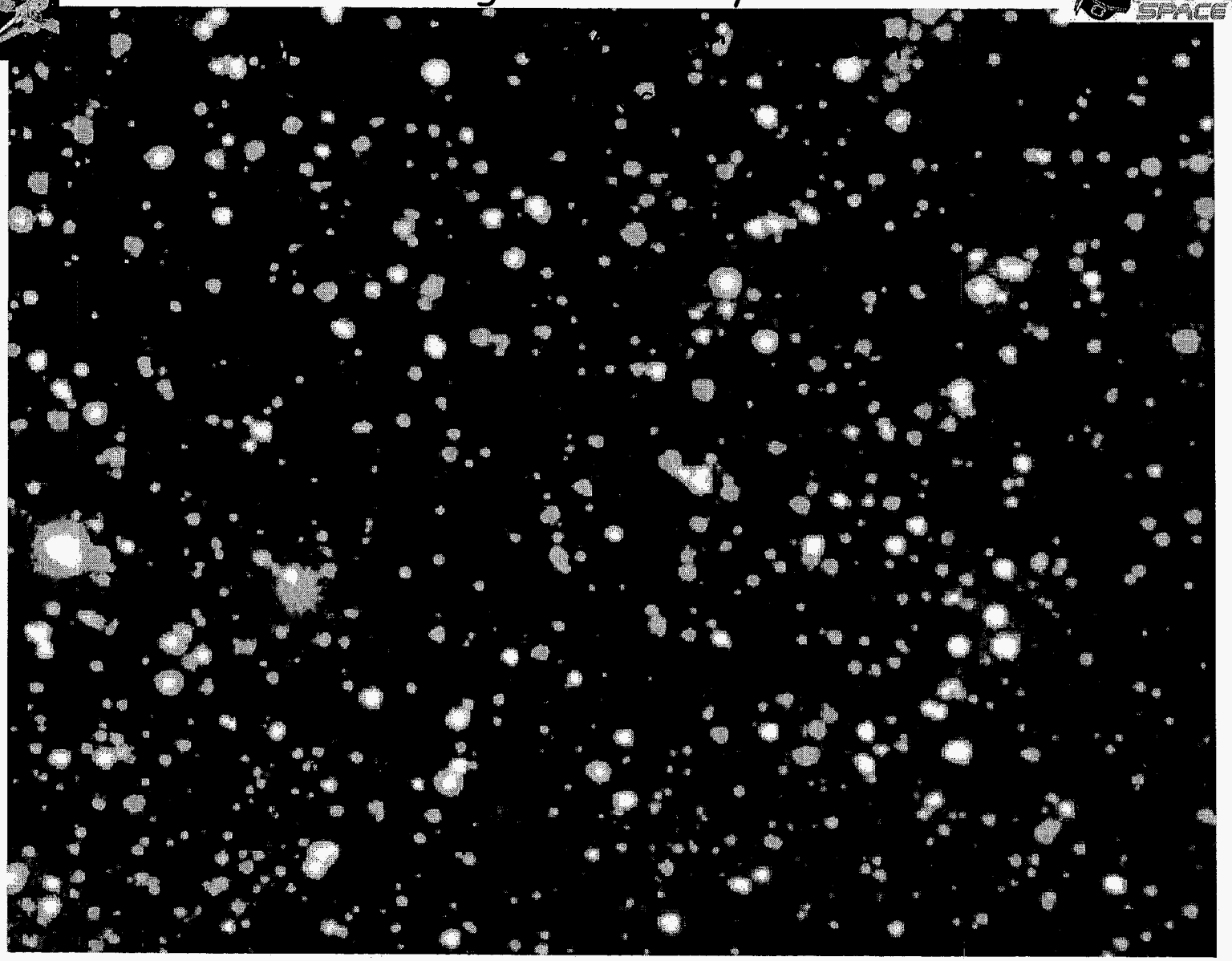
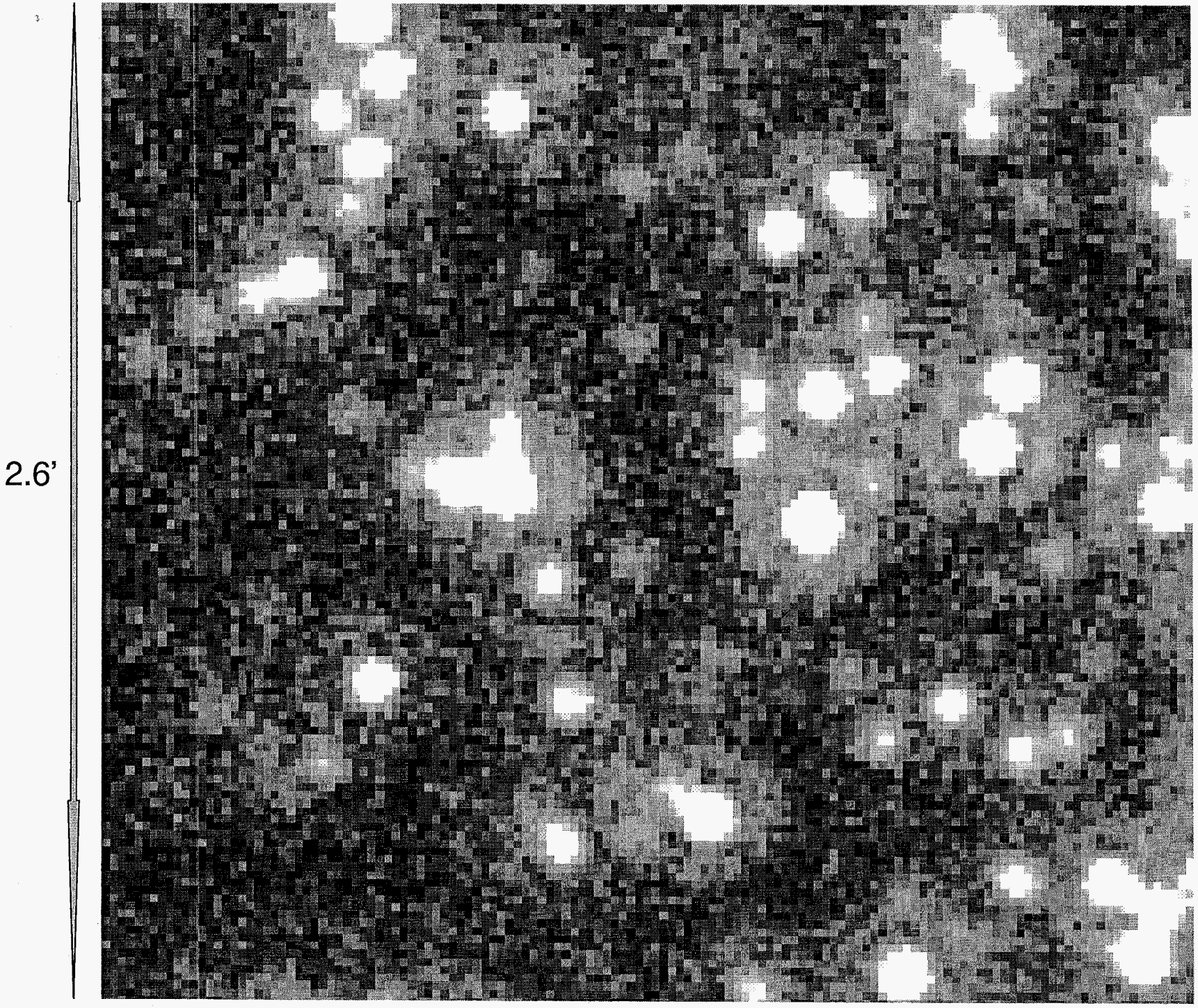
Spitzer/GOODS - Constraints on the EBL and Galaxy Evolution

Ranga-Ram Chary

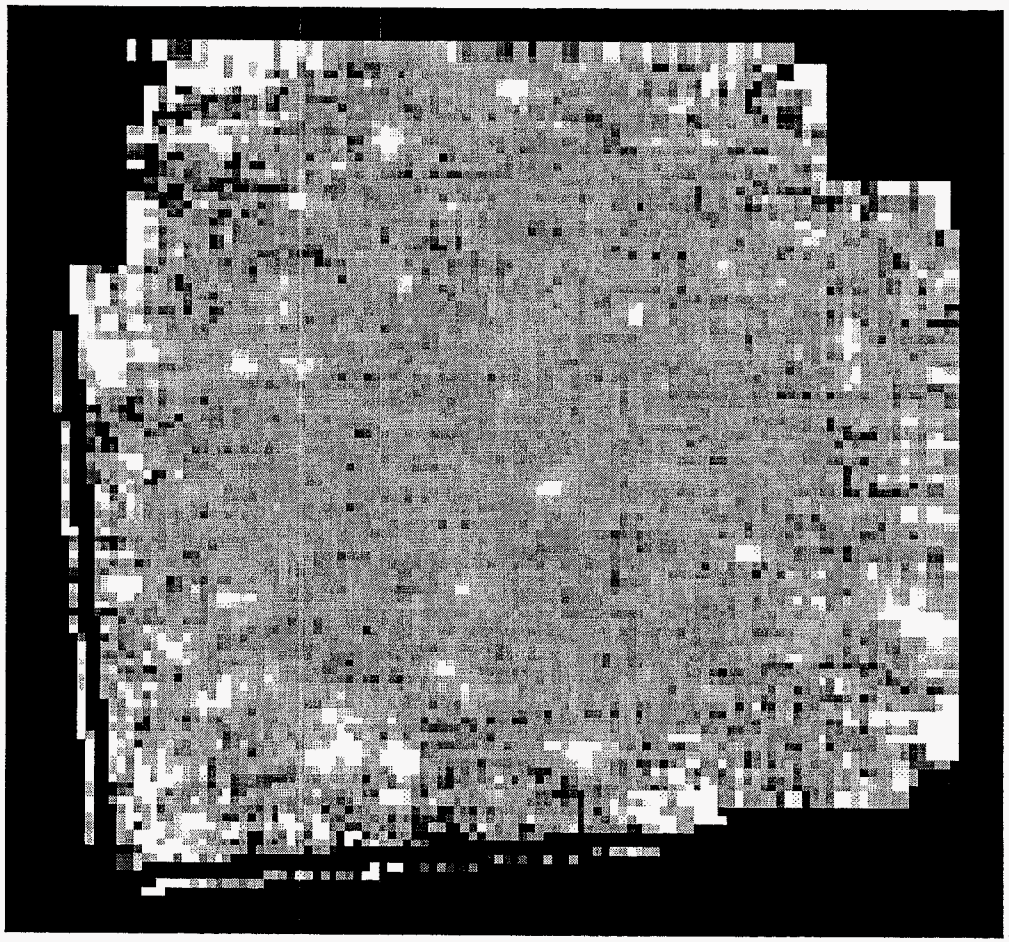


GOODS-gang

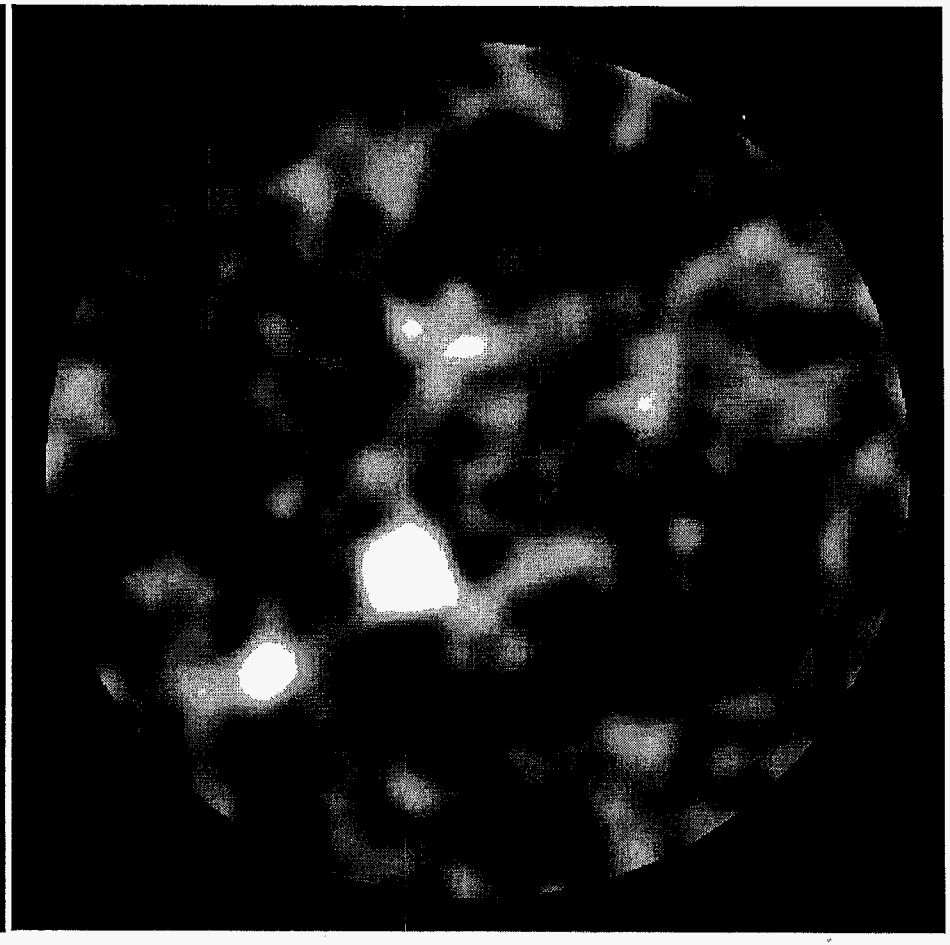
- Ocean's 10: Dickinson, Eisenhardt, Ferguson, Ned Wright, Bob Williams, Bill Reach, Papovich, Tollestrup, Elbaz, Chary (April 2000)
- And now, ~100 collaborators including Gemini, ESO, STScI, JPL, Yale, Cambridge etc.
- Key members: Stefano Casertano, Norman Grogin, Lexi Moustakas, Haojing Yan, Mobasher, Vicki Laidler etc.
- New Entrants: Glenn Morrison, Emily Macdonald (NOAO)
- Ancillary Data: Teplitz 16micron IRS Peak-up CDF-S, Frayer 70μm HDFN etc.


2.6'
3.6μm
25 hrs
5.8μm
25 hrs
24μm
10.9 hrs

State of the Art from the '90s



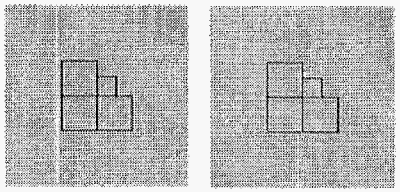
ISOCAM 15 microns (Mann et al. 1997)



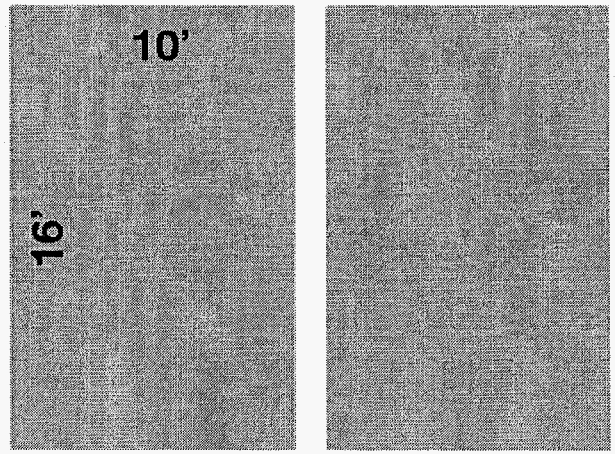
SCUBA 850 microns (Hughes et al.)

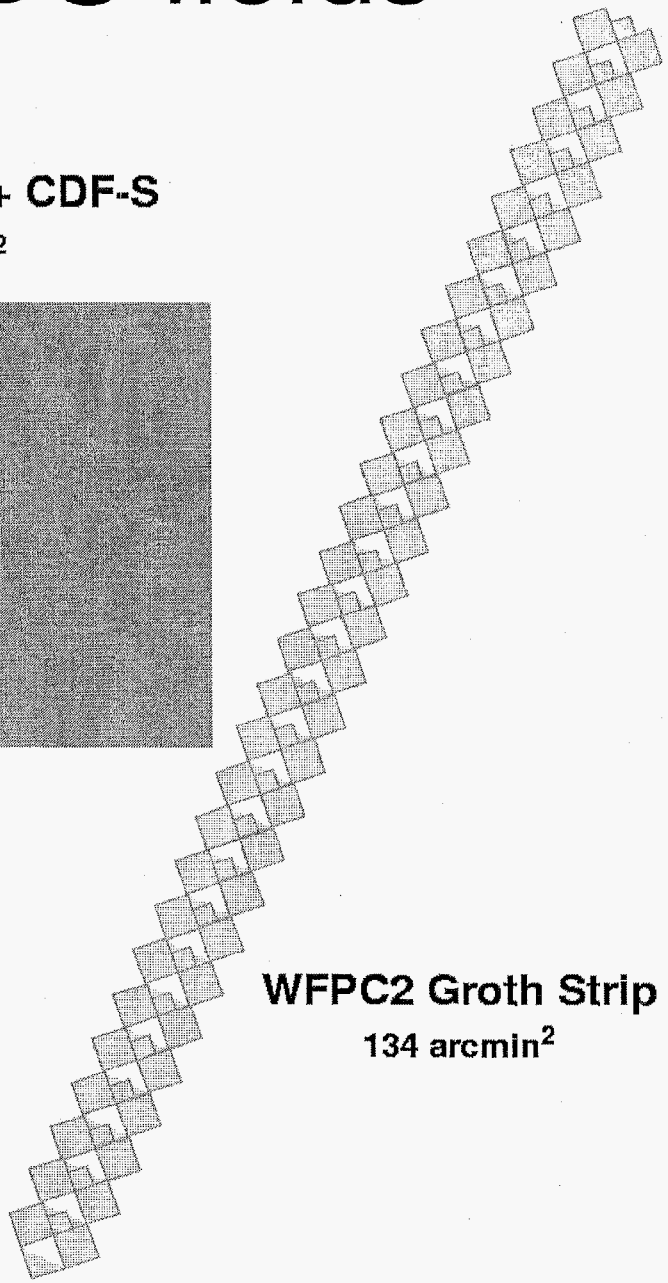
The GOODS fields

WFPC2 HDF N+S
+ flanking fields
10 + 85 arcmin^2



GOODS HDF-N + CDF-S
330 arcmin^2





WFPC2 Groth Strip
134 arcmin^2

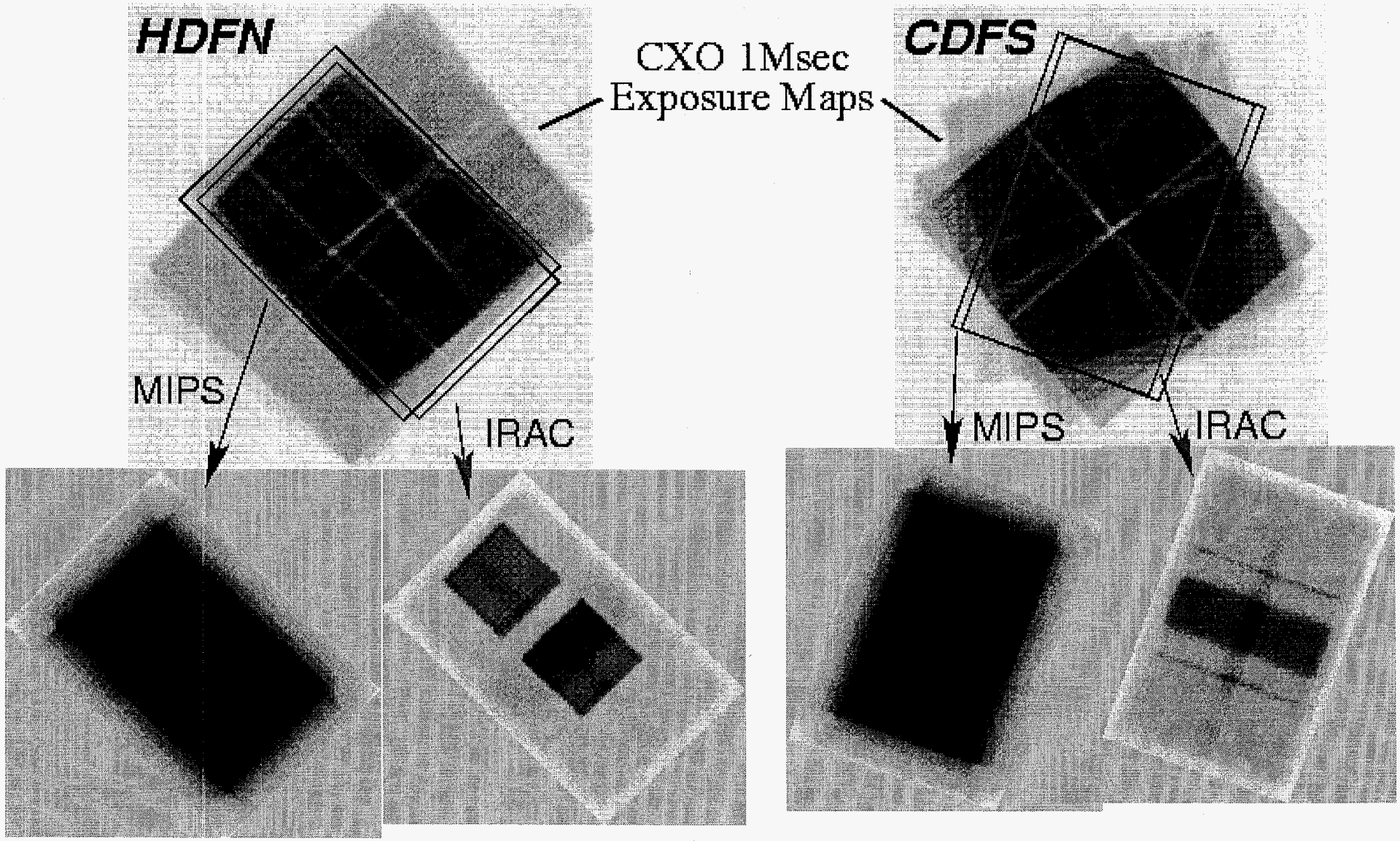
Two GOODS fields: HDF-North & CDF-South
~33x solid angle of combined HDF-N+S central fields
~ 4x solid angle of combined HDF-N+S flanking fields
~2.5x solid angle of WFPC2 Groth Strip
~18 x 30 h_{70}^{-1} Mpc co-moving transverse extent at $z = 3$

Two fields provide:

- Access to observers in both hemispheres
- Insurance against cosmic variance
- Maximal overlap with deepest X-ray data

Both fields at high galactic & ecliptic latitude, with low zodiacal & galactic foregrounds, N(HI), stellar & radio contamination, etc.

