq 30\ \mu m$ ($\lambda \geq 24\ \mu m$)
  - Sub-mm ⇒ Mihkel Jõeveer
- Source counts in the HST images are considerably greater than at other wavelengths
- 10-20% of the faint radio, IR and X-ray detections have no obvious optical counterparts
- Heavily obscured in the optical
  - AGN
  - Star-forming galaxies
- Substantial fraction of the total radiation in the Universe is emitted from these obscured systems
- A view of the high redshift, **dusty Universe**

From GOODS Abstract

- The Multiband Imaging Photometer (MIPS) for the Space Infrared Telescope Facility (SIRTF) Guaranteed Time Observer (GTO) survey will complete the SIRTF census by observing these fields to the confusion limit at 70 and 160μm. (http://mips.as.arizona.edu/mipspage/)
- The GOODS fields are already the most data-rich portions of the sky for studying the distant universe, with extremely deep X-ray and radio data, sub-mm observations, extensive optical and near-infrared imaging, and a wealth of faint galaxy spectroscopy.
- Ultra violet, mid- and far-infrared, sub-mm, radio, and Balmer line observations all provide windows on star formation at high redshift.

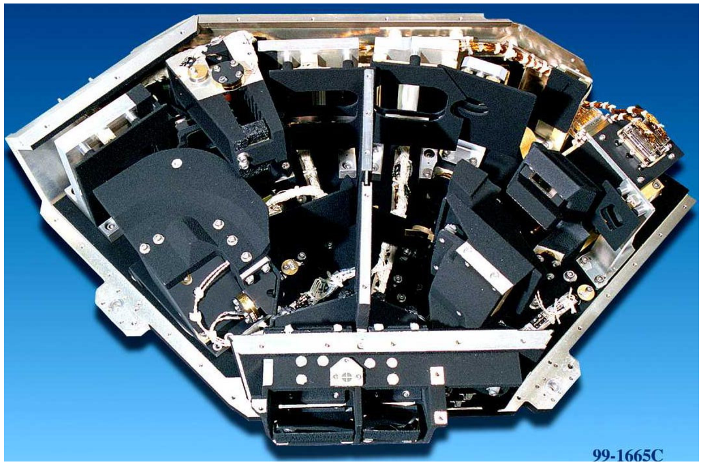
The MIPS: Instrument

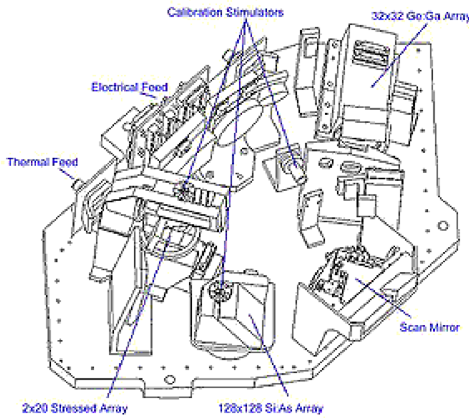
- It is designed to provide very deep imaging and mapping at 24, 70, and 160 microns.
- In integrations of 2000 seconds, it will reach a 5-sigma detection limits at these wavelengths of 0.2, 0.5, and 8 mJy, respectively
- It will also measure low-resolution (R = 15-25) spectral energy distributions between 50 and 100 microns.
- The field of view varies from about 5x5 arcmin at the shortest wavelength to about 0.5x5 arcmin at the longest wavelength.