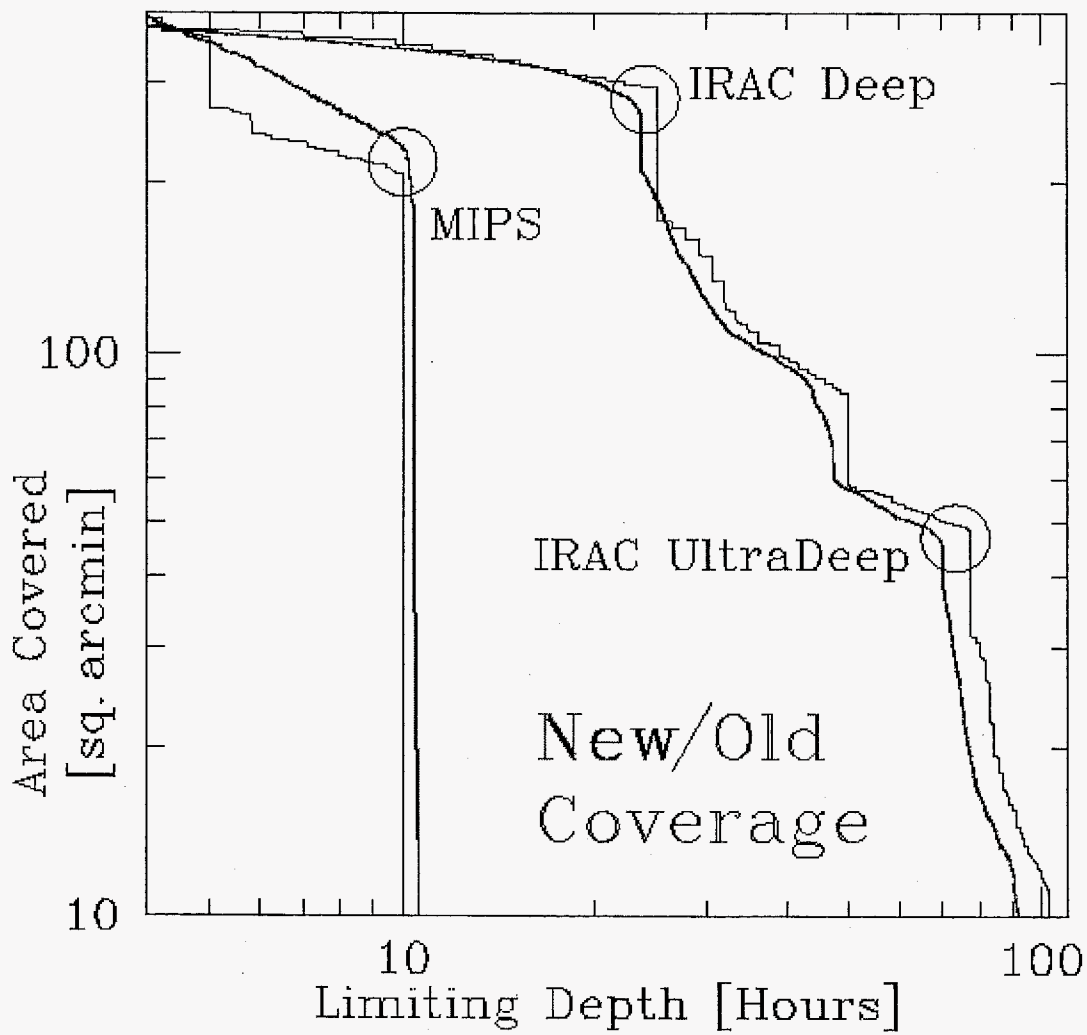
CXO vs. GOODS exposure maps



Summary of SIRTF observations

Component	IRAC Deep	IRAC Ultradeep	MIPS
Nominal area	~300 arcmin^2	~50 arcmin^2	~300 arcmin^2
Exposure time per map position	23.6 h (47.2 h in overlap)	+46.5 h (total 70.1/93.7 h)	10.4 h
Total time	409 h	99.3 h	139.2 h
Individual exposure time	200 s	200 s	30 s
Total dithers per map position	425	837	240
AOR information:			
Map positions per AOR	2 x 2	1	2
Number of AORs	68	18	48
Total clock time per AOR	21653 s	19852 s	10442 s
Time per map position per AOR	5000 s	18600 s	4680 s
Dithers per map position	25	93	30
Repeats within each AOR	1	1	5 (6)
AOR repeats	17	9	4
Epochs per field / total	2 / 4	2 / 2	1 / 2

GOODS area vs. depth



The Great Observatories Origins Deep Survey (GOODS)

Aim: **to establish ultradeep reference fields with public data sets from X-ray through radio wavelengths for the study of galaxy and AGN evolution over the broadest accessible range of redshift and cosmic time.**

GOODS unites the deepest surveys from NASA's Great Observatories (*Spitzer, Hubble, Chandra*), ESA's *XMM-Newton*, and the best ground-based observatories.

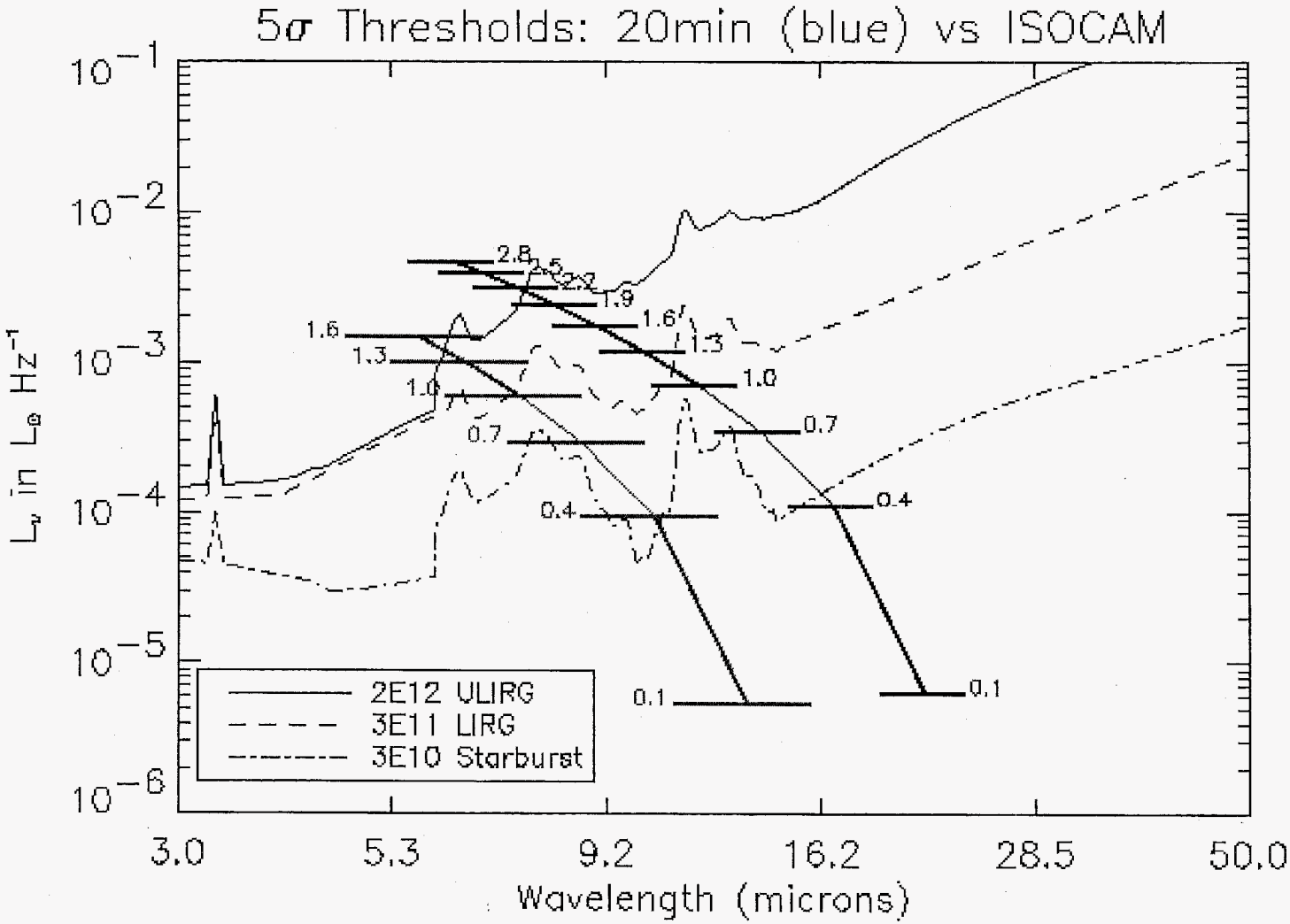
GOODS provides:

- Deepest SIRTF coverage from 3.6 – 24 μm (IRAC-G. Fazio et al., MIPS-G. Rieke et al.)
- "Near-HDF" depth 4-band HST/ACS imaging
- Deepest X-ray coverage from Chandra & XMM-Newton
- Extensive supporting observations (NOAO, ESO, Gemini, Keck, ATCA, VLA, etc.)
- Public release of data and data products

Primary science goals:

- The mass assembly history of galaxies
- Census of energetic output from star formation and supermassive black holes
- Emergence of the Hubble Sequence
- Supernovae at high redshift and the cosmic expansion
- Dark matter distribution through weak gravitational lensing
- Measurements or limits on the discrete source component of the EBL

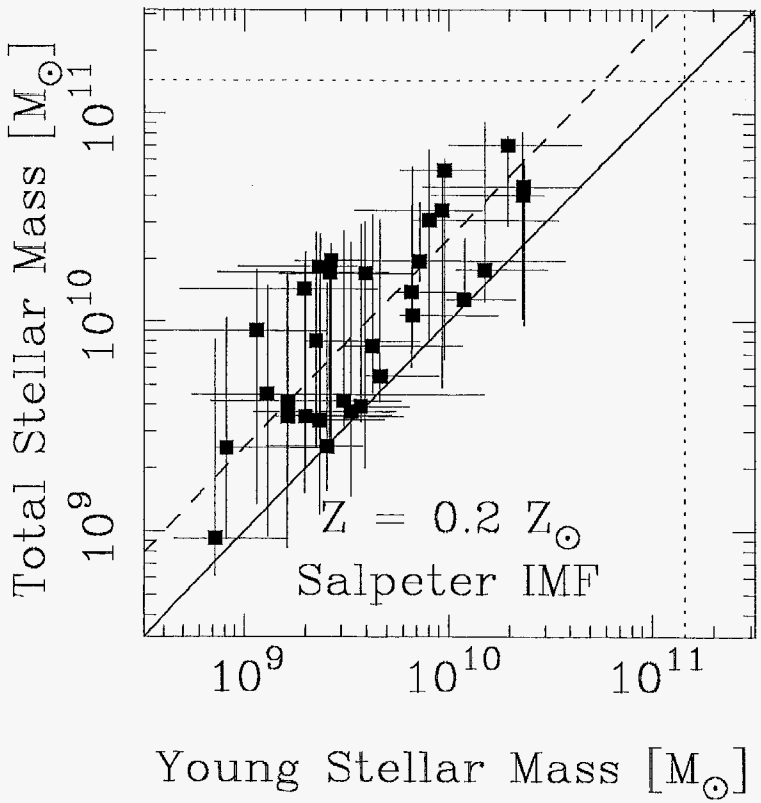
The Motivation for Deep MIPS 24 micron: Detect thermal dust emission from LIGs at z~2

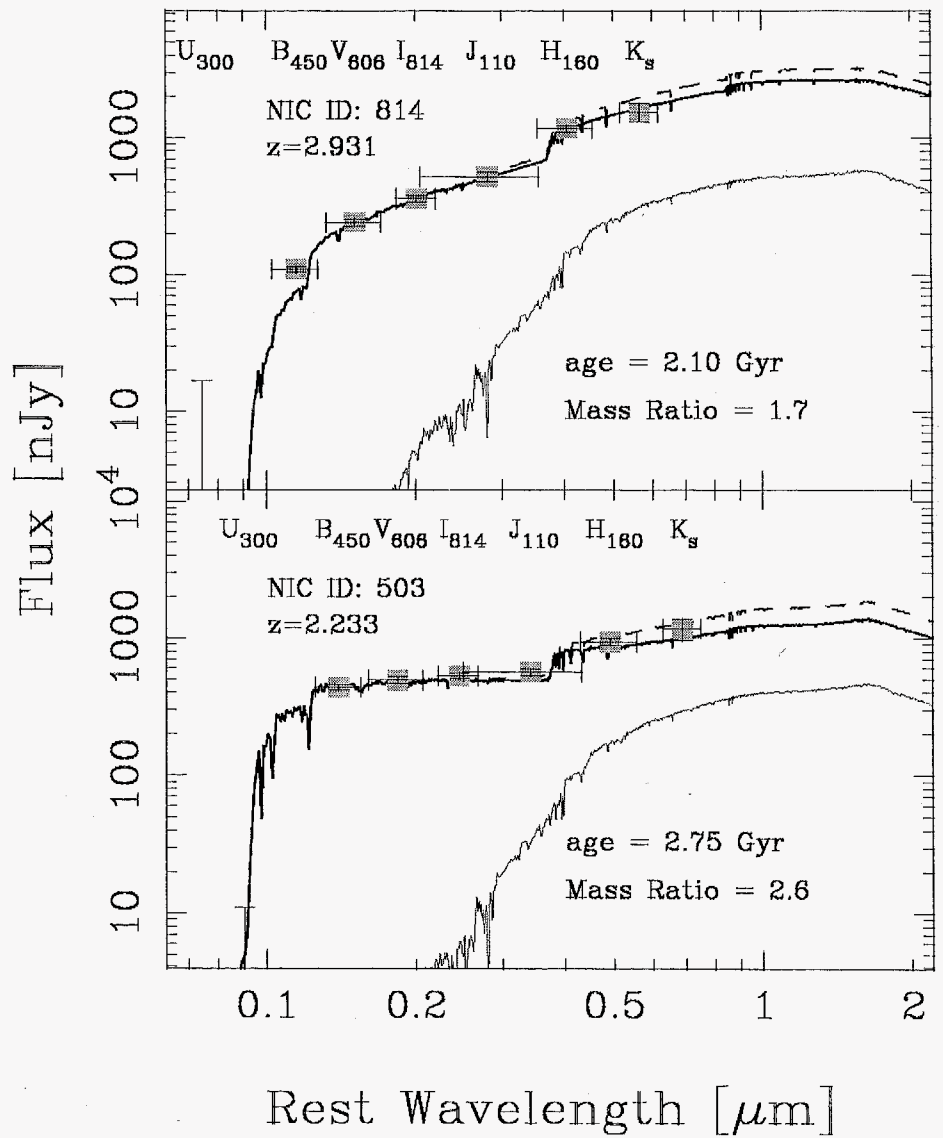


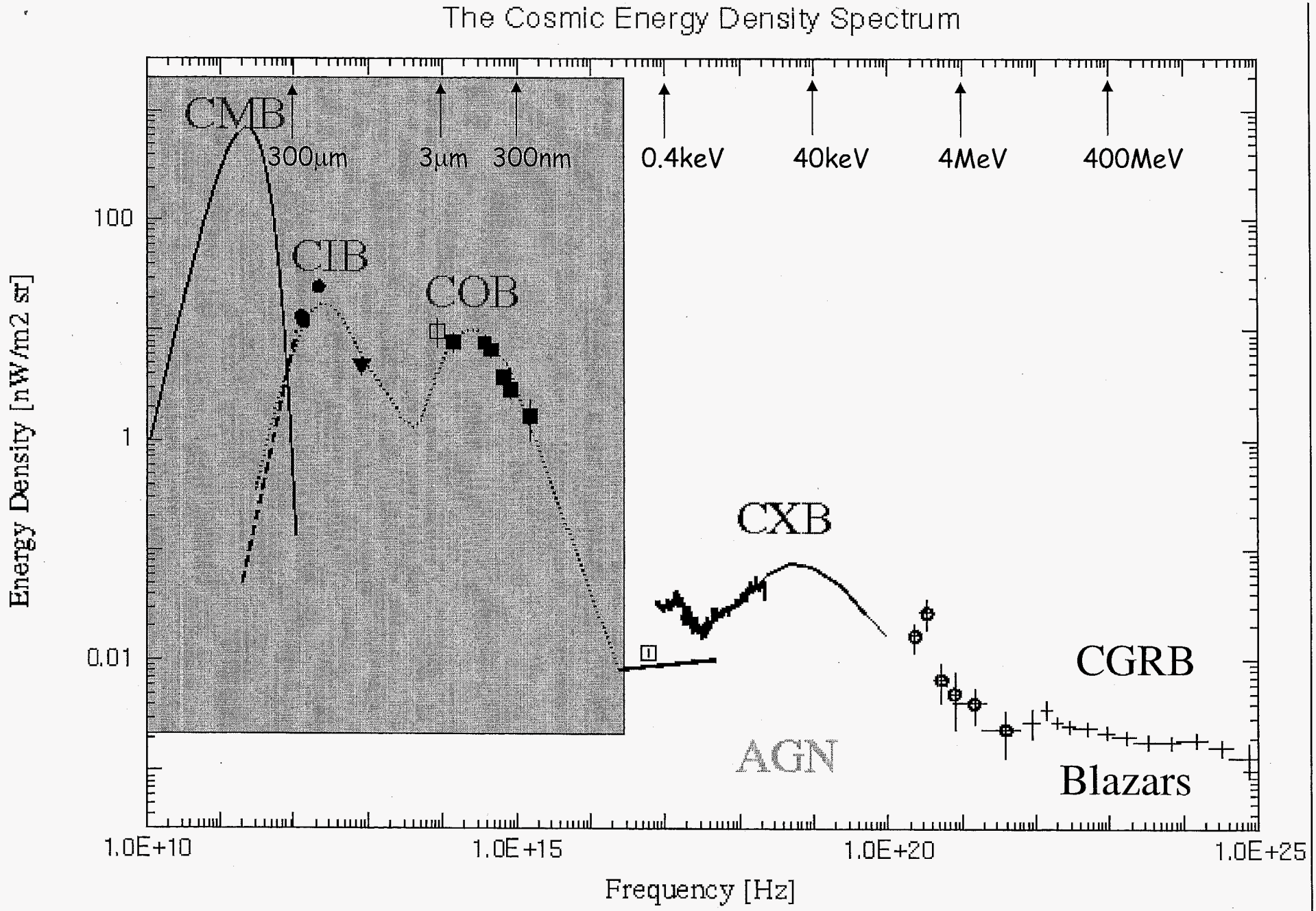
ISOCAM HDF-N depth of 0.1 mJy

Motivation for Deep IRAC - Detect old stellar component of L* galaxies to z~3

Significant mass from an older stellar population could be hidden by ongoing star formation.



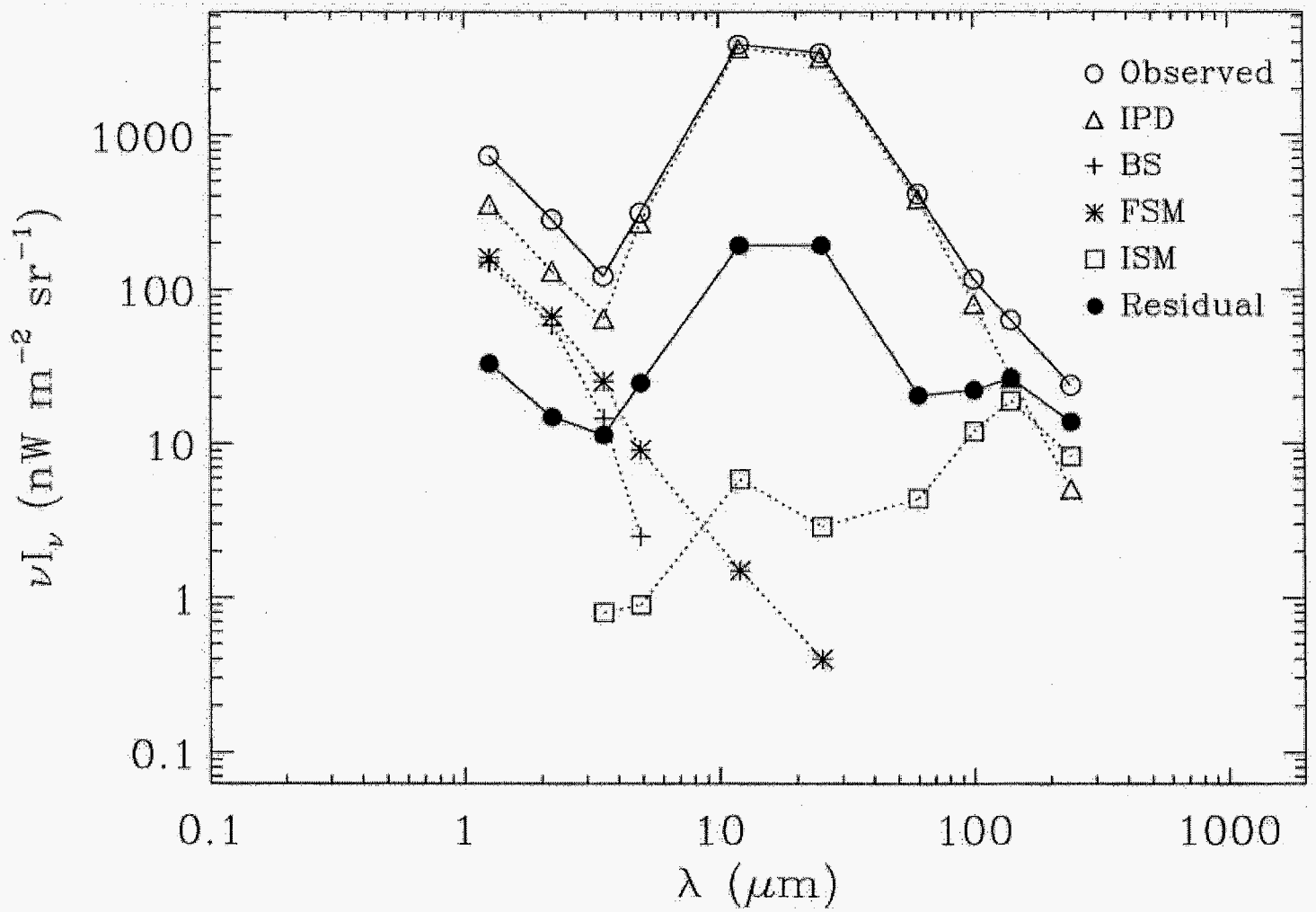



The Cosmic Energy Density Spectrum
CMB
300μm
3μm
300nm
0.4keV
40keV
4MeV
400MeV
CIB
COB
CXB
CGRB
AGN
Blazars
100
1
0.01
Energy Density [nW/m2 sr]
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]

Hasinger '00

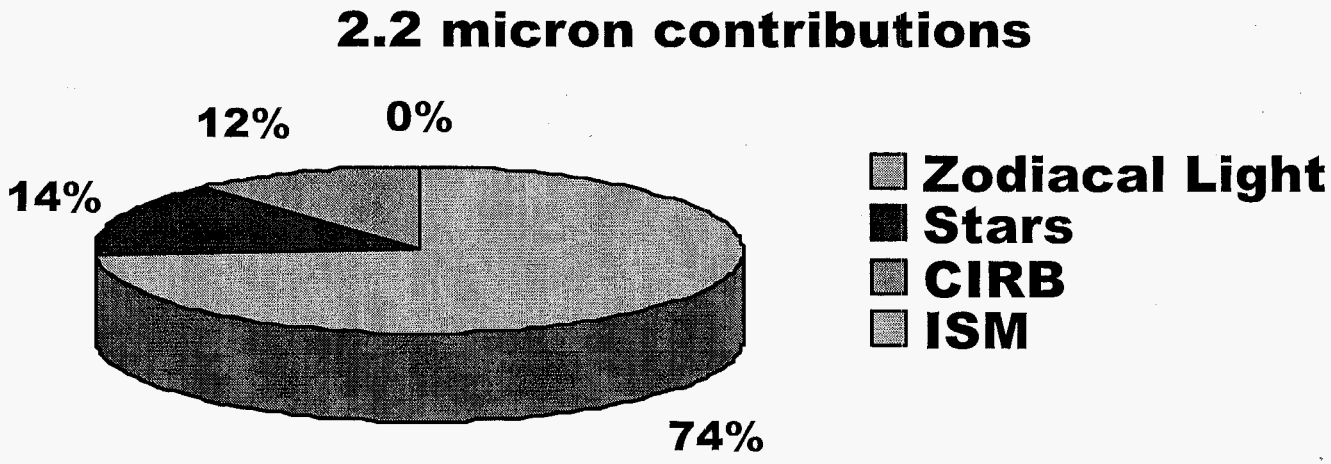
The Infrared Background

- Atmospheric foreground
- Instrumental thermal foreground
- Zodiacal light : thermal emission and scattering; minimum of both at 3.5 microns.
- Galactic foreground: stars at near- infrared (λ<5 μm) wavelengths; dust at mid- (5-30μm) and far-infrared (30-1000 μm) wavelengths.
- The residual is the Cosmic Infrared Background = Extragalactic Background Light $\geq$ Integrated Galaxy Light (IGL).



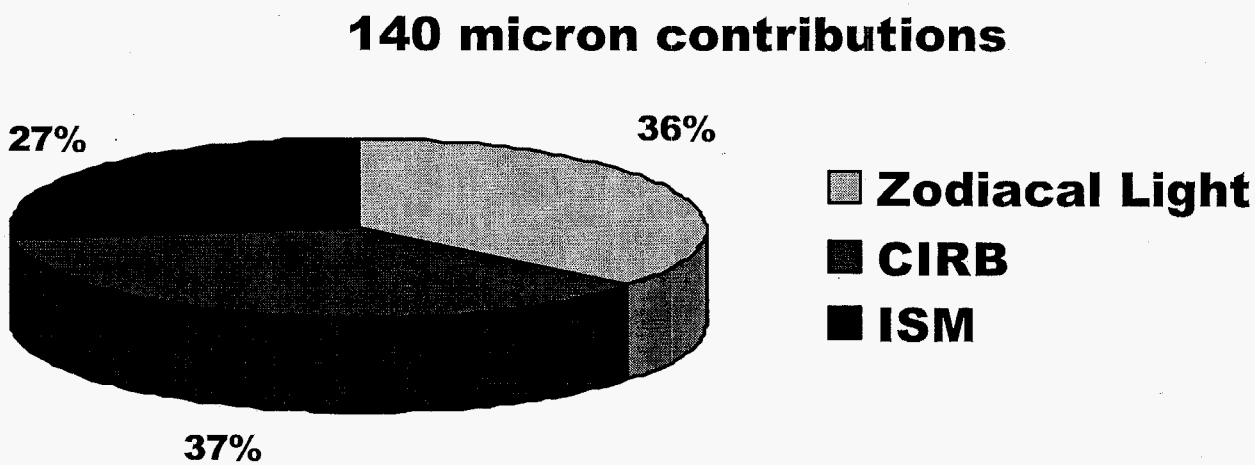
Lockman Hole Intensity Decomposition
(Hauser et al. 1998)

Decomposition of the Sky Background at Infrared Wavelengths

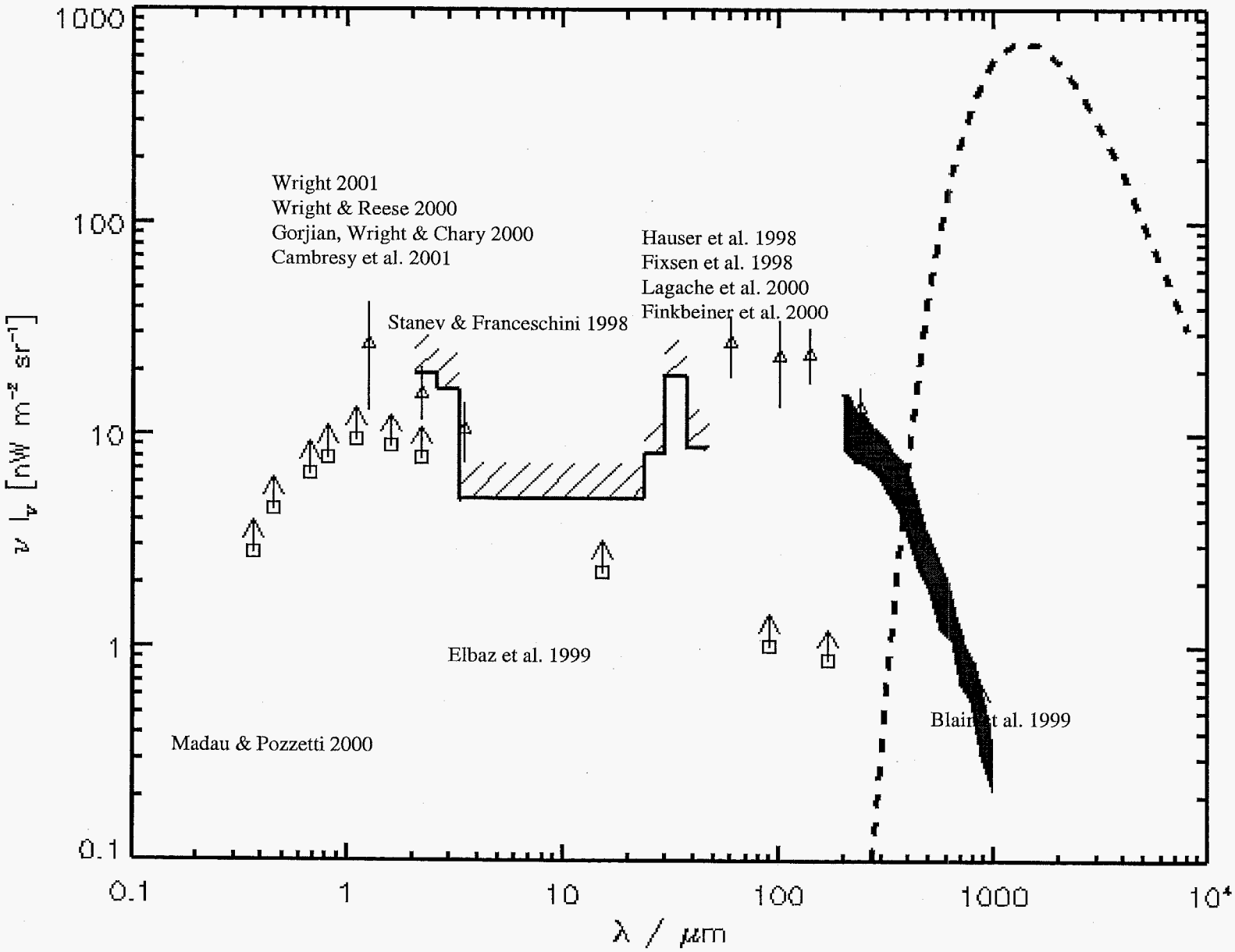


CIRB (nW m^{-2} sr^{-1})

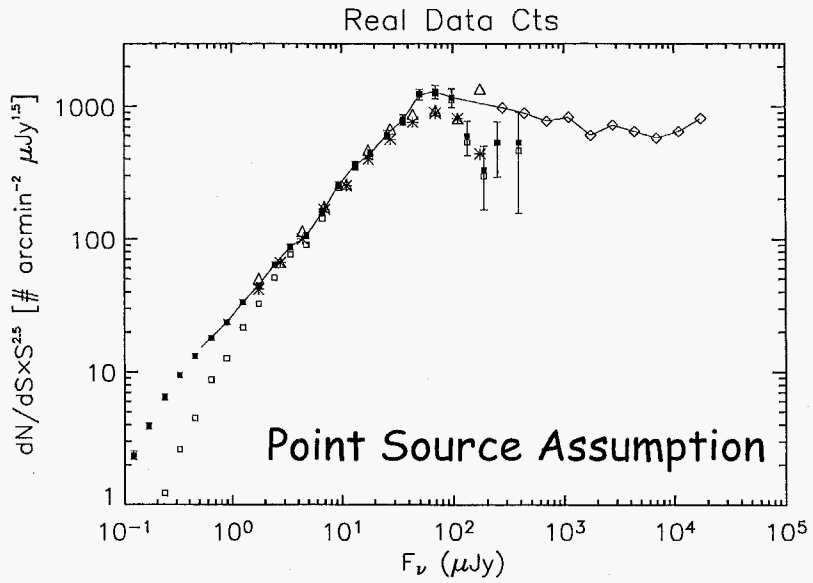
λ	νI_ν
2.2:	22.4±6.0
3.5:	11.0±3.3
140:	25±7
240:	14±3

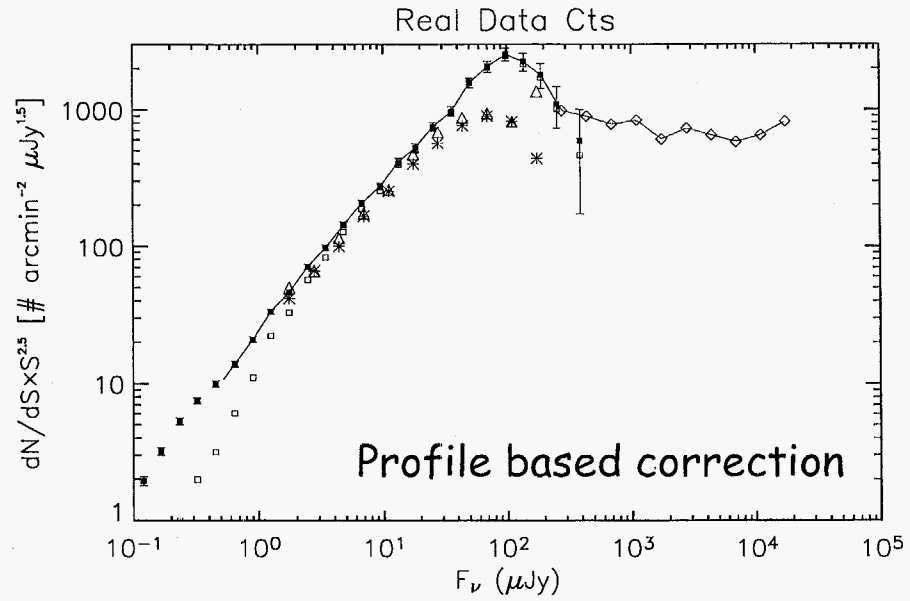


CIRB Spectrum

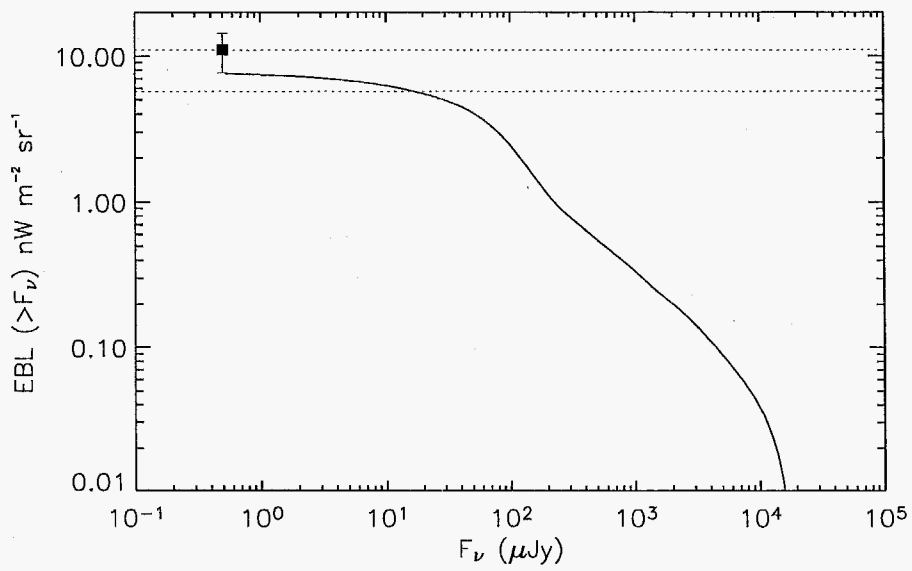


Estimating IGL from Galaxy Counts - Need Aperture Corrections as a function of Galaxy Morphology

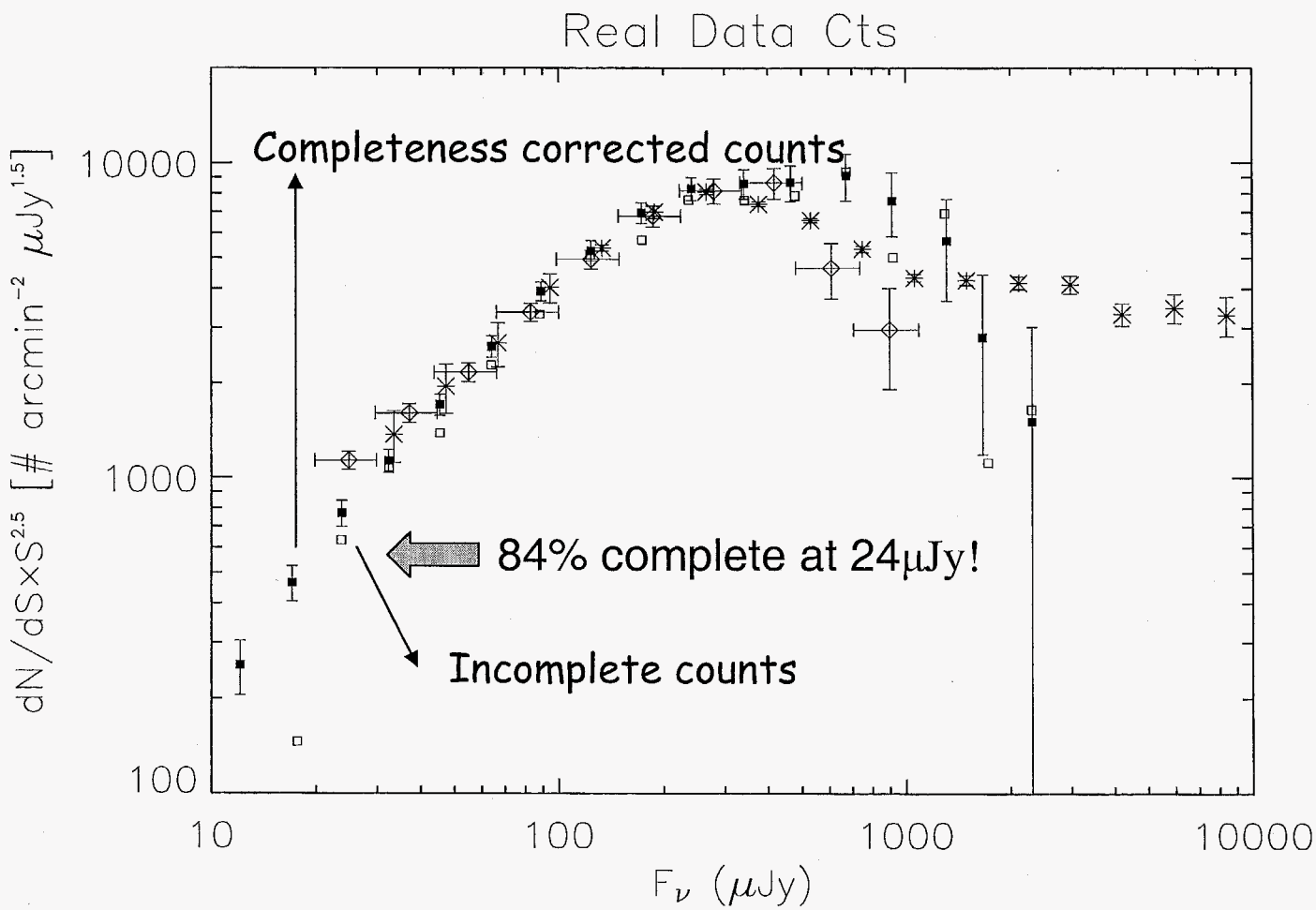




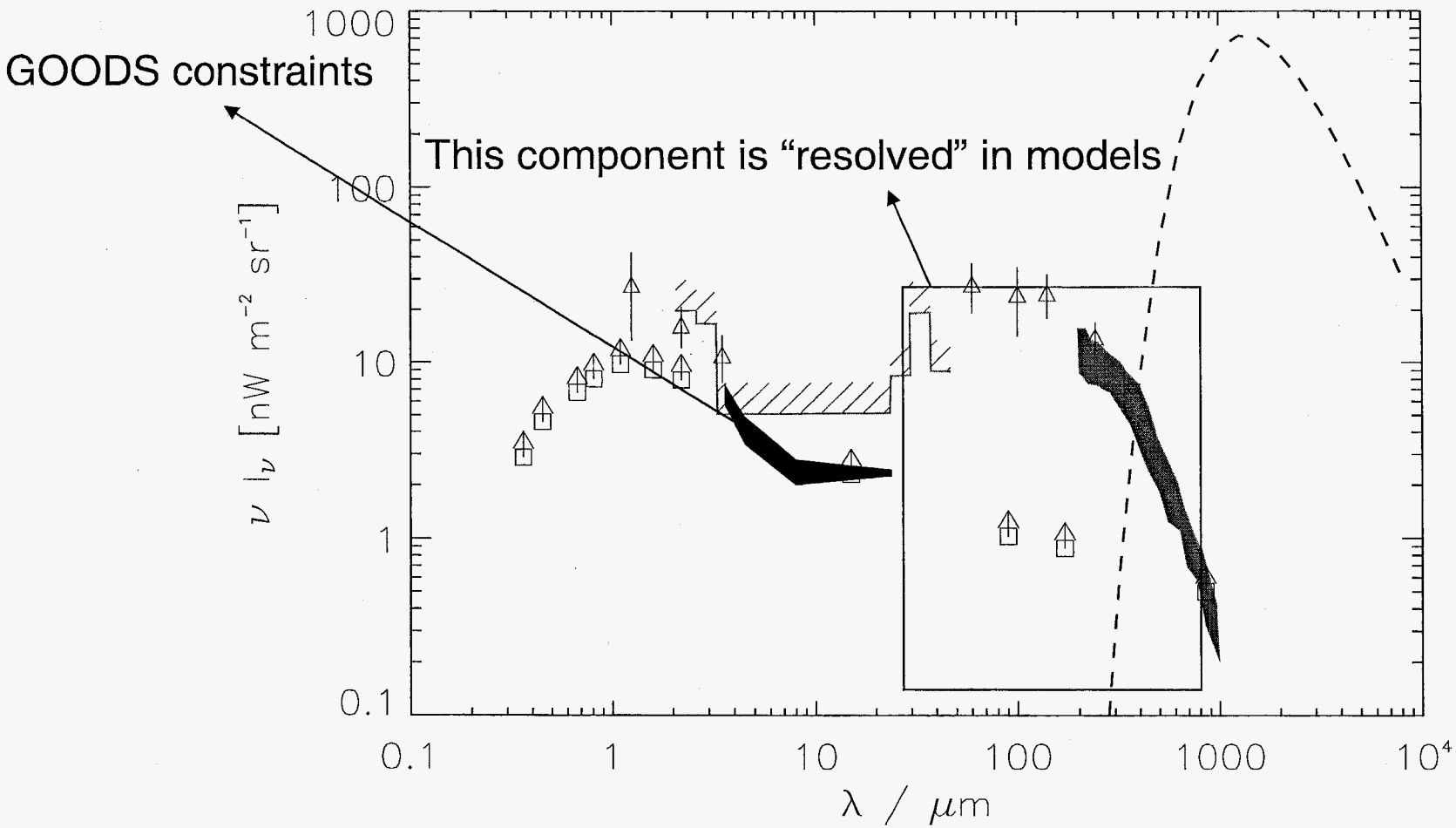
λ (μm)	νI_ν (nW/m^2/sr)
3.6	7.5 (5.7) ~70%
4.5	4.9 (3.4)
8.0	2.8 (2.0)
24	3.3



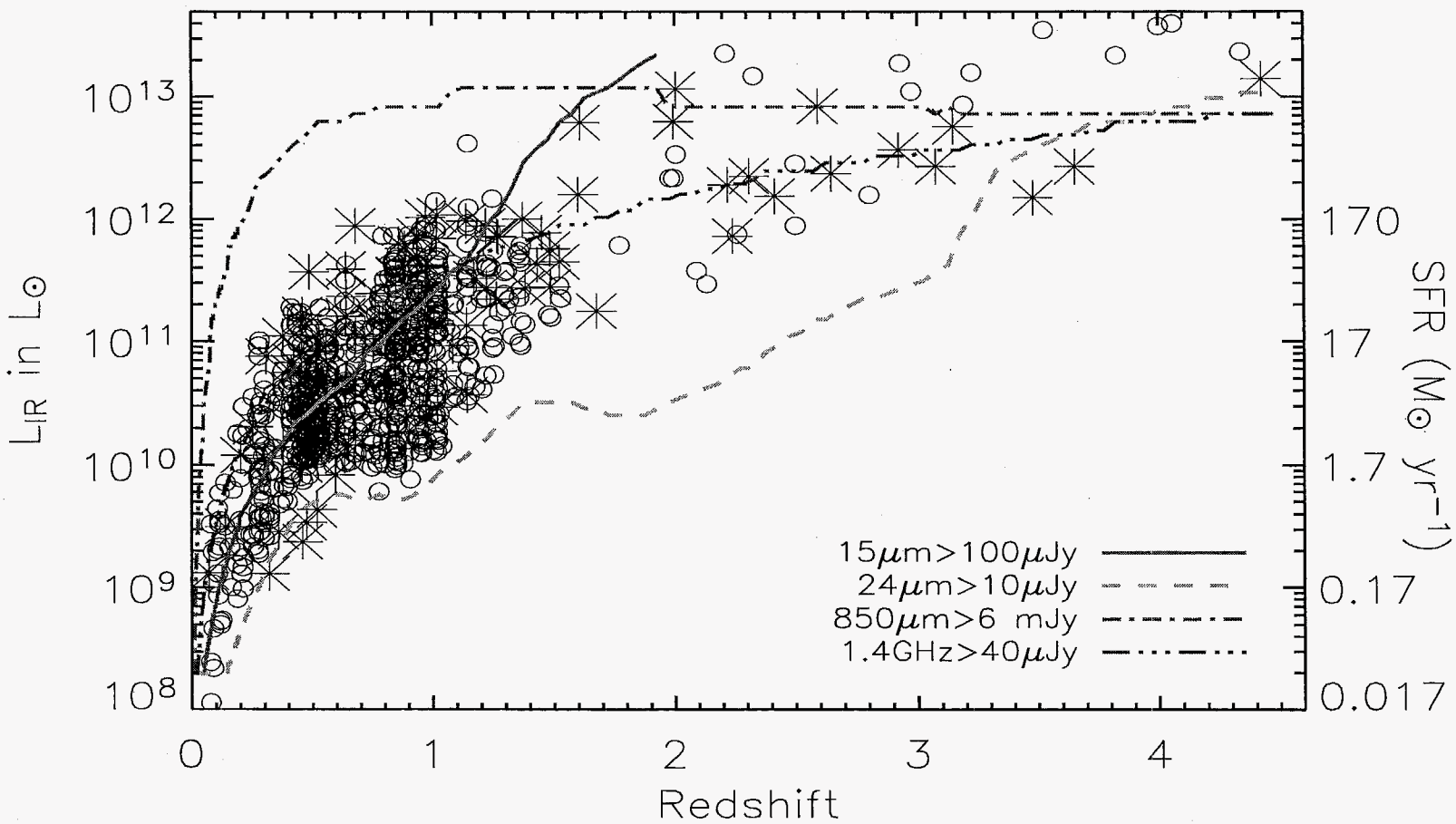
At 24 microns, confusion ? What's that ?