The MIPS: Detectors

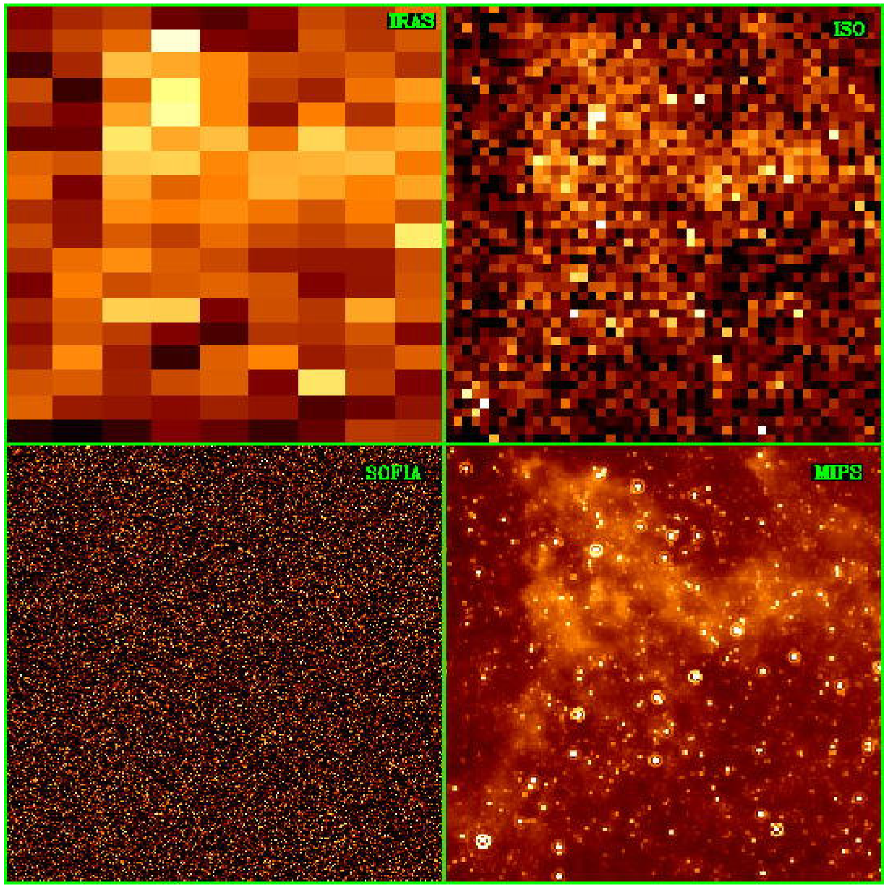
- 128x128 arsenic-doped silicon (Si:As) array, operating at a wavelength of 24 microns and with a 5 arc-minute field;
- 32x32 gallium-doped germanium (Ge:Ga) array for 70 microns and a 5 arc-minute field;
- 2x20 Ge:Ga array, mechanically stressed to extend photoconductive response to 200 microns, with a field of 0.5x5 arc-minutes.
- On-board calibrators for each array.
- A scan mirror to provide mapping with efficient use of telescope time.





The MIPS: Comparison

- IRAS: very large pixels.
- ISO: better spatial resolution but limited by the small field-of-view and low sensitivity.
- SOFIA: excellent spatial resolution but a correspondingly small field-of-view and limited in sensitivity because of warm optics.
- MIPS: performance on the test field is excellent because of the high sensitivity of the detectors, good spatial resolution, and the large field-of-view.



Introduction: CIB

- As much as one third of the luminosity of the local universe is emitted in the far infrared.
- In order to understand the history of energy release in the universe, it is crucial to characterize this rest-frame far-infrared contribution from the present back to the era of initial galaxy formation.
- Over the redshift range from 0 to 10, this energy is received in the 80 μm to 1 mm spectral region.
- To develop a clear history of energy release in the universe, we need numbers and redshifts of representative populations of energetically important objects.
- Observing the sources contributing to the Cosmic Infrared Background (CIB) has become one of the most rapidly evolving fields in observational cosmology since the discovery of the CIB in 1995/6.

Introduction: Sources

- Dole, H.; Lagache, G. & Puget, J.-L. (2003; Ap J., Vol. 585, pp. 617-629.) computed the redshift distributions of the MIPS detected sources at each wavelength and show that they extend
  - up to z~2.7 at 24 μm and
  - up to z~2.5 at 70 and 160 μm,

  leading to the resolution of at most
  - 69% of the CIB at 24 μm,
  - 54% at 70 μm, and
  - 24% at 160 μm,

  respectively.
- Therefore, deep observations in FIR together with observations at other wavelengths for source identification, begin to provide a global view of galaxy evolution.

The MIPS: Surveys

Survey	Mode	Area (deg^2)	Integration time (s)		
			24 µm	70 µm	160 µm
FLS[a]	Scan	5.00	80	80	8
FLS[a] **verification**	Scan	0.25	400	400	40
Legacy SWIRE[b]	Scan	65.00	80	80	8
Legacy GOODS[c]	Photometry	0.04	36000		
GTO[d] **Shallow**	Scan	9.00	80	80	8
GTO[d] **Deep**	Scan	2.45	1200	1200	120
GTO[d] **Ultra Deep**	Photometry	0.02	14700	12500	
GTO[d] **Cluster**	Photometry	0.20	3300	400	80

[a] First Look Survey

[b] The SIRTF Wide-Area Infrared Extragalactic survey

[c] The Great Observatories Origins Deep Survey

[d] Guaranteed Time Observer program

FLS (http://ssc.spitzer.caltech.edu/fls/)

The First Look Survey (FLS) will provide a characteristic "first-look" at the mid-infrared sky at sensitivities that are ≈100 times deeper than previous systematic large-area surveys.

The FLS is composed of:

- extragalactic,
- galactic, and
- ecliptic components.

FLS: Extragalactic goals

- Detect enough extragalactic sources at unexplored sensitivity levels in order to
  - generate a representative sample and
  - reduce the uncertainties in source counts.
- Characterize the dominant source populations with
  - MIPS and
  - IRAC data from Spitzer,

  plus ancillary data at
  - optical,
  - near-infrared and
  - radio wavelengths.
- Explore
  - the cirrus foreground at moderately high galactic latitudes, and
  - its effect on point-source detectability.

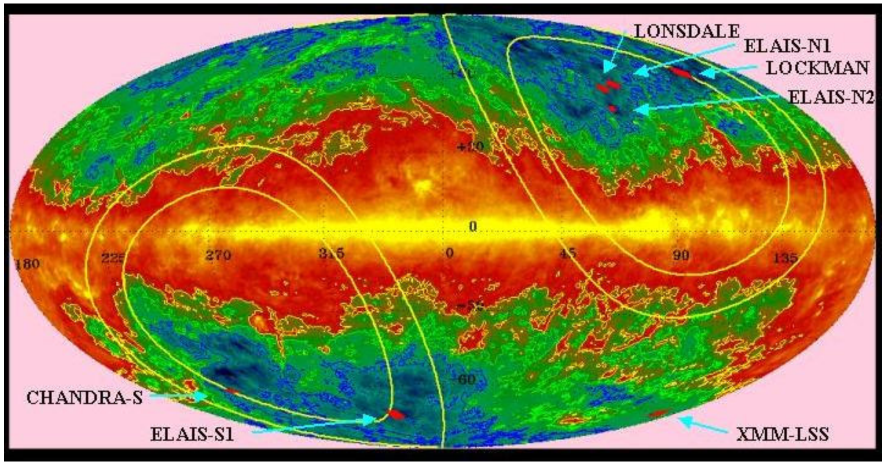
FLS: Results

Marleau, F., et all. 2003: AAS Meeting 203, #90.11

- Performed a redshift survey of ≈800 radio sources covering the redshift range $z = 0$ - 1.5.
- Goal was to map out the star formation history via radio and FIR luminosities as a function of redshift.
- Based on the FIR-radio correlation, they expected that all radio sources which are dominated by star formation will have MIPS counterparts.
- A preliminary investigation suggests that the majority of galaxies in this sample are dominated by star formation.
- Only a small fraction of sources are AGNs, including several quasars (one of which is at $z = 3.5$).

SWIRE (http://www.ipac.caltech.edu/SWIRE/)

The SIRTF Wide-area Infrared Extragalactic (SWIRE) survey is a Legacy Program using 851 hours of SIRTF observing time to conduct a set of large-area (≈67 square degrees split into 7 fields) high Galactic latitude imaging surveys, achieving 5-sigma sensitivities of 0.45 / 2.75 / 17.5 mJy at 24 / 70 / 160 μm. It will provide a complement to smaller and deeper observations in the SIRTF Guaranteed Time Observer and the Legacy Program GOODS, by allowing the investigation of the effect of environment on galaxy evolution.