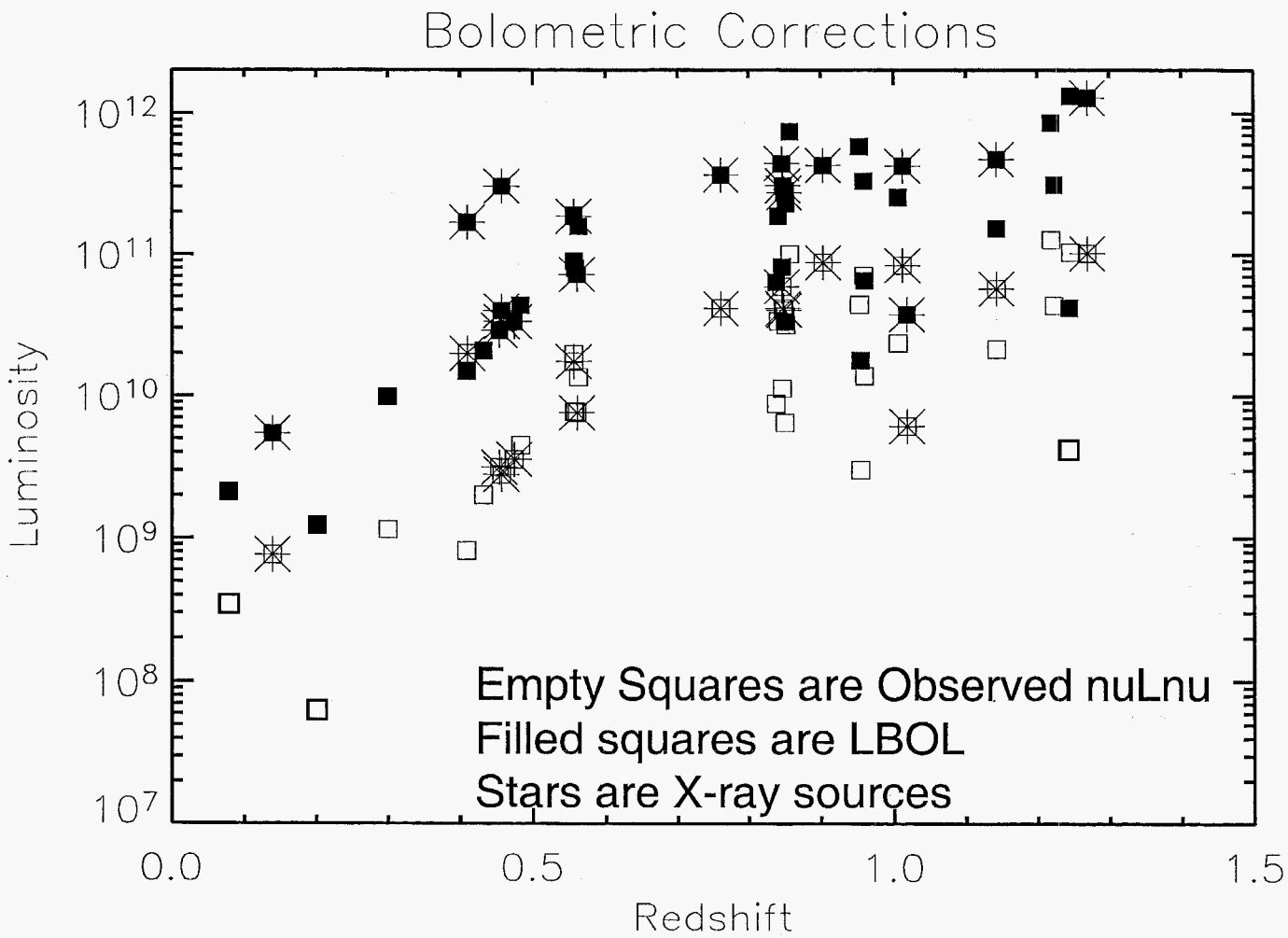
The CIRB is still only partially resolved - However the TeV spectrum of blazars seems to be a bit off !



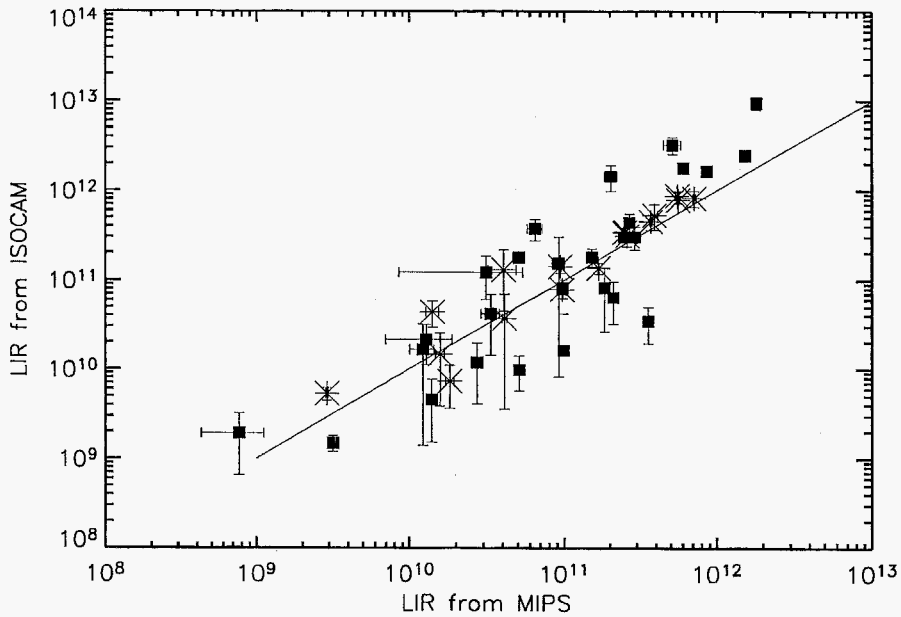
Sensitivities of measurements at different wavelengths to high-z star formation

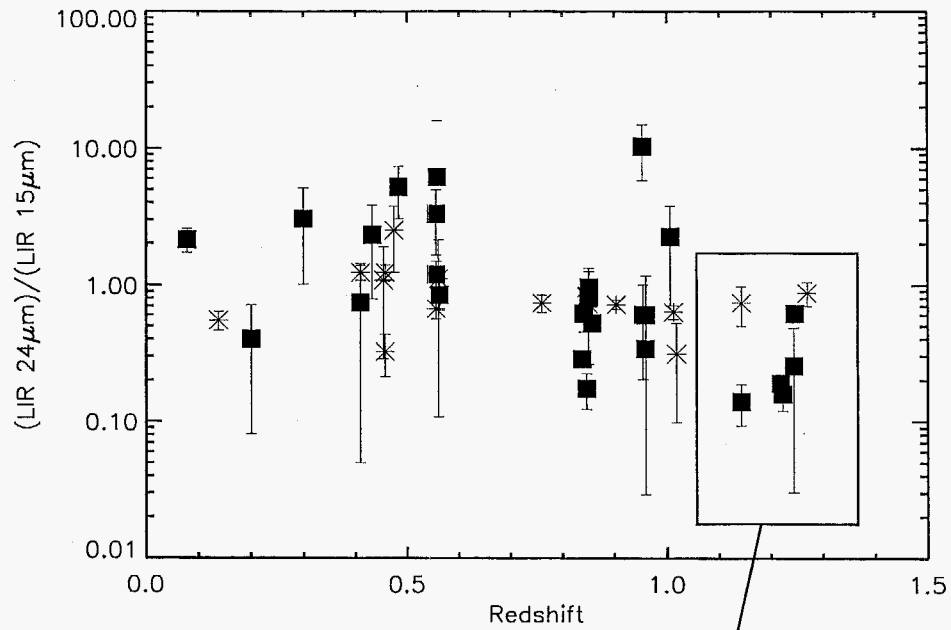


Bolometric Corrections are x10 !



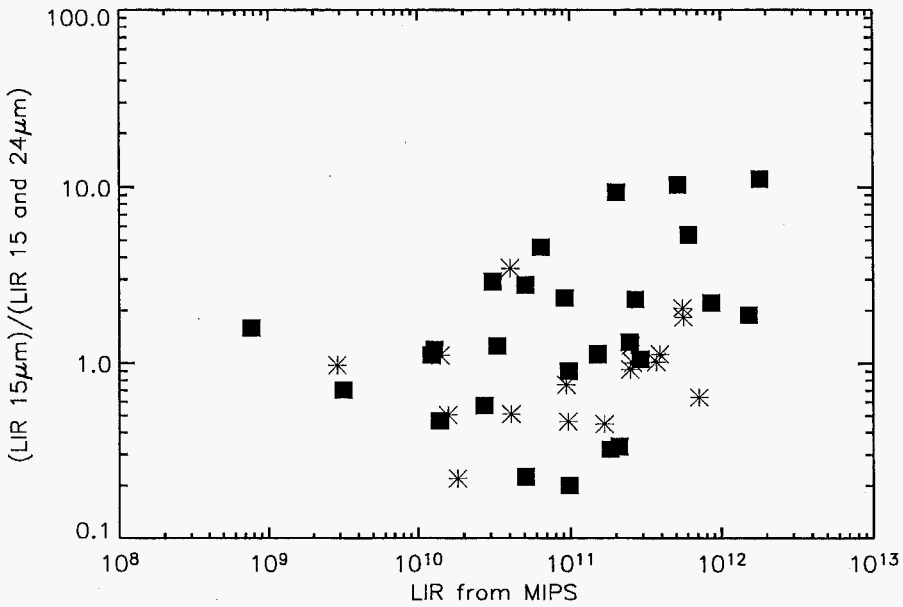
Comparison with z~1 ISOCAM galaxies: General agreement in LIR estimates from mid-infrared

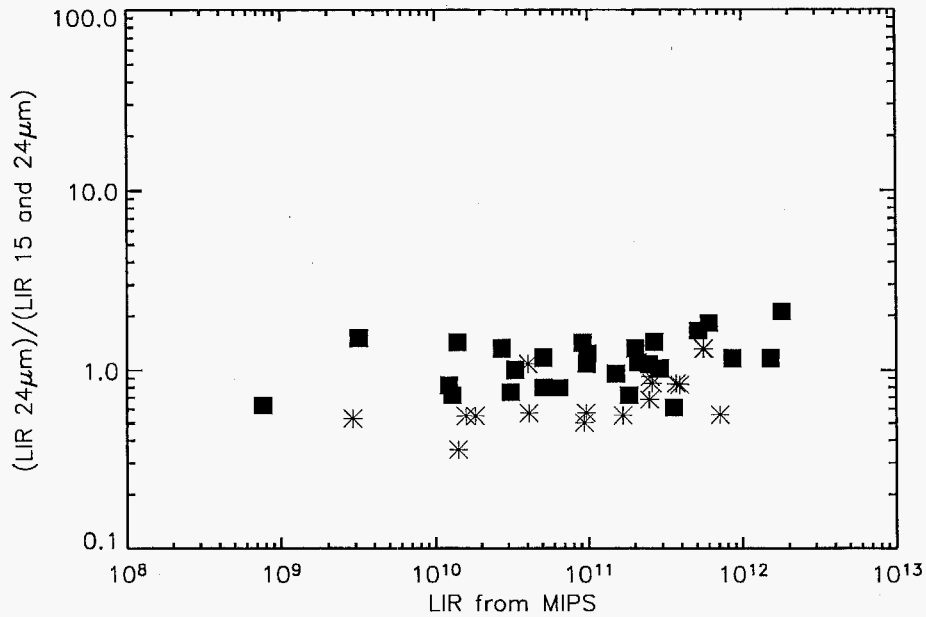


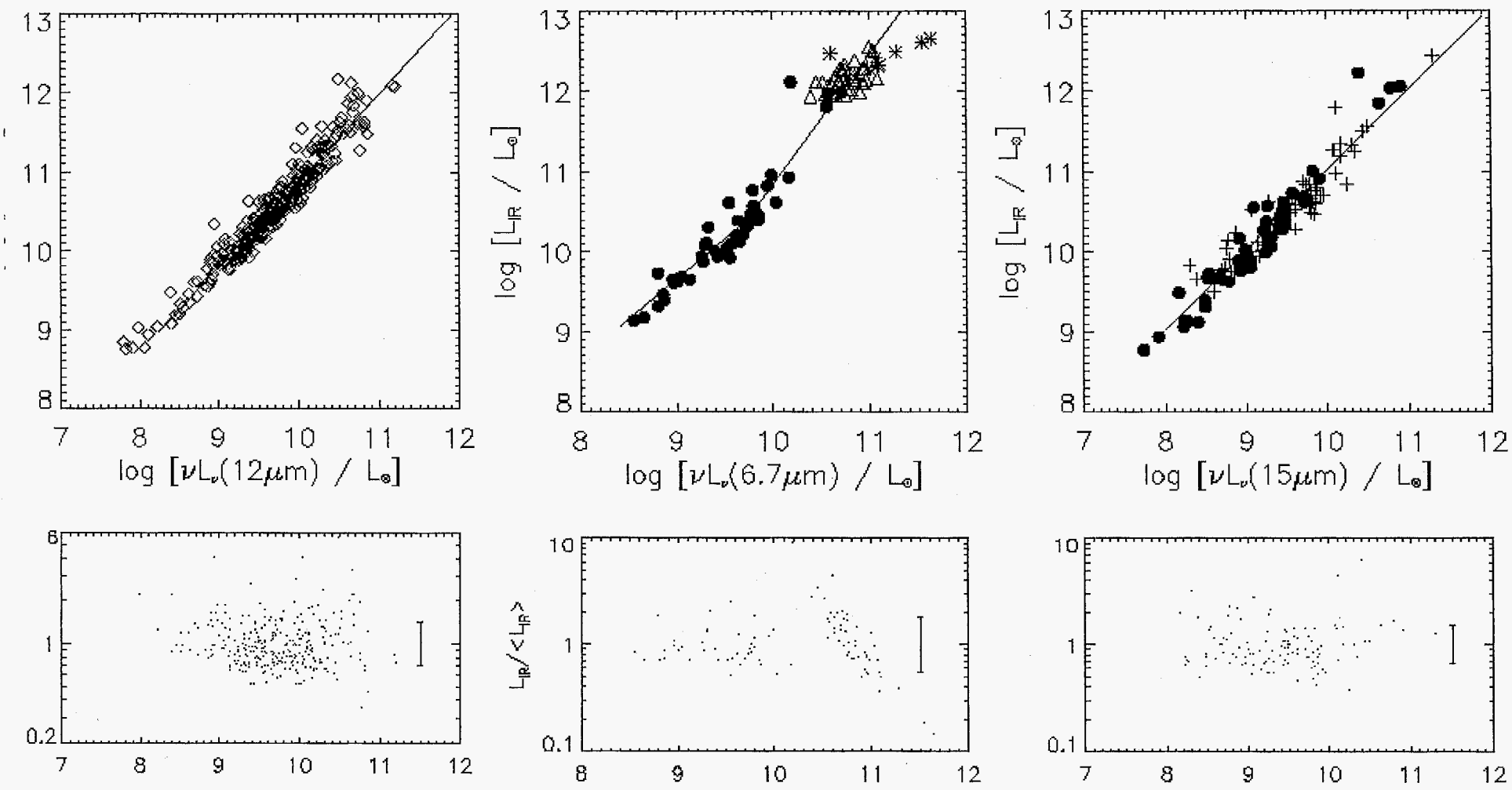


6.2μm PAH emission feature redshifted out of 15μm passband
9.7μm Silicate absorption feature into 24μm filter

However, large scatter possibly associated with variation of PAH strength with redshift: but already seen in local Universe

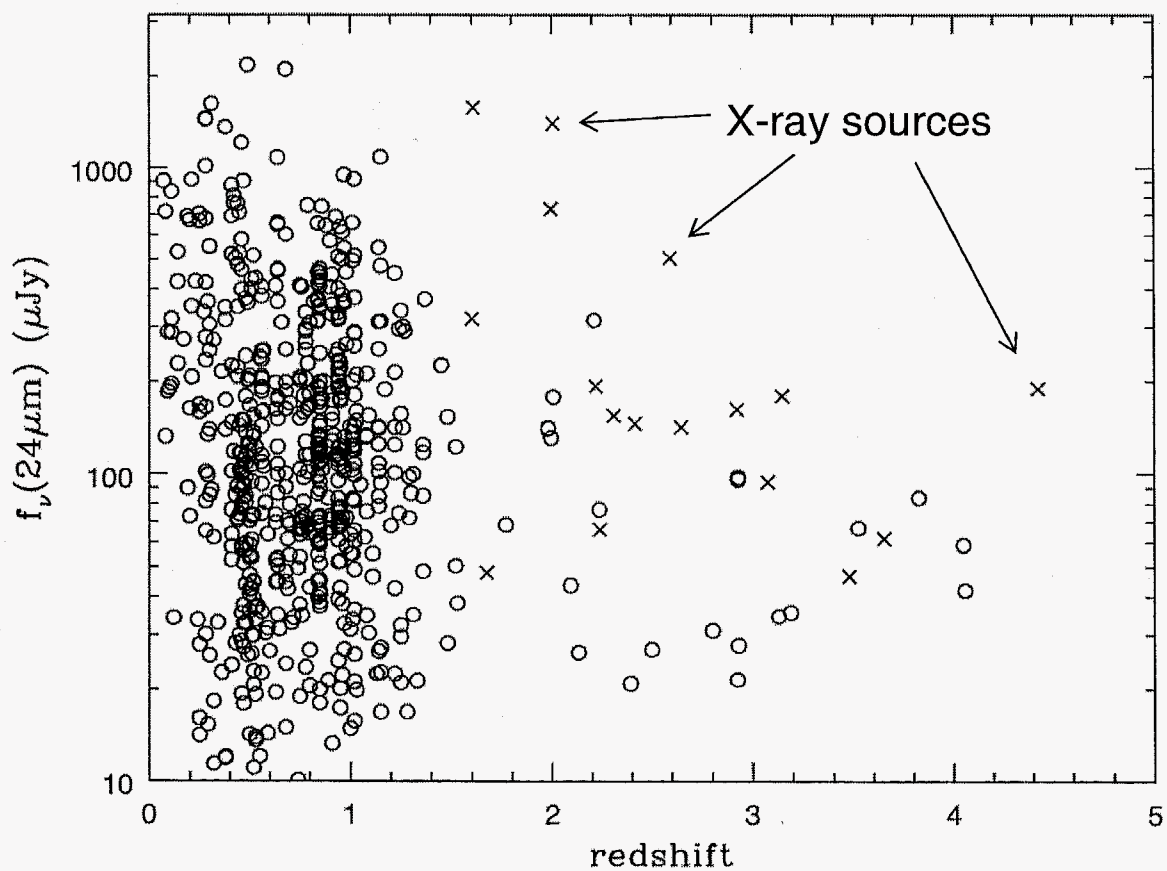


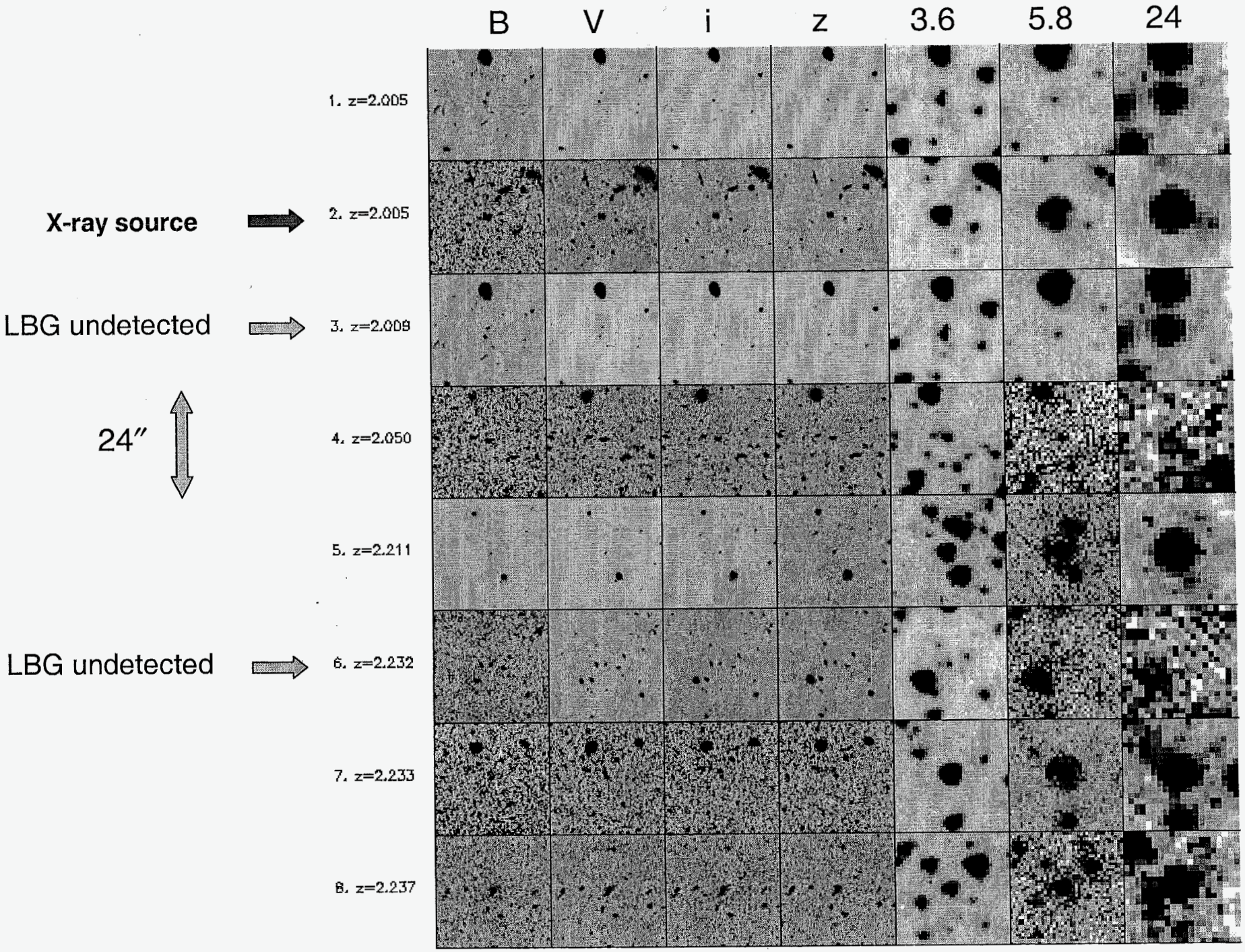




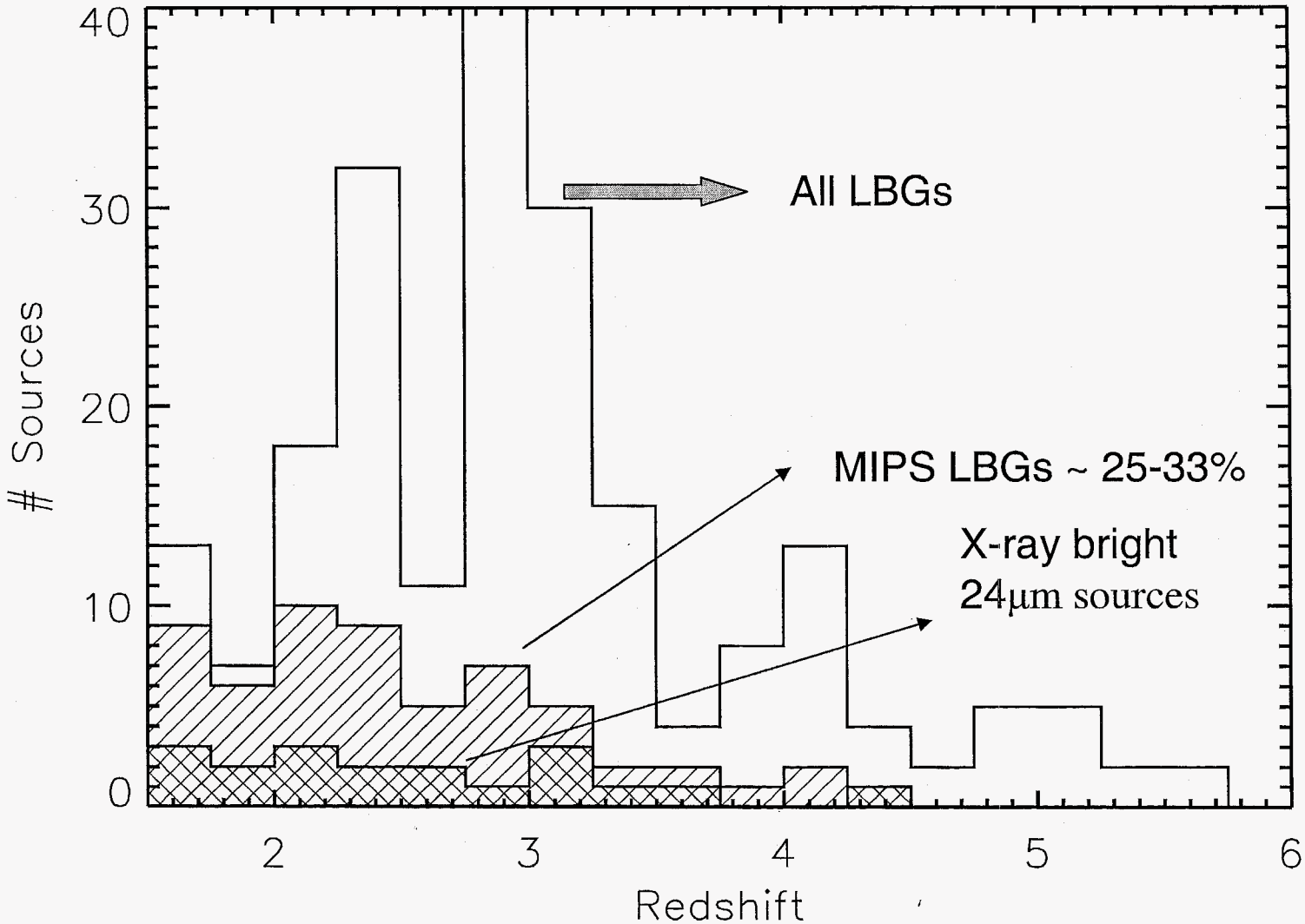
But this scatter in deriving LIR from the PAH is seen in the local Universe already !