SWIRE: Scientific goals

- The evolution of both actively star-forming and passively-evolving galaxies to determine the history of galaxy formation (including the global Star Formation History - SFH), in the context of cosmic structure formation and galaxy environment.
- The spatial distribution and clustering of evolved galaxies, starbursts, and AGN, and the evolution of their clustering in the key redshift range from $0.5 < z < 3$.
- The evolutionary relationship between galaxies and AGN, and the contribution of AGN accretion energy to the cosmic backgrounds, relative to that from nucleosynthesis.
- Search for possible new classes of galaxies such as those with very high ratios of infrared to optical luminosity.

SWIRE: Observed objects

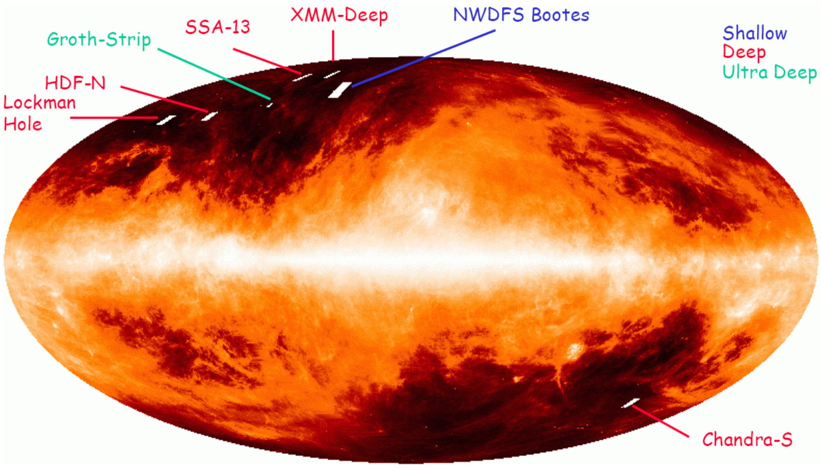
The Legacy Extragalactic Catalog may contain in excess of 2 million IR-selected galaxies, dominated by:

- ~150,000 luminous infrared galaxies (LIRGs; $L_{FIR}>10^{11}$ L_{solar}); up to 40,000 with $z > 2$;
- 1 million early-type galaxies; up to 400,000 with $z > 2$ and
- 30,000 classical AGN, and as many as 250,000 dust-obscured QSO/AGN.

Catalogs and images will be released twice yearly, beginning about 11 months after SIRTF launch (August 25, 2003).

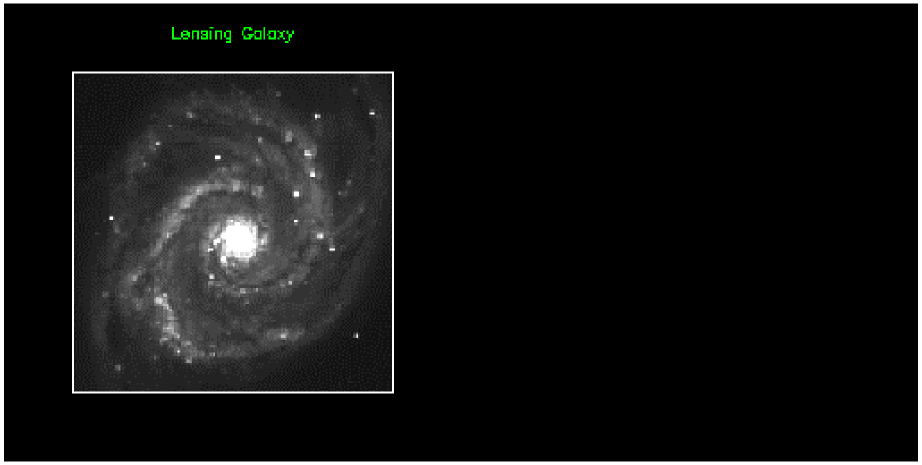
GTO (http://lully.as.arizona.edu/)

The Cosmic Infrared Background (CIB) is the focus of many observations, since its understanding is a key for galaxy formation and evolution studies. In order to resolve a significant part of its contributing sources as well as characterize its fluctuations, the SIRTF MIPS GTO program will devote more than 300 hours of the time to these surveys.



GTO: Surveys

- Shallow (9 sq deg),
- Deep (6 fields covering 0.41 sq deg each, selected to overlap with very deep X-ray surveys to aid in identification of AGNs and study of their evolution) and
- Ultradeep (75 sq. arcmin).
- The results of the ultradeep maps will be extended by observations of 18 massive galaxy clusters in the redshift range $0.2 < z < 0.4$ (clusters will image about 50 square arcmin of the background Universe, raising sources out of the confusion that will limit the sensitivity of the other deep surveys).



GTO: Scientific goals

The unprecedented sensitivity and wavelength coverage will allow:

- to probe the evolution of the luminosity function and to evaluate the star formation rate up to redshifts around 2,
- to estimate the fraction of far-infrared light from AGNs, and thus
- to give constraints on the scenarios of galaxy evolution.

Future

- SIRTF MIPS survey will cover about 100 square degrees at wavelengths out to 160 μm, providing a large sample of energetically important galaxies out to z of ~3.
- In 2005 the Japanese ASTRO-F (IRIS) (http://www.ir.isas.ac.jp/ASTRO-F/index-e.html) 160 μm full sky survey will provide larger samples of the high z galaxy populations and will find intrinsically rare high luminosity objects.
- The SPIRE instrument (http://www.ssd.rl.ac.uk/spire/) on the FIRST facility (launch in 2007) will extend these surveys to longer wavelengths (60-670 μm), providing a view of the Universe at higher redshifts in three spectral bands.
- A concept for an all-sky submillimeter survey is under development, called the Survey of Infrared Cosmic Evolution (SIRCE) (http://pioneer.gsfc.nasa.gov/public/sirce). With a 2 m cryogenic telescope, it can map the entire sky to the confusion limit in the 100 to 500 μm range in six months.

Sub-mJy & μJy Radio Sky

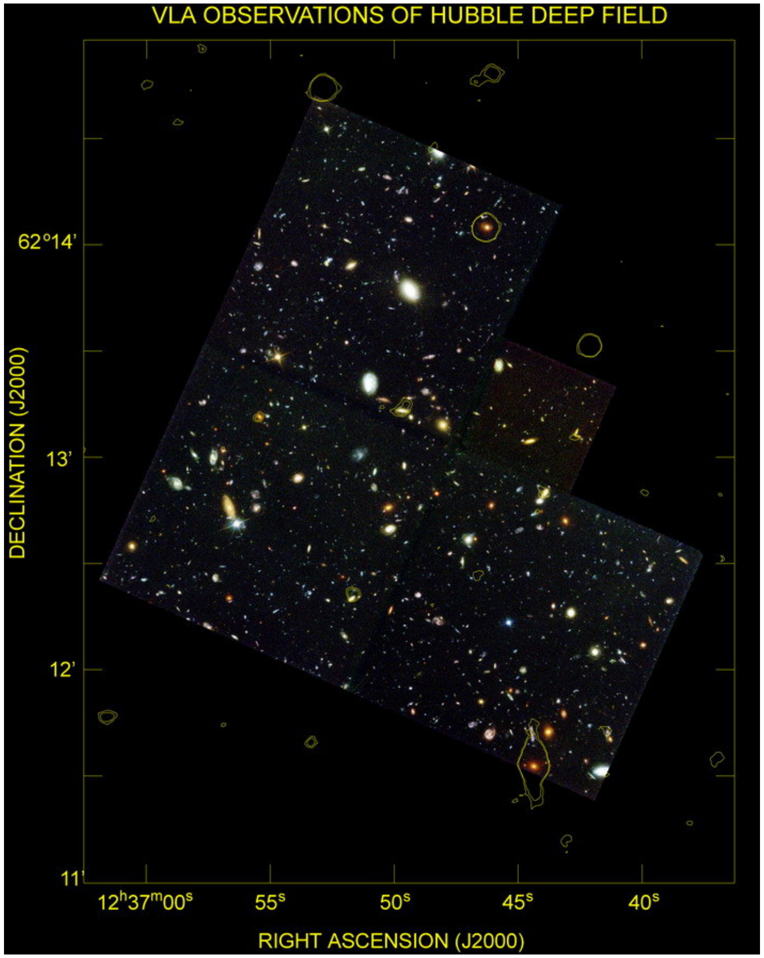
- Single dish telescopes don't have sufficient resolution:
  - Nearby galaxies
- Until recently interferometry targets from the brightest and most compact radio sources:
  - AGN at z ~ 1
- In recent years connected arrays (VLA, WSRT, ATCA, MERLIN) focus towards the nature of the faint radio sky:
  - Moderately redshifted interacting, irregular or peculiar galaxies
- In the future deep, wide-field VLBI studies are possible:
  - New population of star forming galaxies