Moving on to z~2

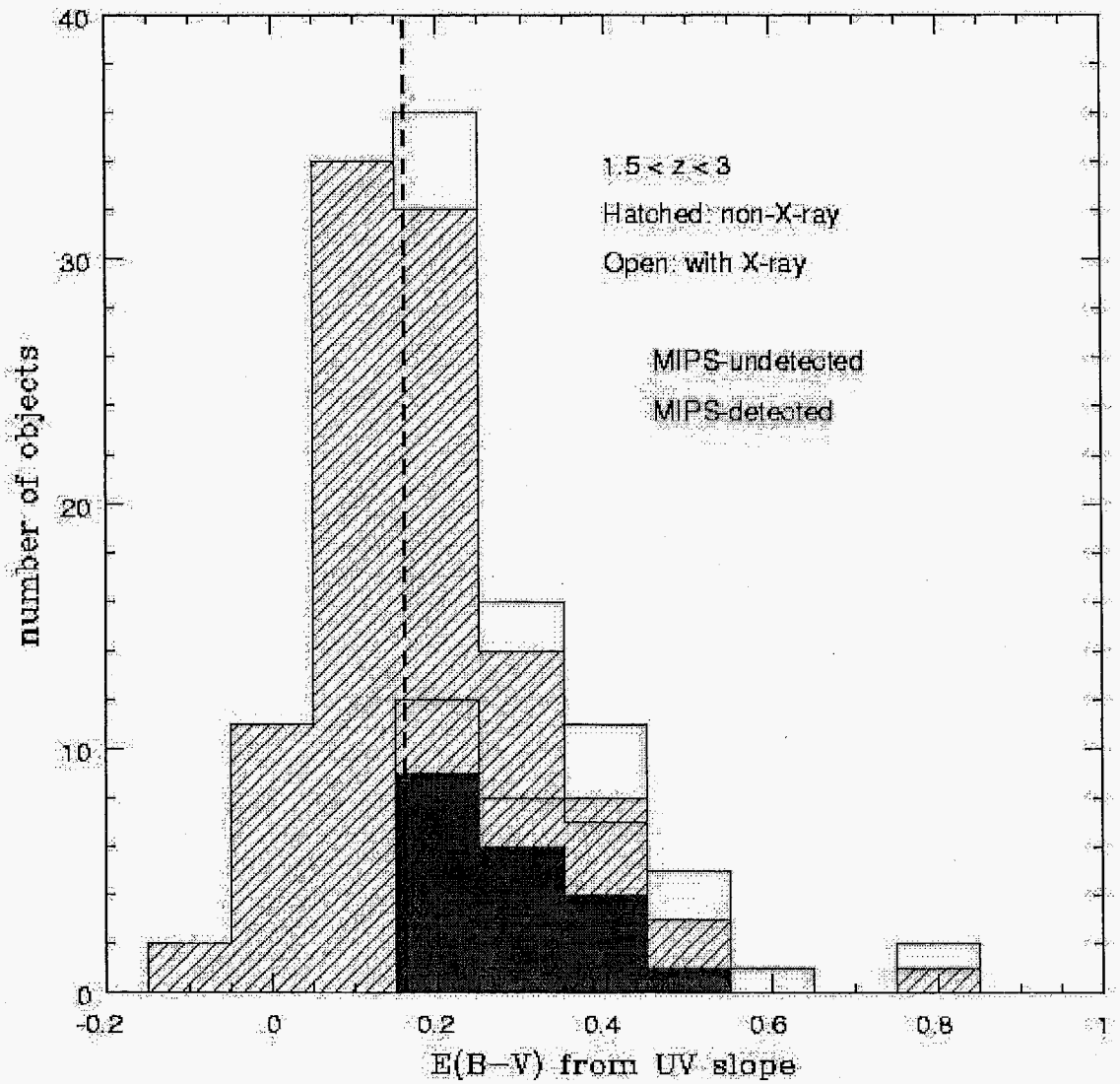



B
V
i
z
3.6
5.8
24
1. z=2.005
2. z=2.005
3. z=2.009
4. z=2.050
5. z=2.211
6. z=2.232
7. z=2.233
8. z=2.237
X-ray source
LBG undetected
24″
LBG undetected

Redshift distribution of z>1.5 Sources

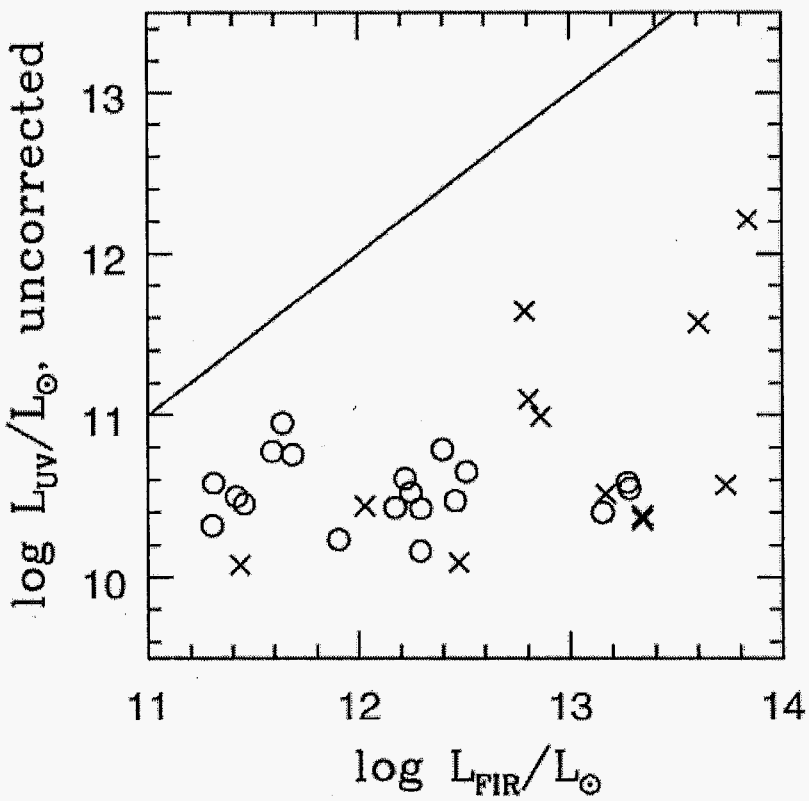


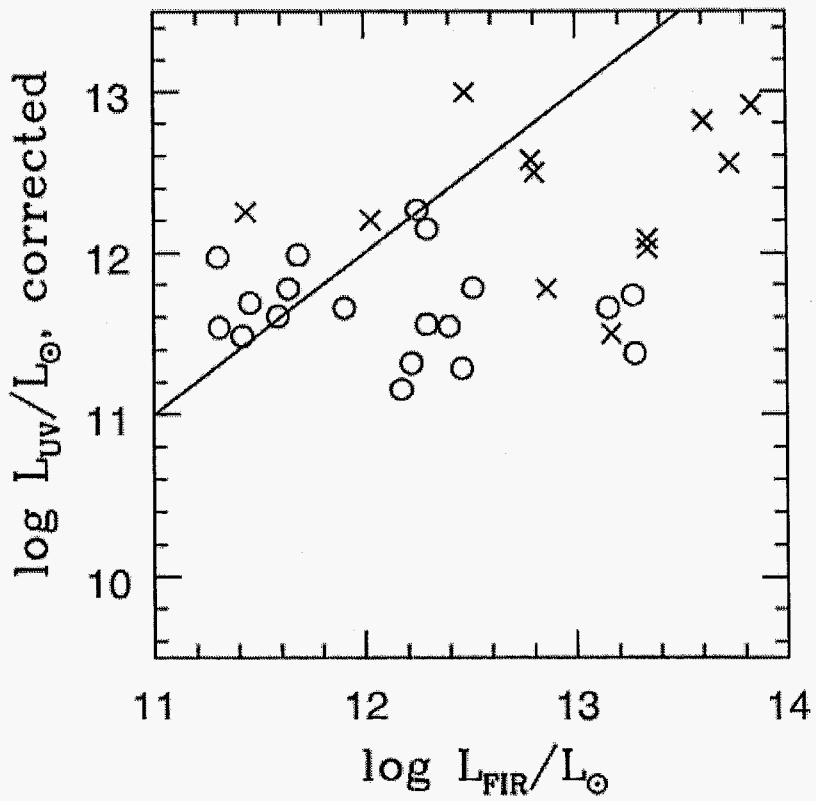
Colors of MIPS detected z~2 sources



Comparing mid-IR vs. UV luminosities at 1.5 < z < 3

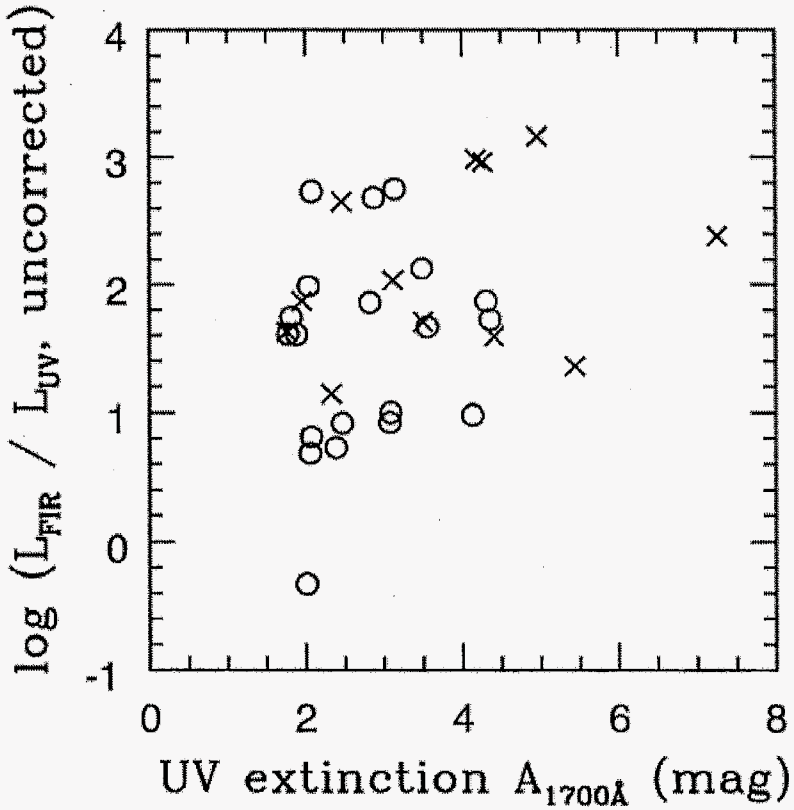
L_{FIR} always exceeds uncorrected LUV.
This remains true at $L_{FIR} > 10^{12}$ L_{sun} even when nominal UV extinction corrections have been applied.



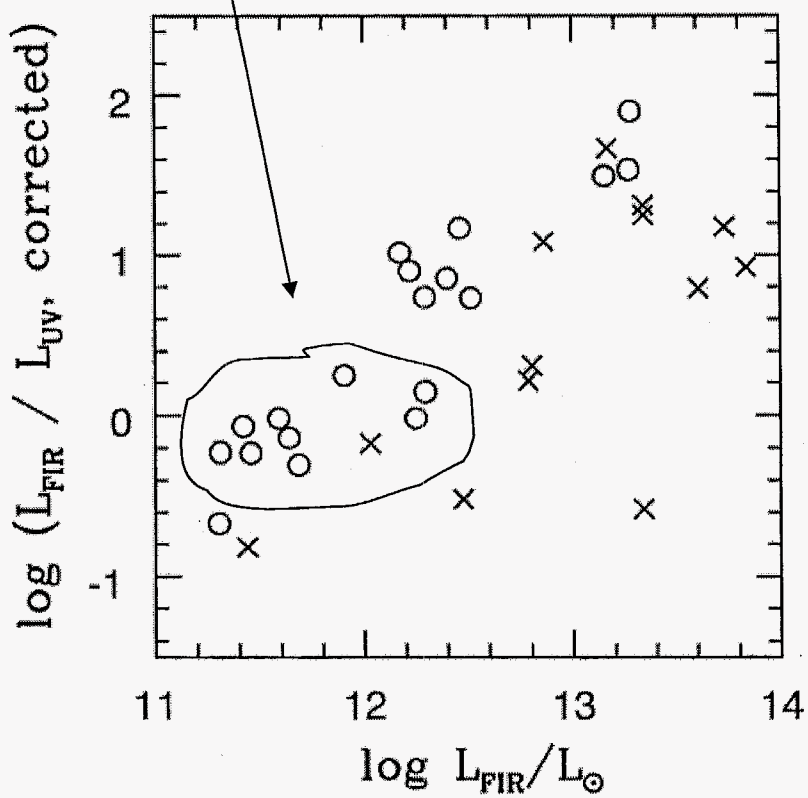


Extinction scaling with L_{IR}

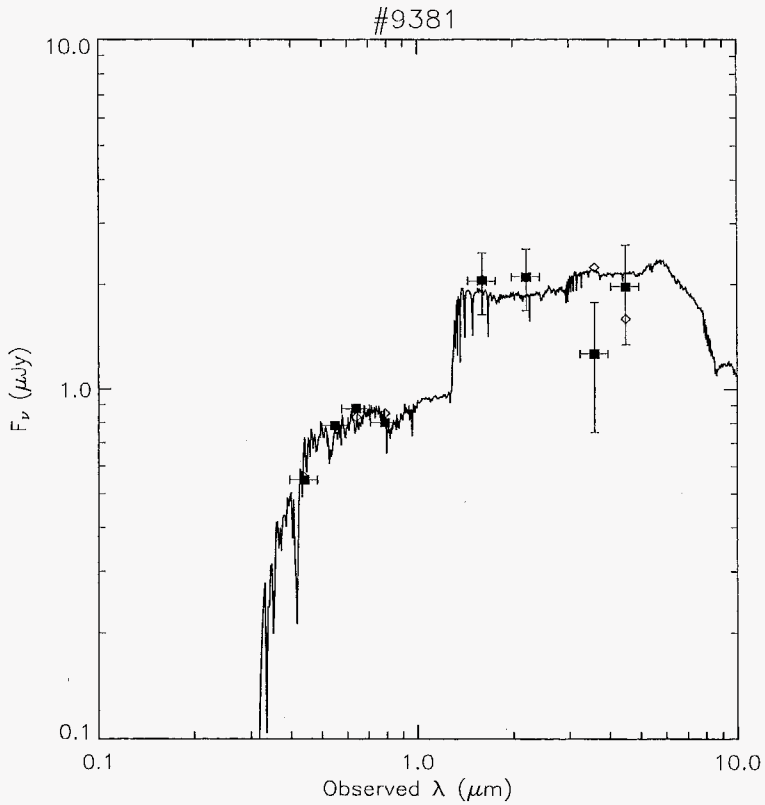
"IRX-β" diagram
(as per Meurer et al.)



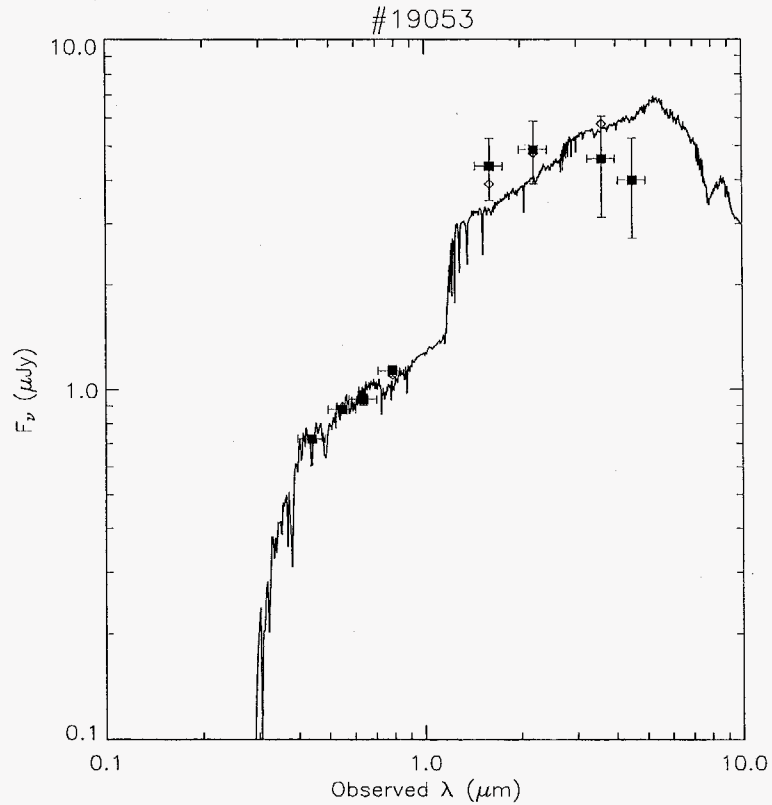
L_{FIR}/L_{UV}(corr.) ~ 1 for many objects at $L_{FIR} < 10^{12}\ L_{sun}$, but >>1 at higher L_{FIR}



Stellar population fitting for LBGs

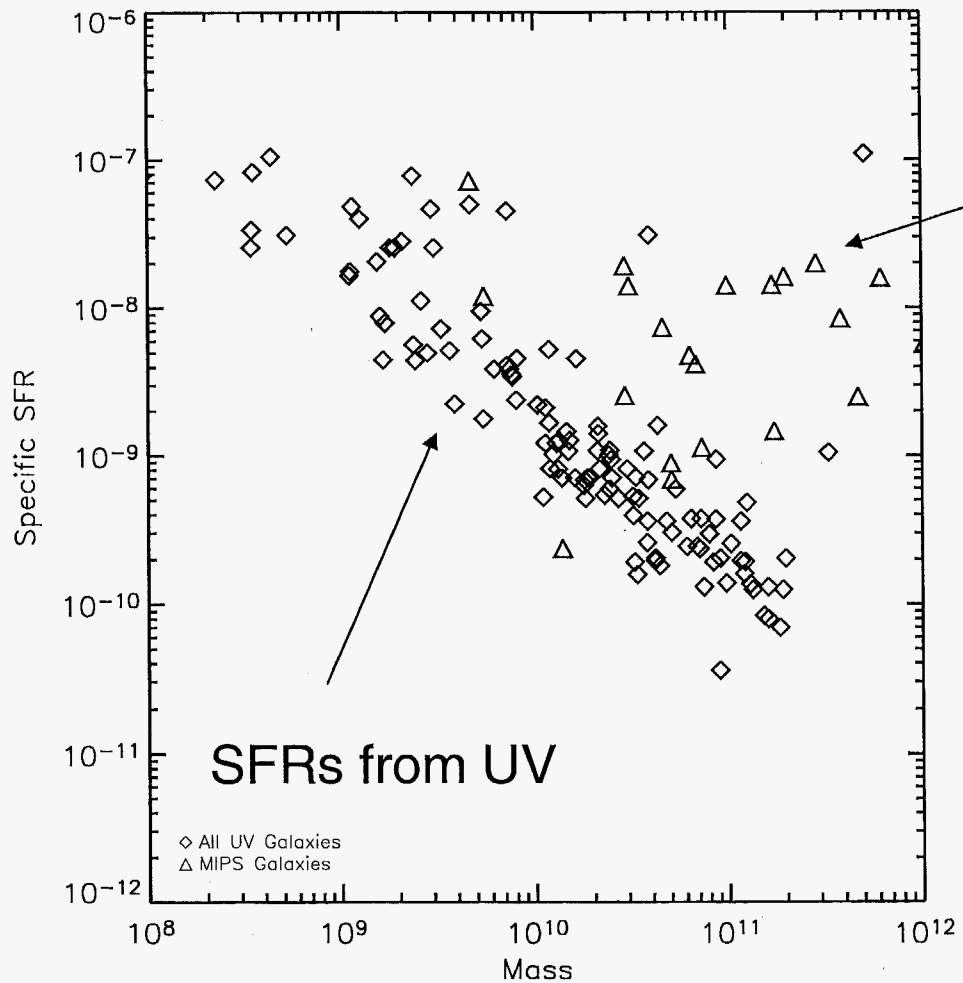


z=2.4, 1.3E11 $M_\odot$, 180 MYr old SB,
A_V~0.1, SFR~20 $M_\odot$/yr



z=2.1, 5E10 M⊙, 450 MYr old SB,
A_V~0.6, SFR(IR)~35, SFR(UV)~10

Specific SFRs vs. stellar mass



SFRs from MIPS

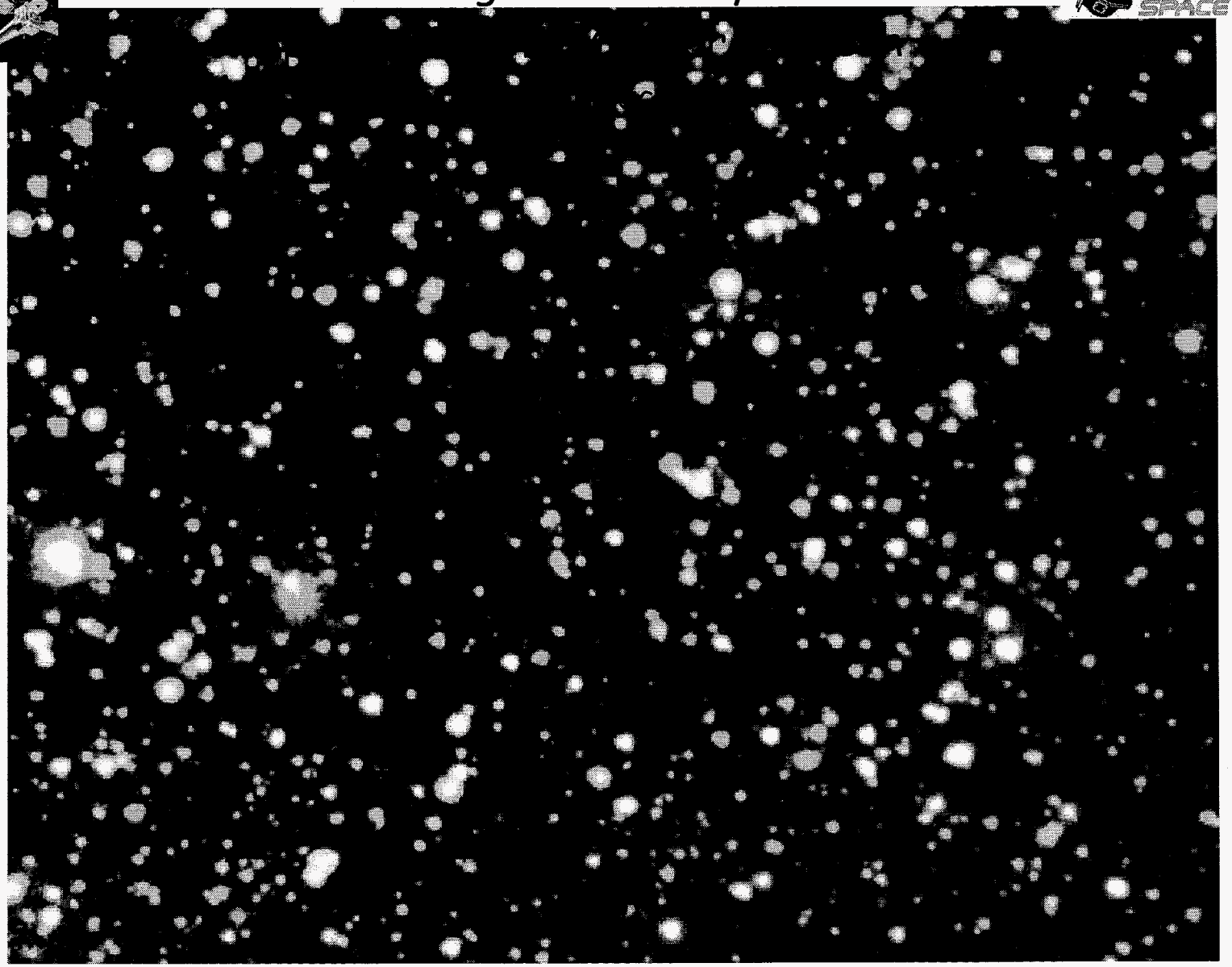
Objects with high 24μm SFRs tend to be among the more massive galaxies

Summary

- There seems to be an unresolved fraction of the near-infrared background. Isotropic zodiacal light or population III stars ?
- Strong evolution of IR luminosity function between z~0 and 1 is confirmed.
- High SFR in ISOCAM galaxies but large scatter in bolometric correction due to variation in strength of PAH
- Dusty star-formation reasonably well traced in the LIG range from UV but fails at higher bolometric luminosities.
- 24μm detected galaxies appear to be more massive – is there a bias or are massive galaxies more likely to have violent star-formation ?
- A wealth of results forthcoming !

Spitzer/GOODS - Constraints on the EBL and Galaxy Evolution

Ranga-Ram Chary



GOODS-gang

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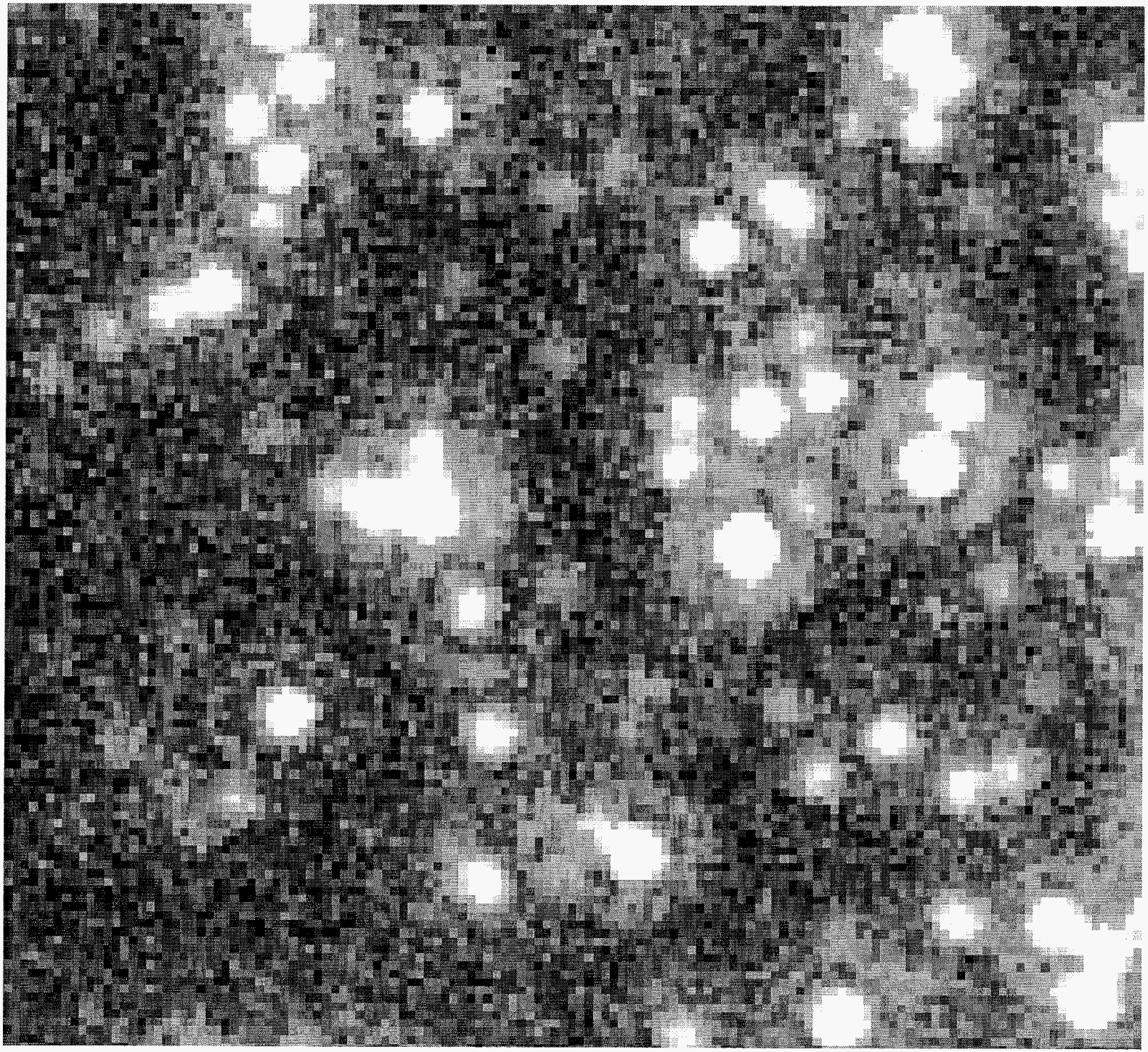


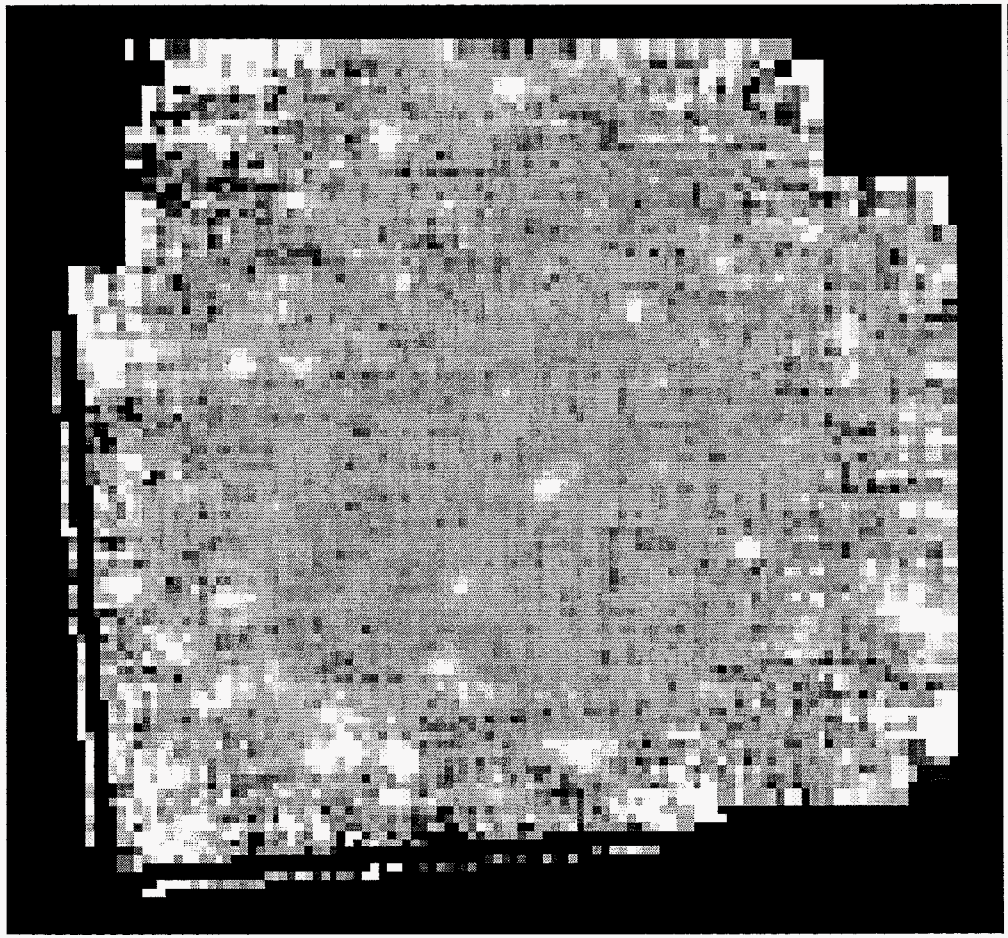
2.6'

3.6μm
25 hrs

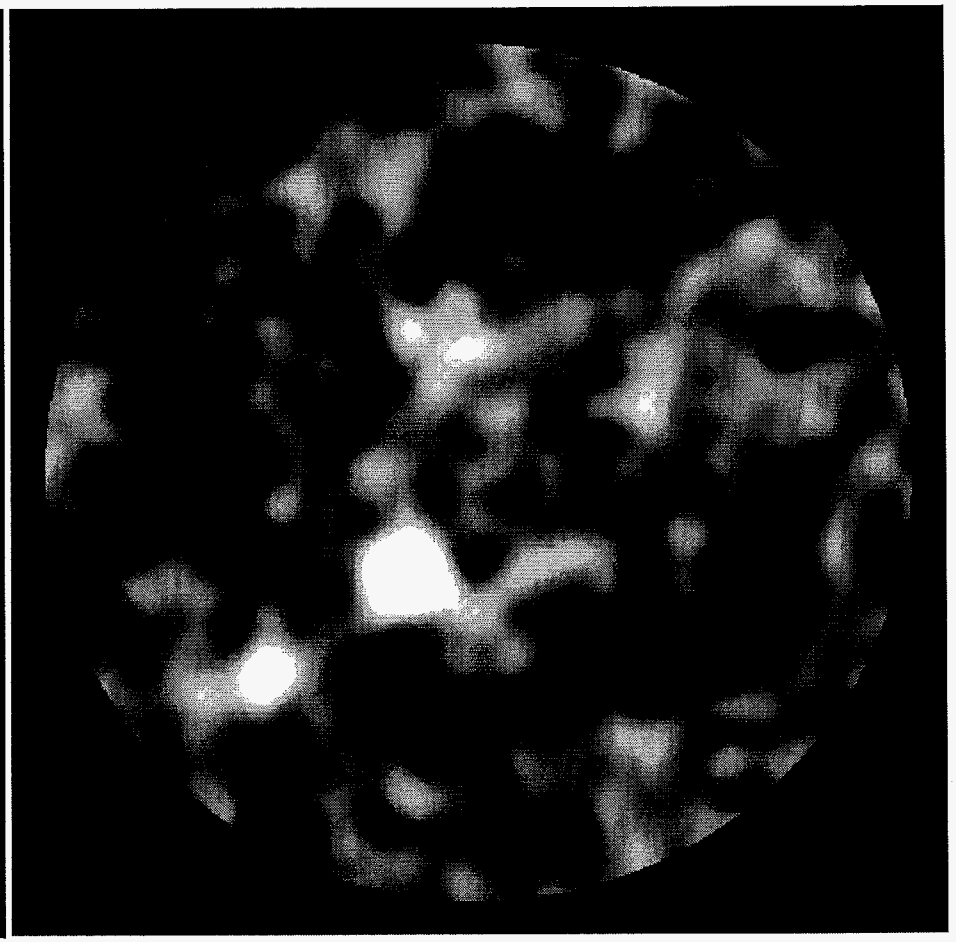
5.8μm
25 hrs

24μm
10.9 hrs

State of the Art from the '90s



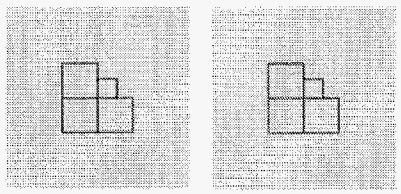
ISOCAM 15 microns (Mann et al. 1997)



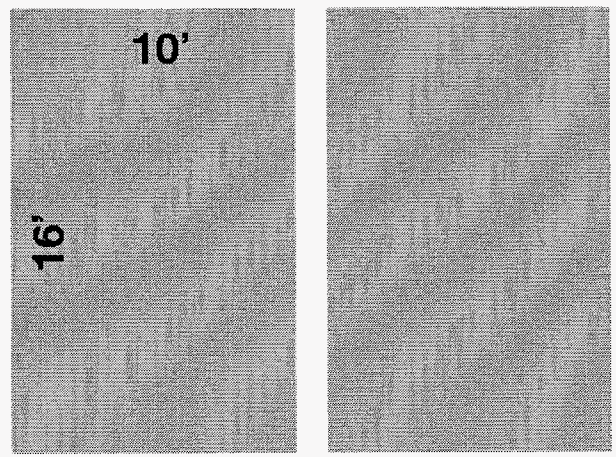
SCUBA 850 microns (Hughes et al.)

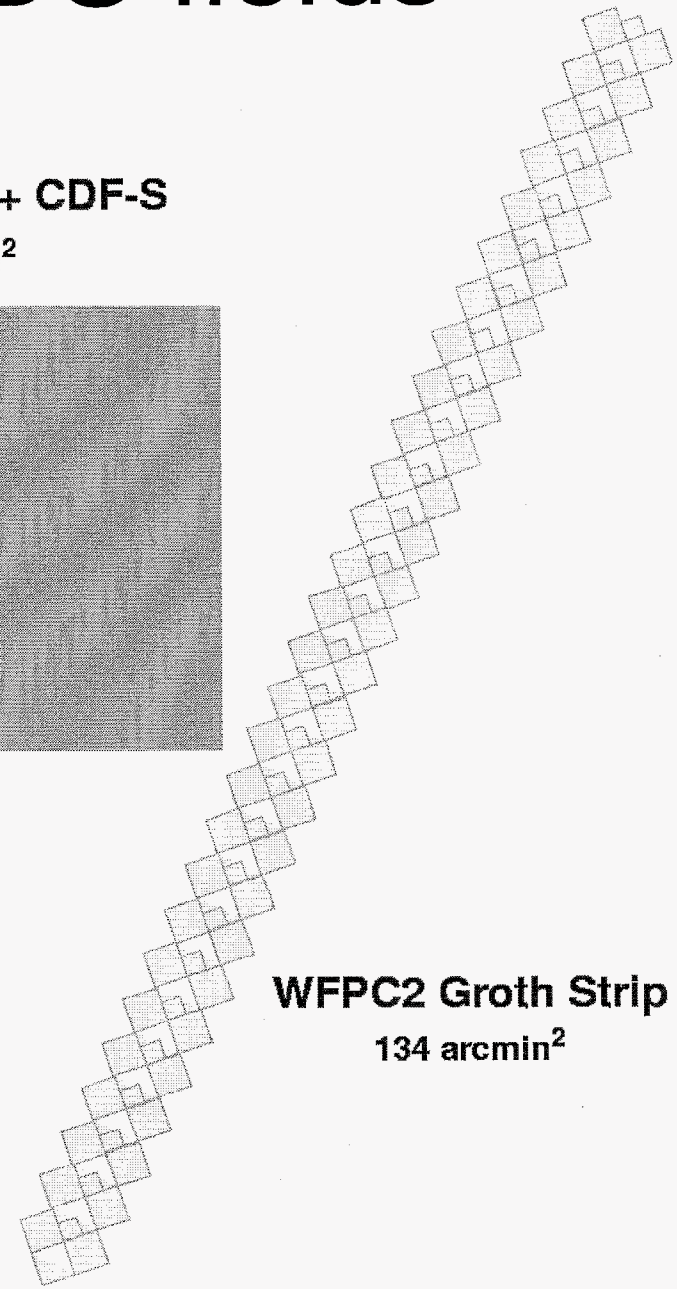
The GOODS fields

WFPC2 HDF N+S
+ flanking fields
10 + 85 arcmin^2



GOODS HDF-N + CDF-S
330 arcmin^2





WFPC2 Groth Strip
134 arcmin^2

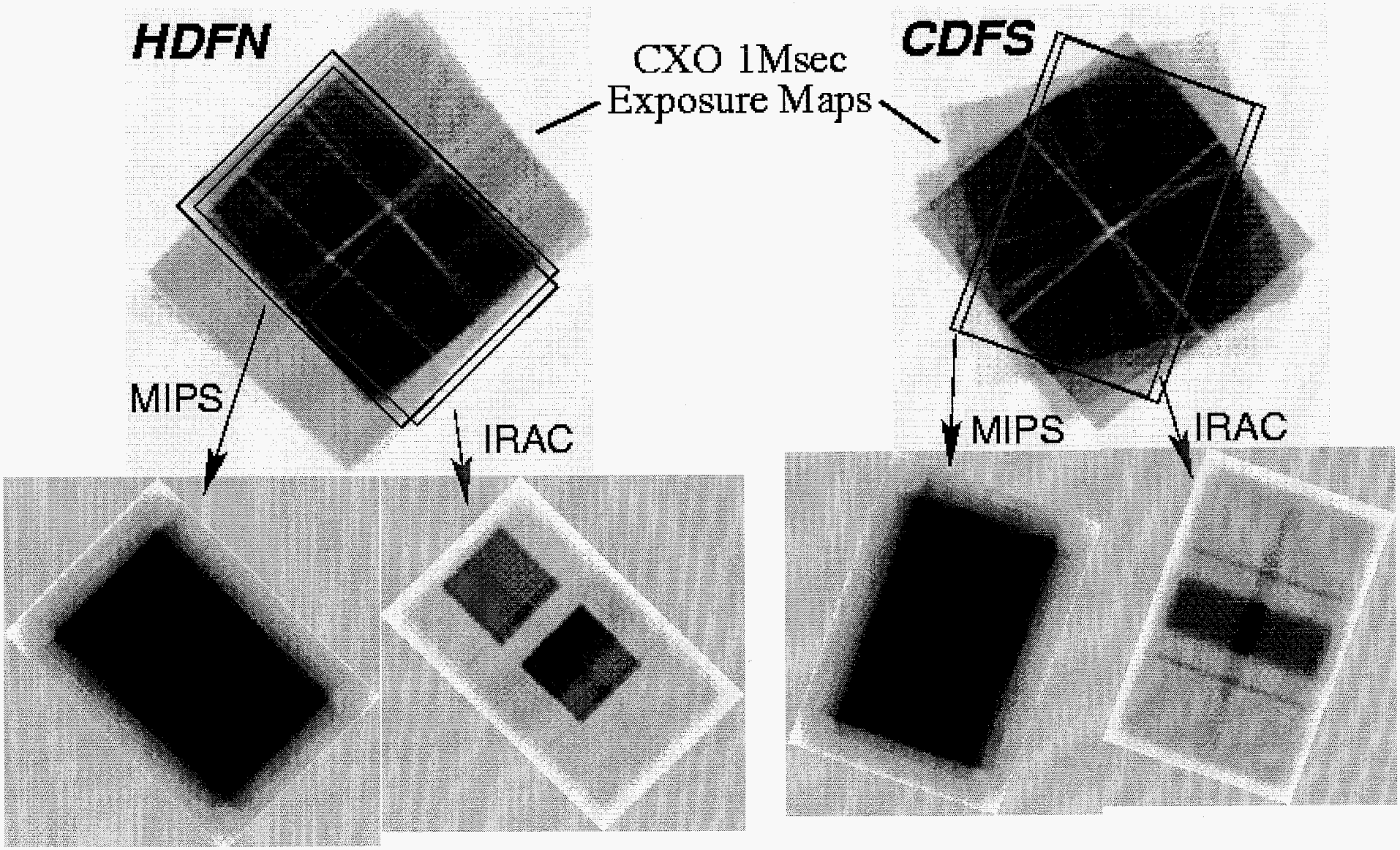
Two GOODS fields: HDF-North & CDF-South
~33x solid angle of combined HDF-N+S central fields
~ 4x solid angle of combined HDF-N+S flanking fields
~2.5x solid angle of WFPC2 Groth Strip
~18 x 30 h_{70}^{-1} Mpc co-moving transverse extent at $z = 3$

Two fields provide:

- Access to observers in both hemispheres
- Insurance against cosmic variance
- Maximal overlap with deepest X-ray data

Both fields at high galactic & ecliptic latitude, with low zodiacal & galactic foregrounds, N(HI), stellar & radio contamination, etc.

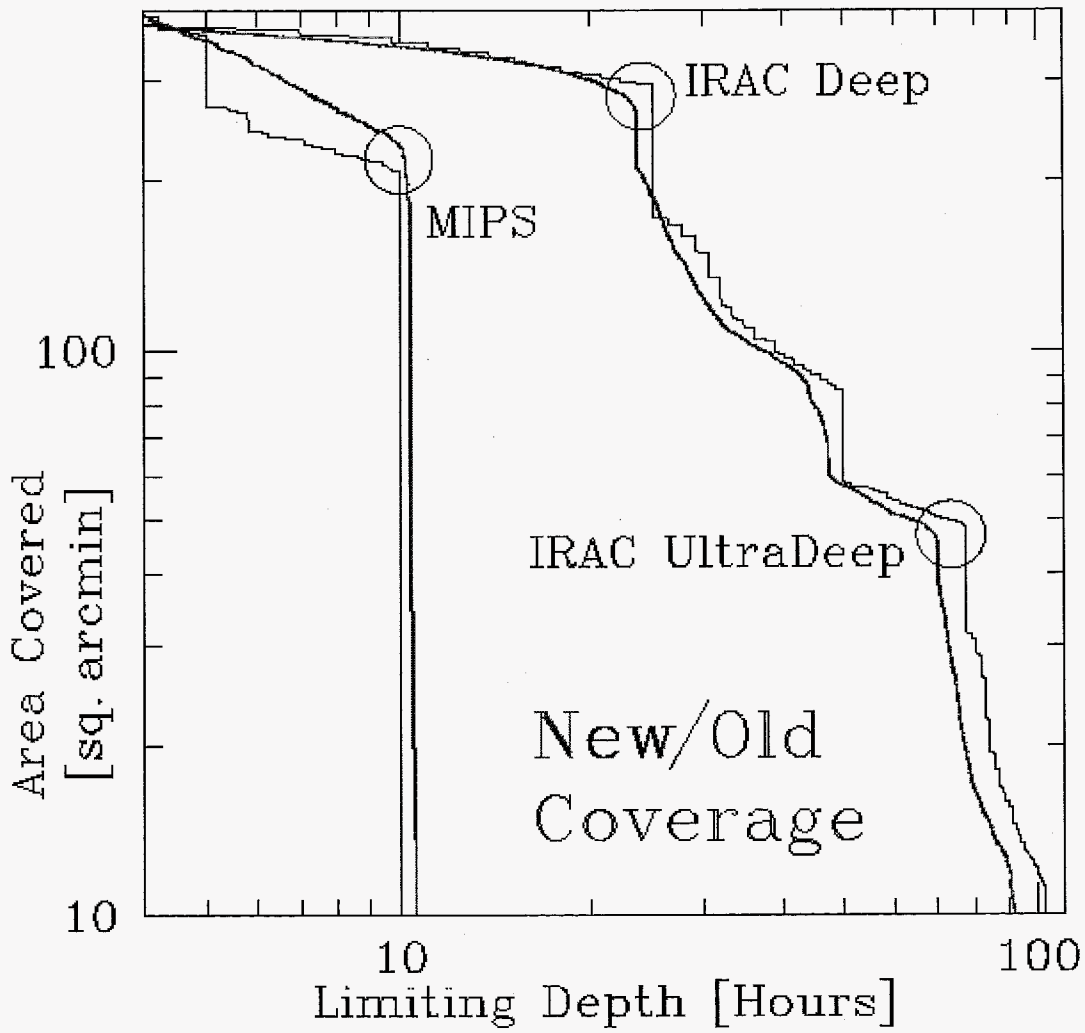
CXO vs. GOODS exposure maps



Summary of SIRTF observations

Component	IRAC Deep	IRAC Ultradeep	MIPS
Nominal area	~300 arcmin^2	~50 arcmin^2	~300 arcmin^2
Exposure time per map position	23.6 h (47.2 h in overlap)	+46.5 h (total 70.1/93.7 h)	10.4 h
Total time	409 h	99.3 h	139.2 h
Individual exposure time	200 s	200 s	30 s
Total dithers per map position	425	837	240
AOR information:			
Map positions per AOR	2 x 2	1	2
Number of AORs	68	18	48
Total clock time per AOR	21653 s	19852 s	10442 s
Time per map position per AOR	5000 s	18600 s	4680 s
Dithers per map position	25	93	30
Repeats within each AOR	1	1	5 (6)
AOR repeats	17	9	4
Epochs per field / total	2 / 4	2 / 2	1 / 2

GOODS area vs. depth



The Great Observatories Origins Deep Survey (GOODS)

Aim: **to establish ultradeep reference fields with public data sets from X-ray through radio wavelengths for the study of galaxy and AGN evolution over the broadest accessible range of redshift and cosmic time.**

GOODS unites the deepest surveys from NASA's Great Observatories (*Spitzer, Hubble, Chandra*), ESA's *XMM-Newton*, and the best ground-based observatories.