Deep Radio Imaging of the HDF

- To detect radio sources, noise levels of a few μJy must be achieved
- Requires integration times ranging from a few days, to some weeks
  - VLA at 1.4 and 8.3 GHz ($1° \times 1°$, 6″, 17 μJy, 56^h)
    - Fomalont, E.B., Kellermann,K.I., Richards, E.A., Windhorst, R.A. & Patridge, R. B. 1997, *ApJ Letters*, **475**, L5
    - Richards, E.A., Kellermann, K.I., Fomalont, E.B., et al. 1998, *AJ*, **116**, 1039
    - Richards, E.A. 2000, *ApJ*, **533**, 611
  - WSRT 1.4 GHz observations ($10' \times 10'$, 1.5″, 8 μJy, 72^h)
    - Garrett, M.A., de Bruyn, A.G., Giroletti, M., Baan, W.A., Schilizzi, R.T. 2000, *A&A Letters*, **361**, L41
  - VLA-MERLIN 1.4 GHz observations ($10' \times 10'$, 0.2″, 3.3 μJy, 18^d)
    - Muxlow, T.W.B., Wilkinson, P.N., Richards, A.M.S., et al. 1999, *NewAR*, **43**, 623

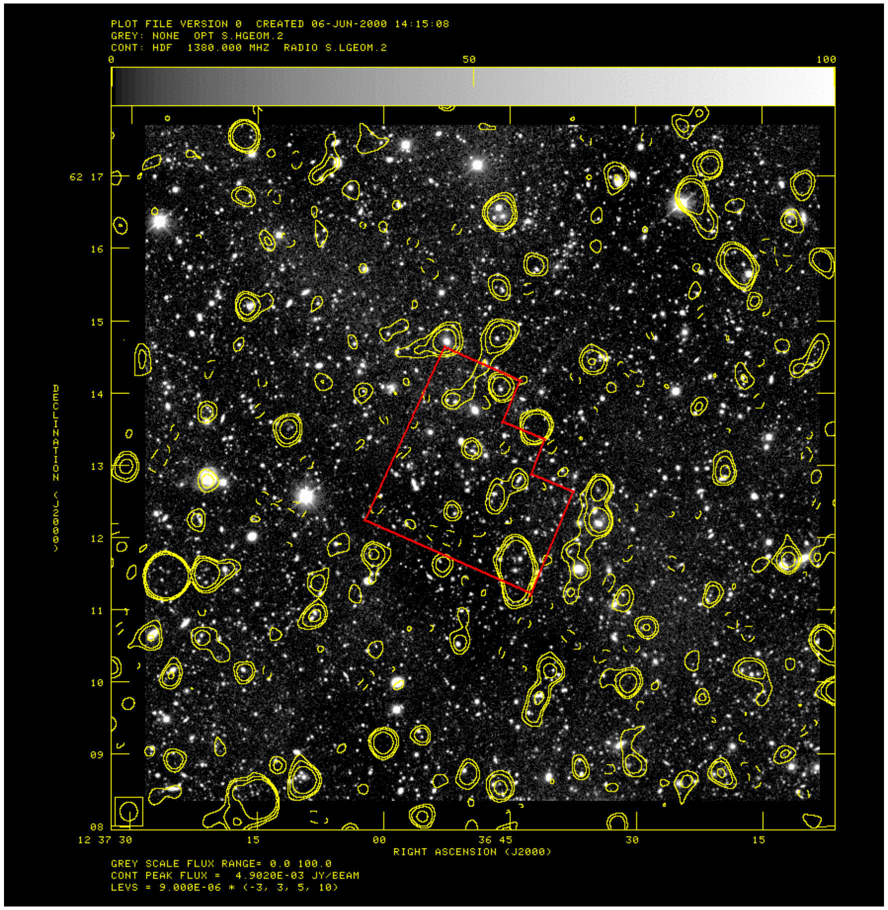
VLA

- 14 sources in HDF
- fluctuation analysis suggests nearly 60 sources per arcmin^2 at the 1 μJy level
- sources are identified primarily with disc systems composed of irregulars, peculiars, interacting or merging galaxies and a few isolated field spirals
- 20% of the sources can be attributed to AGN
- redshifts range from 0.1 to 3, with a mean of about 0.8
- About 20% of the radio sources remain unidentified



WSRT

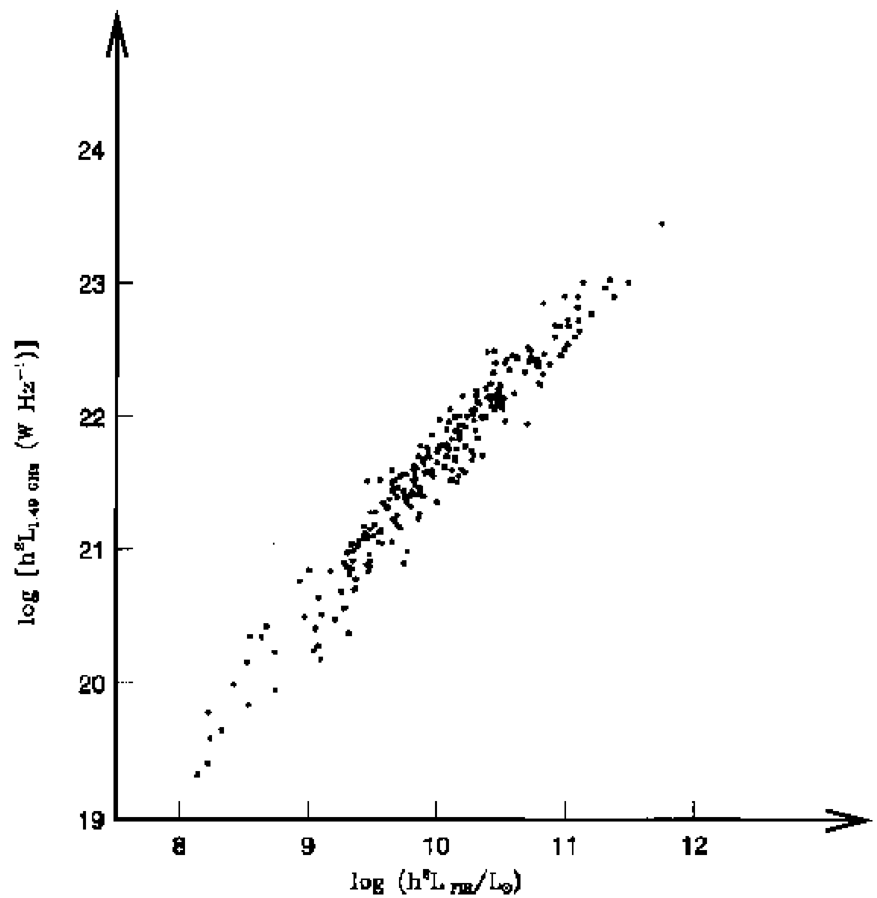
- Detects a small but significant population of both:
  - star forming galaxies
  - AGN
- A comparison between the VLA and WSRT 1.4 GHz images shows evidence for significant variability for a few percent of the sub-mJy radio source population
- There is a strong correspondence between the mid-IR ISO detections and the radio detections