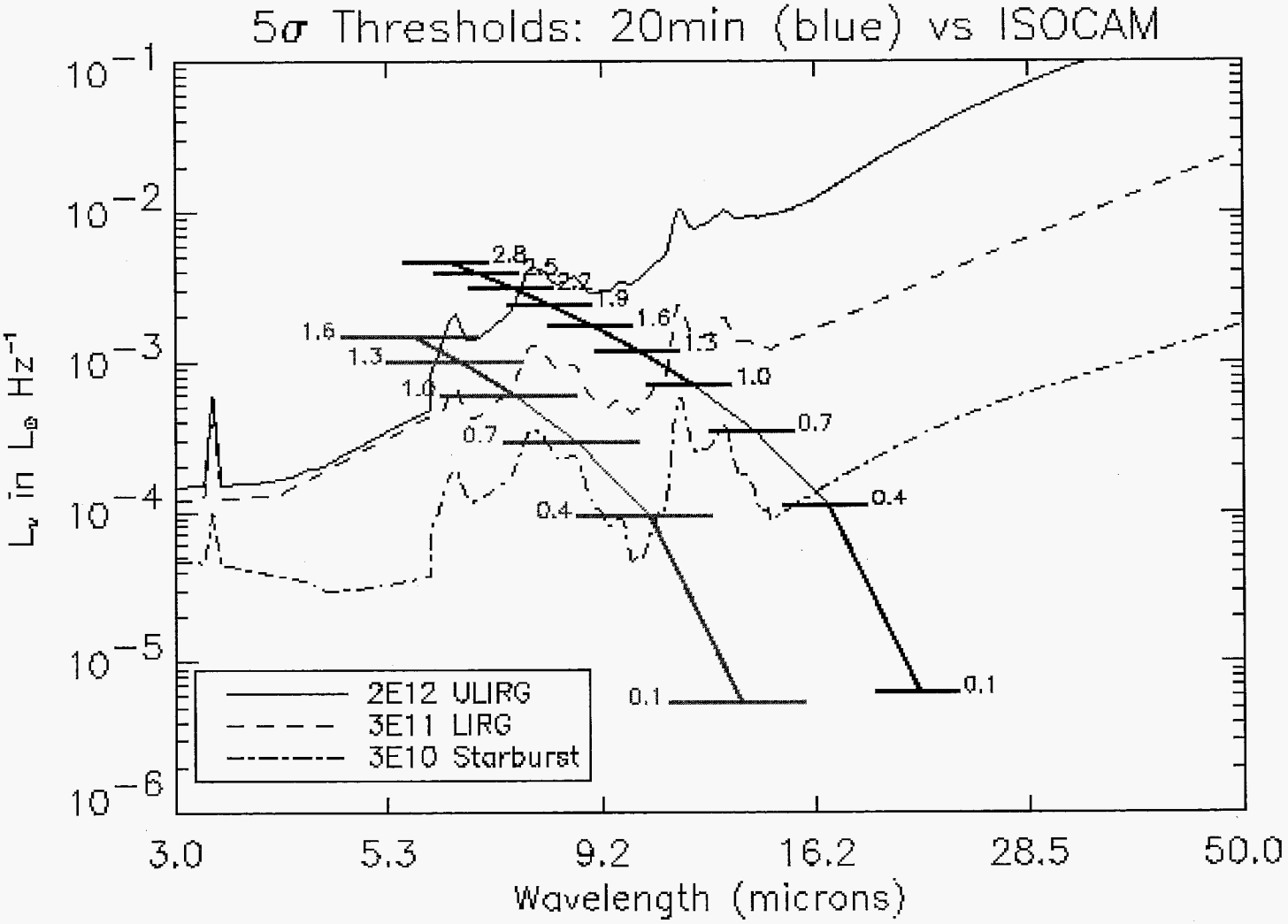
GOODS provides:

- Deepest SIRTF coverage from 3.6 – 24 μm (IRAC-G. Fazio et al., MIPS-G. Rieke et al.)
- "Near-HDF" depth 4-band HST/ACS imaging
- Deepest X-ray coverage from Chandra & XMM-Newton
- Extensive supporting observations (NOAO, ESO, Gemini, Keck, ATCA, VLA, etc.)
- Public release of data and data products

Primary science goals:

- The mass assembly history of galaxies
- Census of energetic output from star formation and supermassive black holes
- Emergence of the Hubble Sequence
- Supernovae at high redshift and the cosmic expansion
- Dark matter distribution through weak gravitational lensing
- Measurements or limits on the discrete source component of the EBL

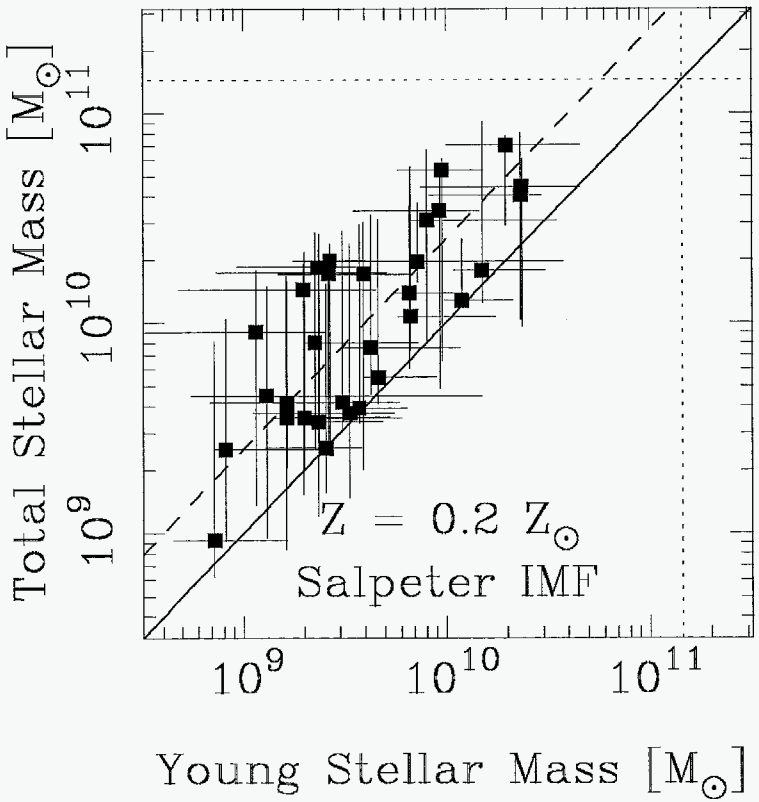
The Motivation for Deep MIPS 24 micron: Detect thermal dust emission from LIGs at z~2

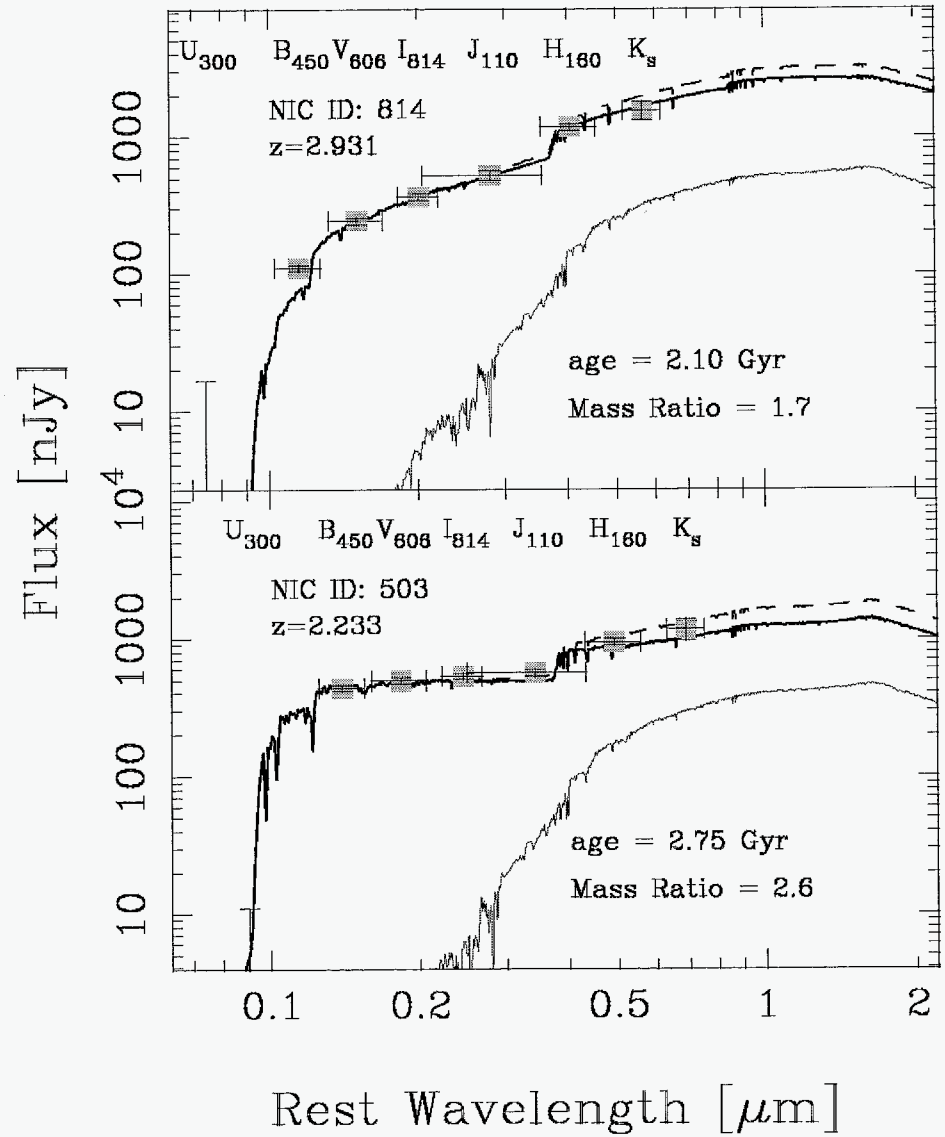


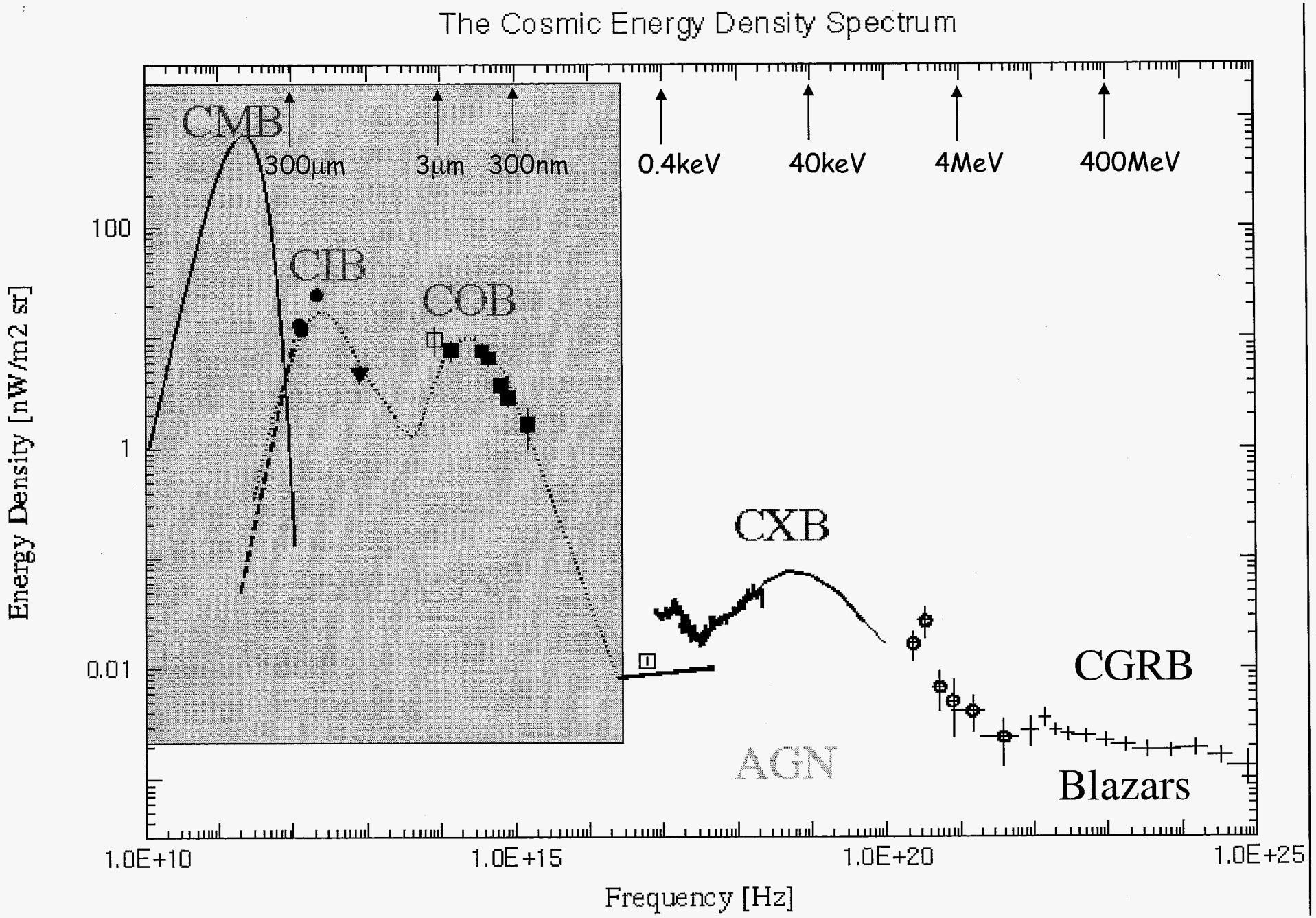
ISOCAM HDF-N depth of 0.1 mJy

Motivation for Deep IRAC – Detect old stellar component of L* galaxies to z~3

Significant mass from an older stellar population could be hidden by ongoing star formation.



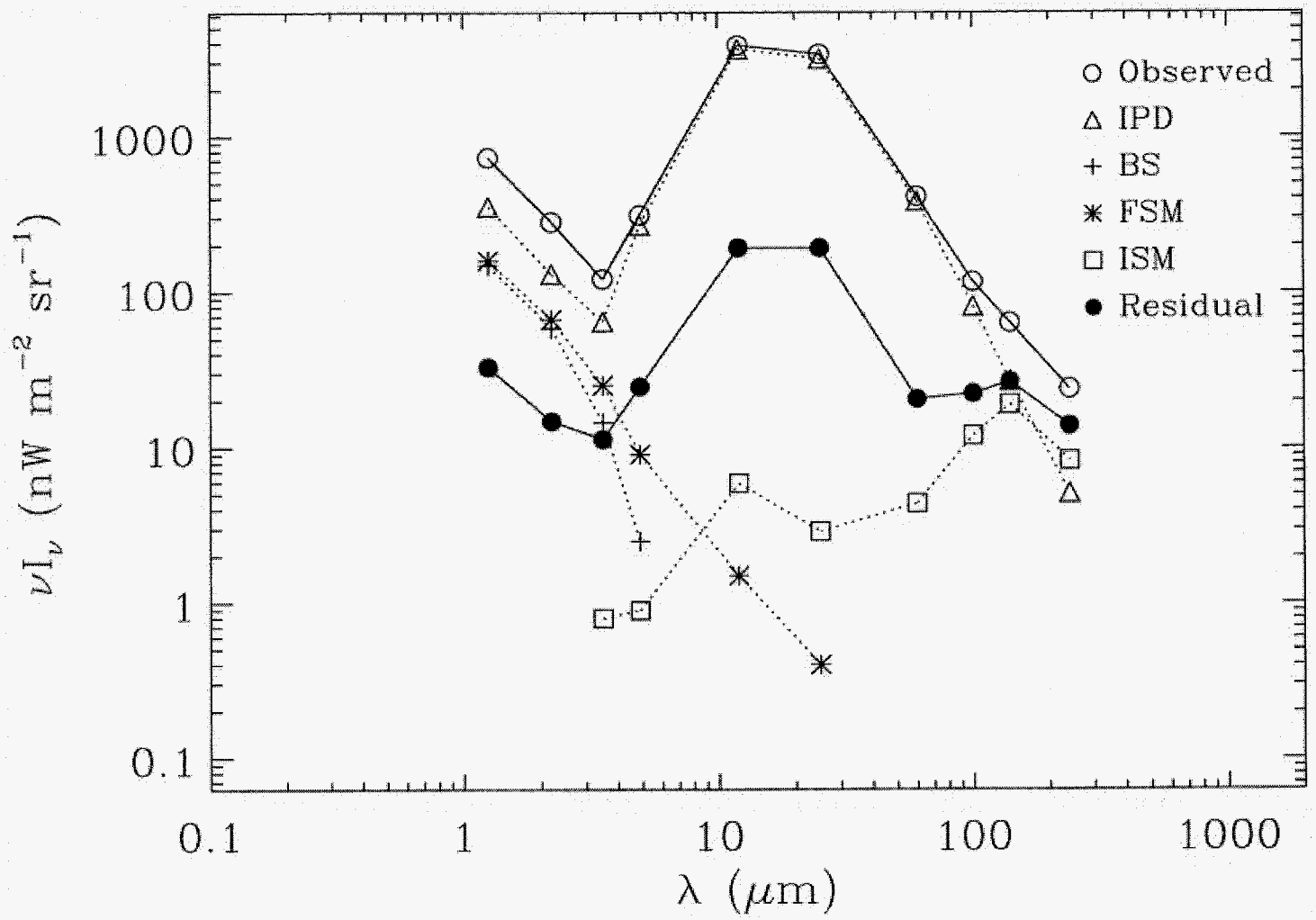



The Cosmic Energy Density Spectrum
CMB
300μm
3μm
300nm
0.4keV
40keV
4MeV
400MeV
CIB
COB
CXB
CGRB
AGN
Blazars
100
1
0.01
Energy Density [nW/m2 sr]
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]

Hasinger '00

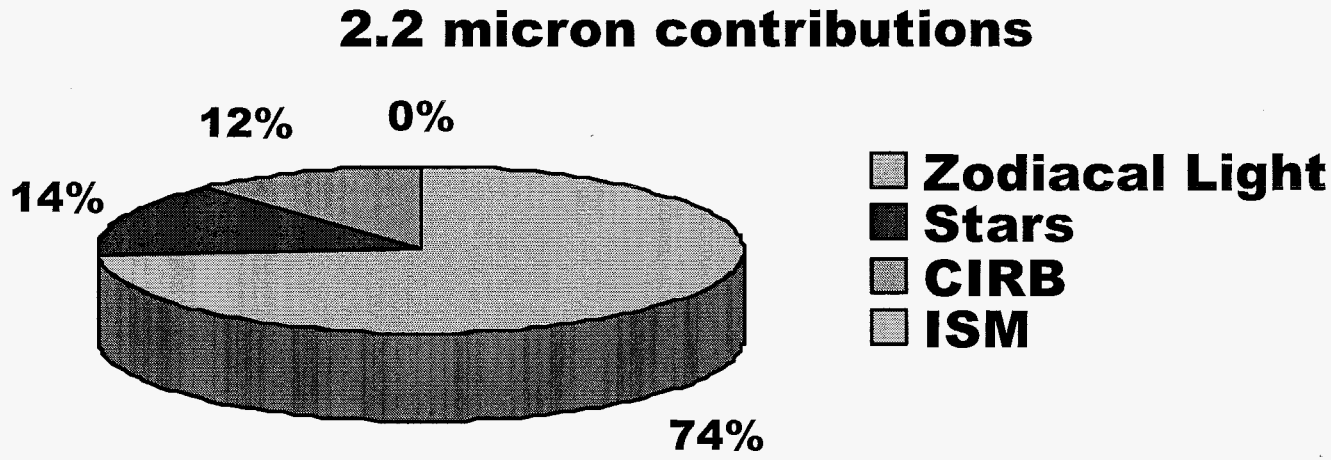
The Infrared Background

- Atmospheric foreground
- Instrumental thermal foreground
- Zodiacal light : thermal emission and scattering; minimum of both at 3.5 microns.
- Galactic foreground: stars at near- infrared (λ<5 μm) wavelengths; dust at mid- (5-30μm) and far-infrared (30-1000 μm) wavelengths.
- The residual is the Cosmic Infrared Background = Extragalactic Background Light $\geq$ Integrated Galaxy Light (IGL).