FIR-Radio Correlation

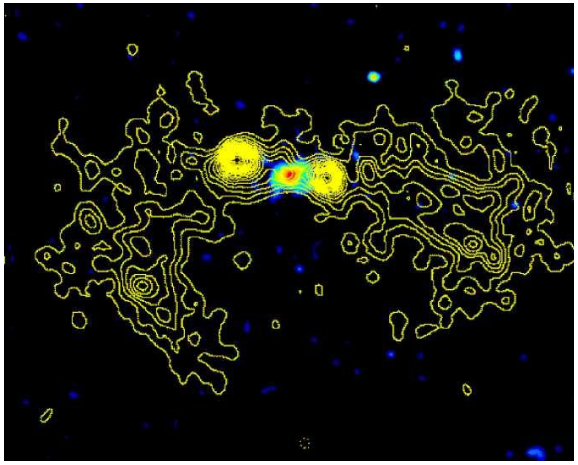
- The radio luminosity ⇐ SN event rate ⇐ the star formation rate (SFR) of massive stars
- The FIR emission ⇐ absorption and re-radiation (via dust) of the intense uv emission from massive stars
- Assuming
  - IMF for the stellar population, and
  - some scaling factors

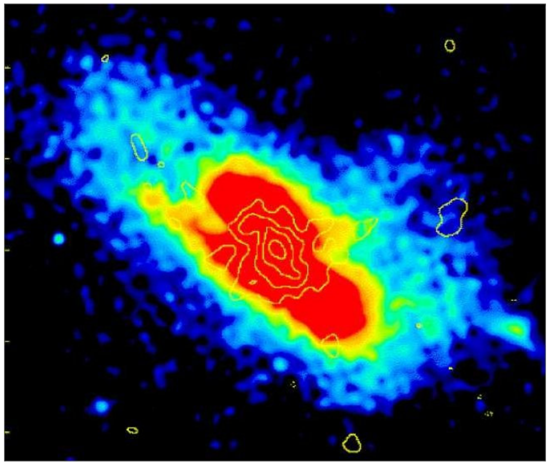
  radio observations ⇒ estimates of the SFR
- Radio emission of the most distant radio sources in the HDF ⇒ ~ 1000 $M_\odot$/yr



VLA-MERLIN

- 85% of the sources have been optically identified:
  - 30% have active galactic nuclei and
  - 70% are starburst galaxies
- Of the 91 sources detected the majority show radio structure on sub-galactic scales





Radio Populations

- Bright (> 1 mJy):
  - Radiogalaxies, quasars;
  - Sources at large z.
- Near 1 mJy:
  - Local, high star-formation rate galaxies appear;
  - Median z decreases.
- Near 1 μJy:
  - Distant star formers;
  - Median z rises again.

EVN (European VLBI Network)

- Pilot HDF-N in-beam phase-calibration observations on 12-14 Nov 1999.
- 12 arcmin^2, 0.002″, 33 μJy, 32^h at 256 Mb/s
- 3 detections:
  - VLA J123644+621133 (z = 1.013, resolved into a core + large scale jet)
  - VLA J123642+621331 (z = 4.424, a dusty starburst system)
  - VLA J123646+621404 (z = 0.96, a face-on spiral galaxy)

Future

- VLBI in-beam phase-calibration - Fomalont, E.B., Goss, W.M., Beasley, A.J. & Chatterjee, S. 1999, *AJ*, **117**, 3025
  - 0.001″, 1 µJy in 24^h at 256 Mb/s
- Allen Telescope Array (ATA) - http://www.seti-inst.edu/science/ata.html
  - 0.5-11 GHz, 350 elements, á ∅ 6.1 m, 1.5 µJy in 12^h, op. 2005
- Low-Frequency Array (LOFAR) - http://www.lofar.org
  - 10-240 MHz, ∅ 400 km, 100 stations á 100 antennas, op. 2008
- Square Kilometre Array (SKA) - http://www.skatelescope.org
  - 0.15 - 20 GHz, 1 deg^2, 0.1″, 100 nJy in 12^h, ∅ >1000 km, op. 2015