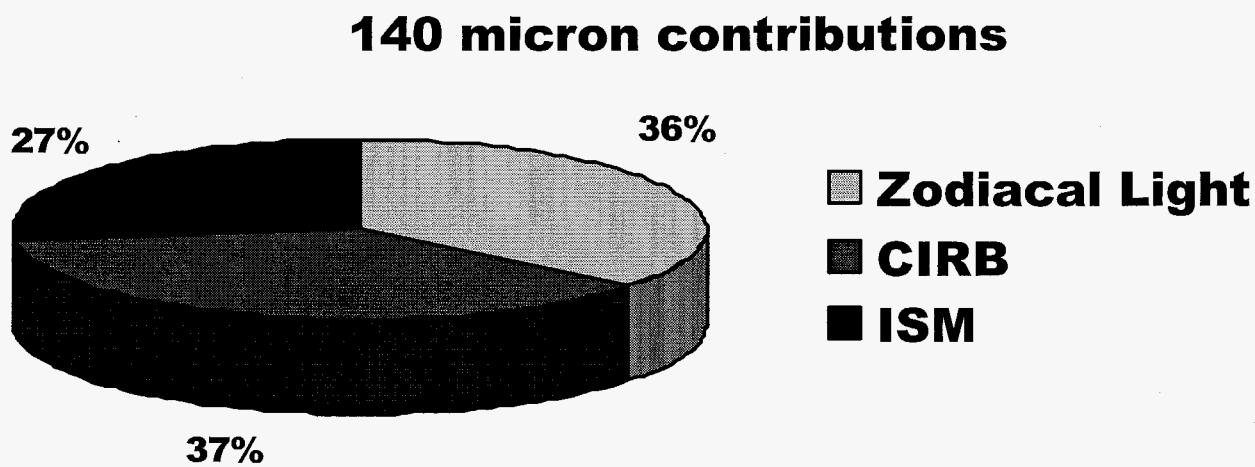
Lockman Hole Intensity Decomposition
(Hauser et al. 1998)

Decomposition of the Sky Background at Infrared Wavelengths

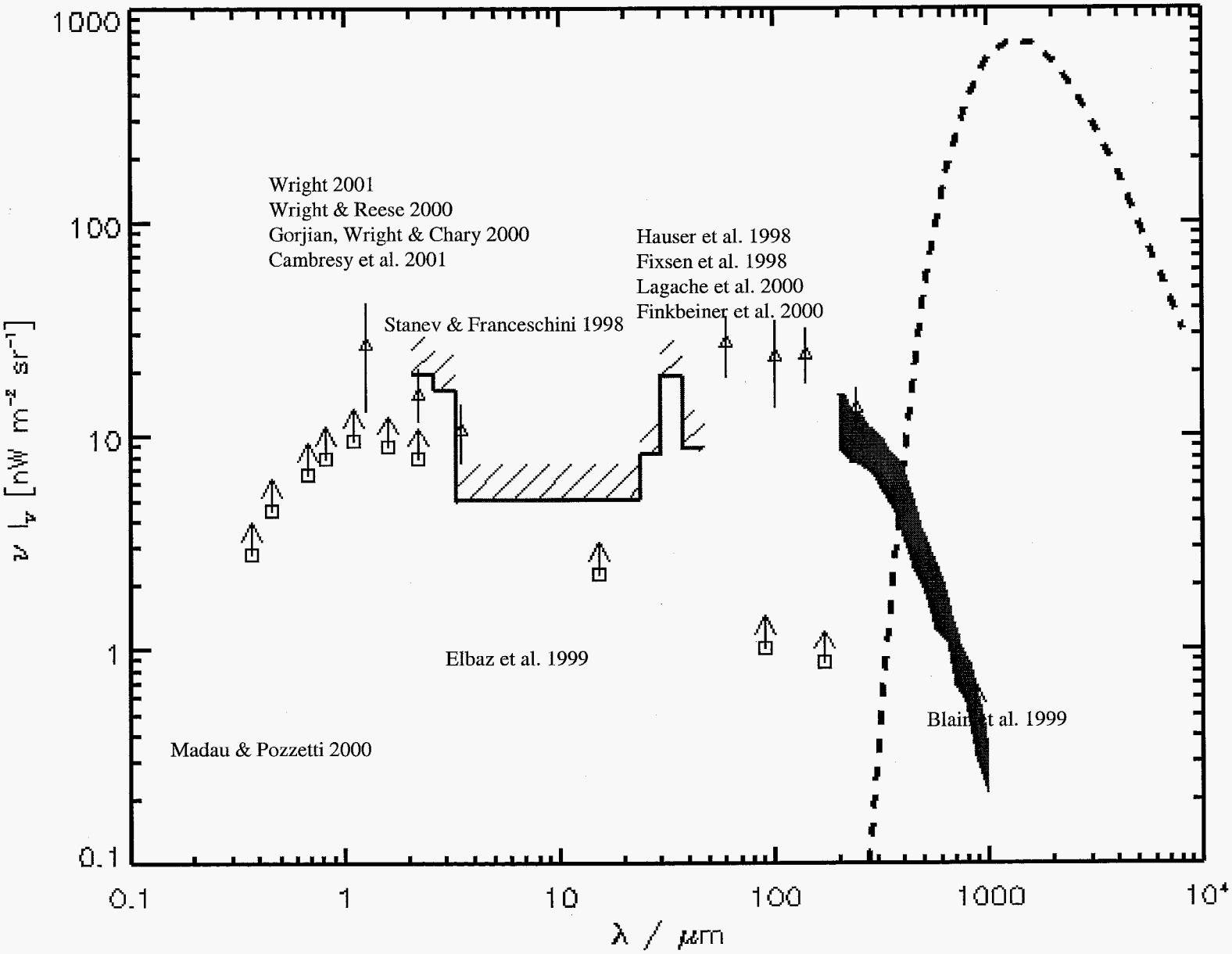


CIRB (nW m^{-2} sr^{-1})

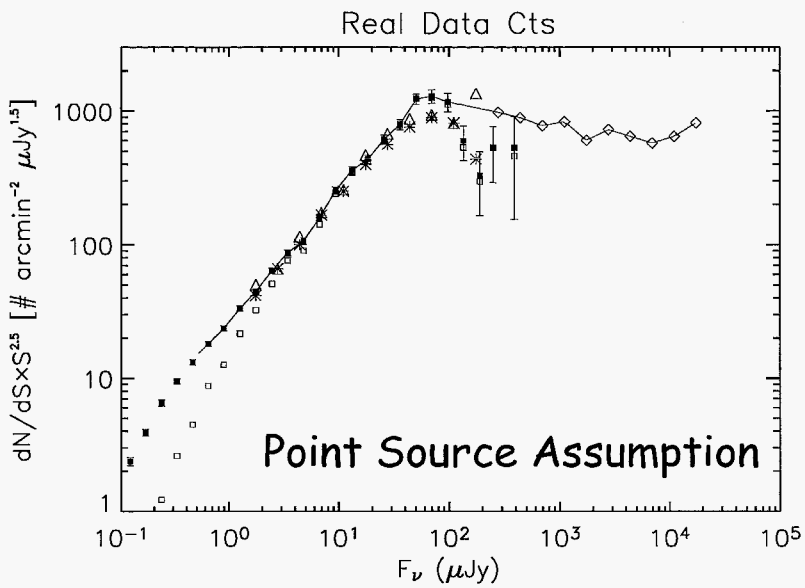
λ	νI_ν
2.2:	22.4±6.0
3.5:	11.0±3.3
140:	25±7
240:	14±3

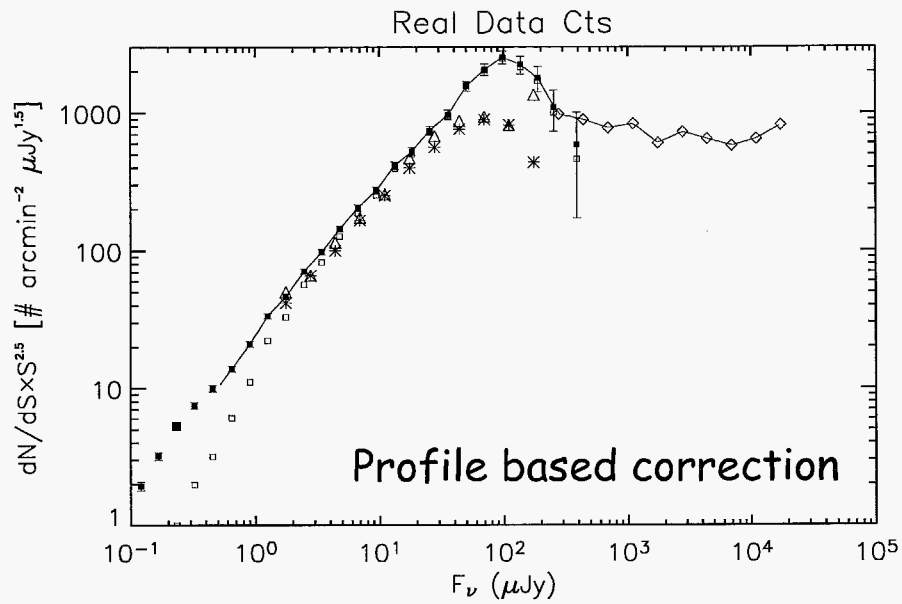


CIRB Spectrum

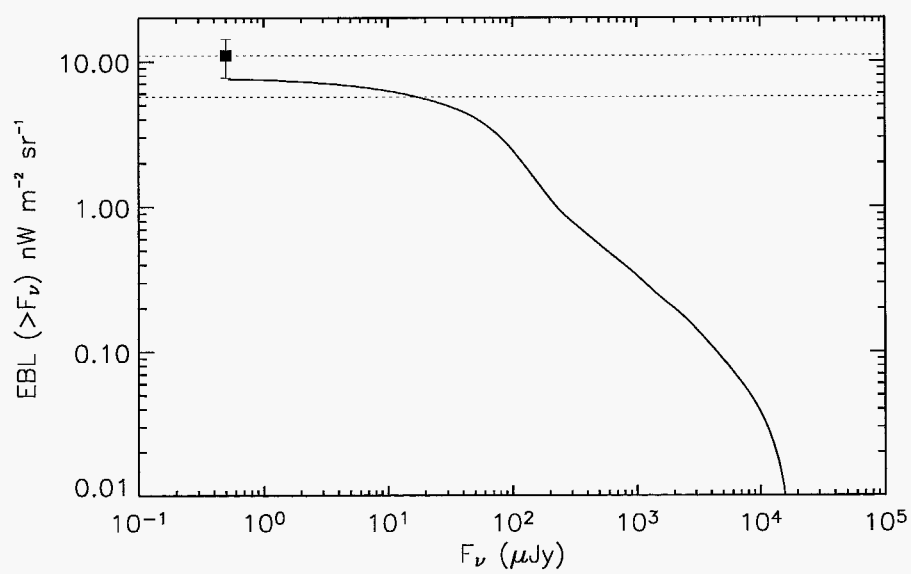


Estimating IGL from Galaxy Counts - Need Aperture Corrections as a function of Galaxy Morphology

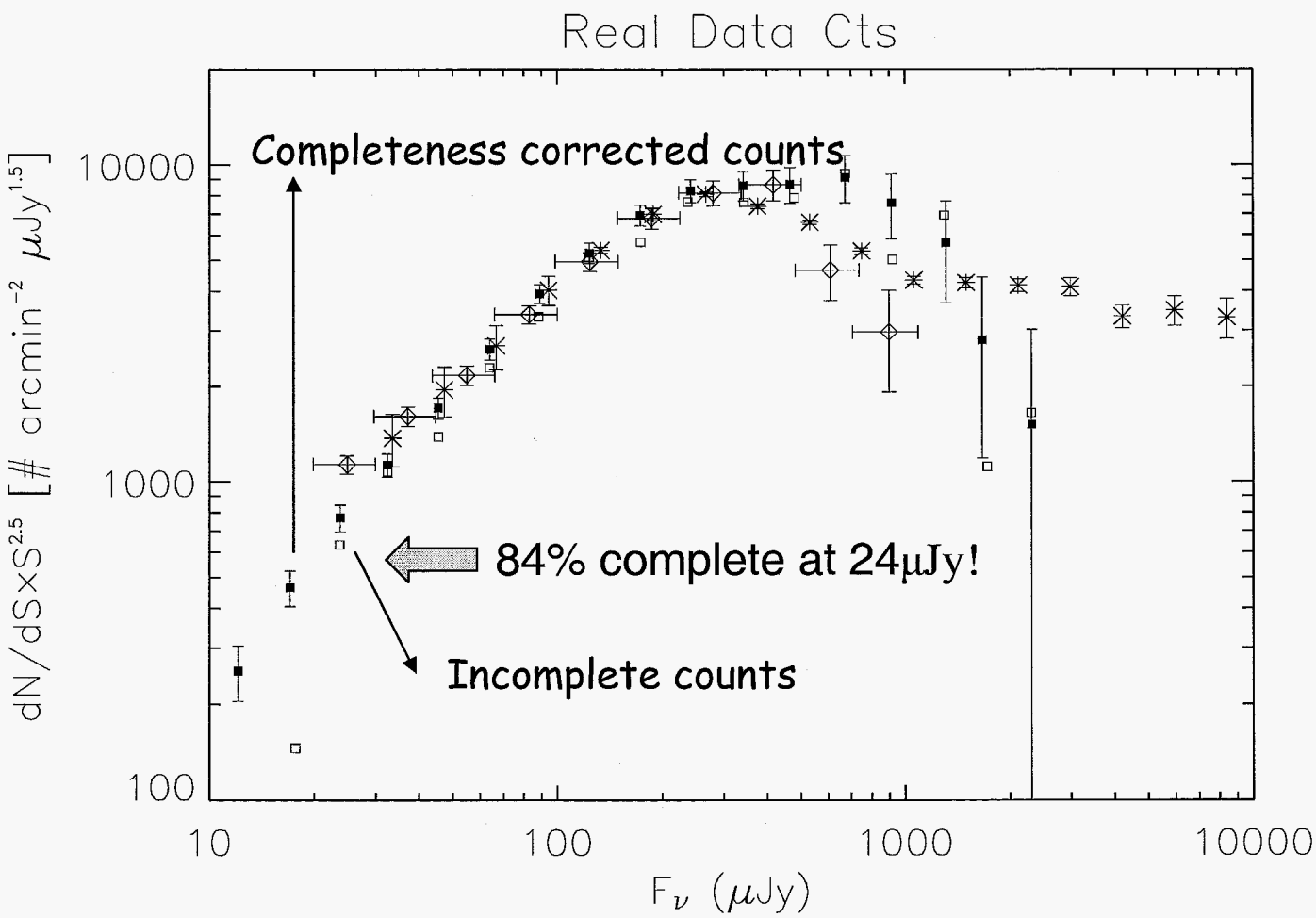




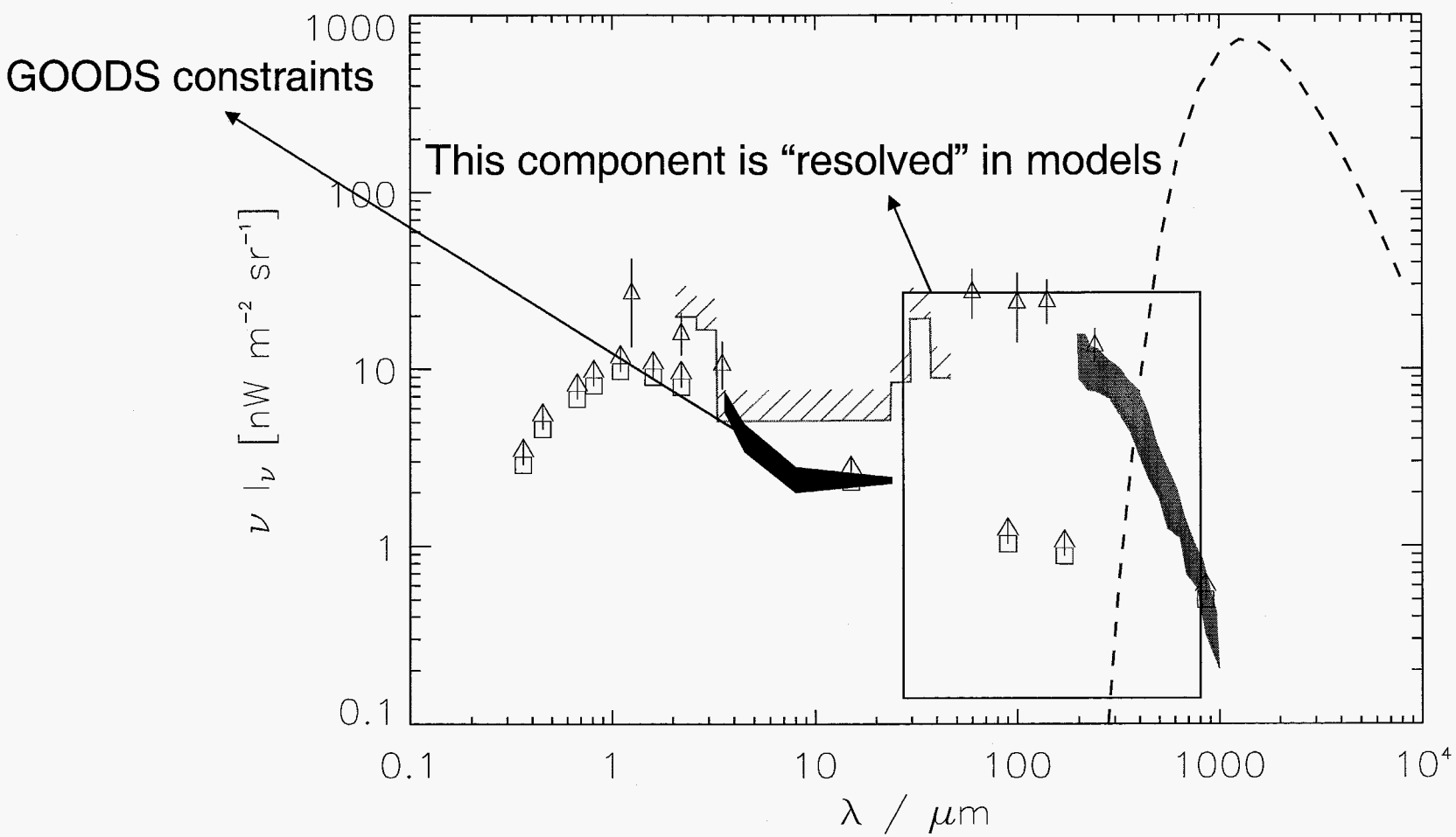
λ (μm)	νI_ν (nW/m^2/sr)
3.6	7.5 (5.7) ~70%
4.5	4.9 (3.4)
8.0	2.8 (2.0)
24	3.3



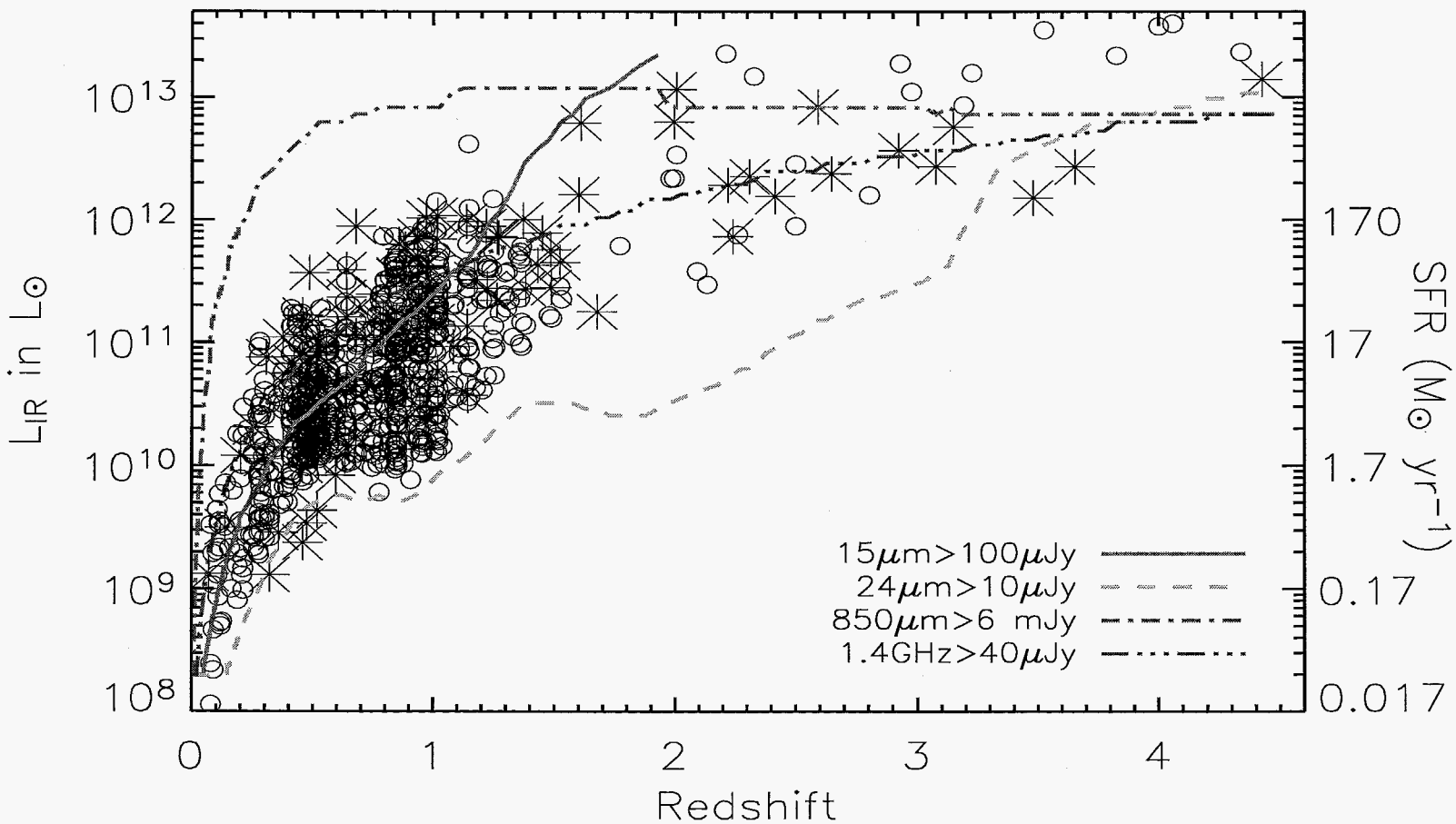
At 24 microns, confusion ? What's that ?



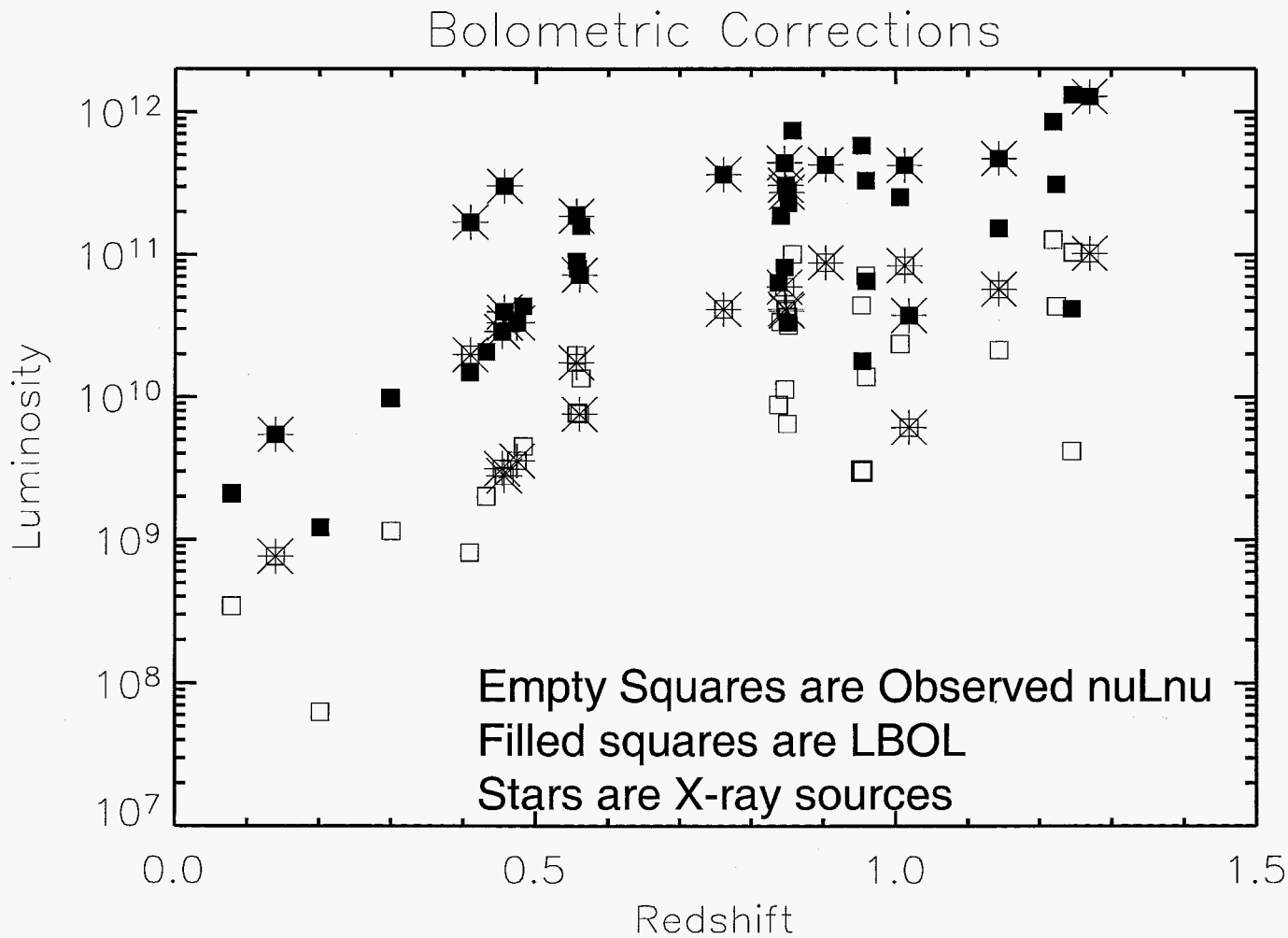
The CIRB is still only partially resolved - However the TeV spectrum of blazars seems to be a bit off !



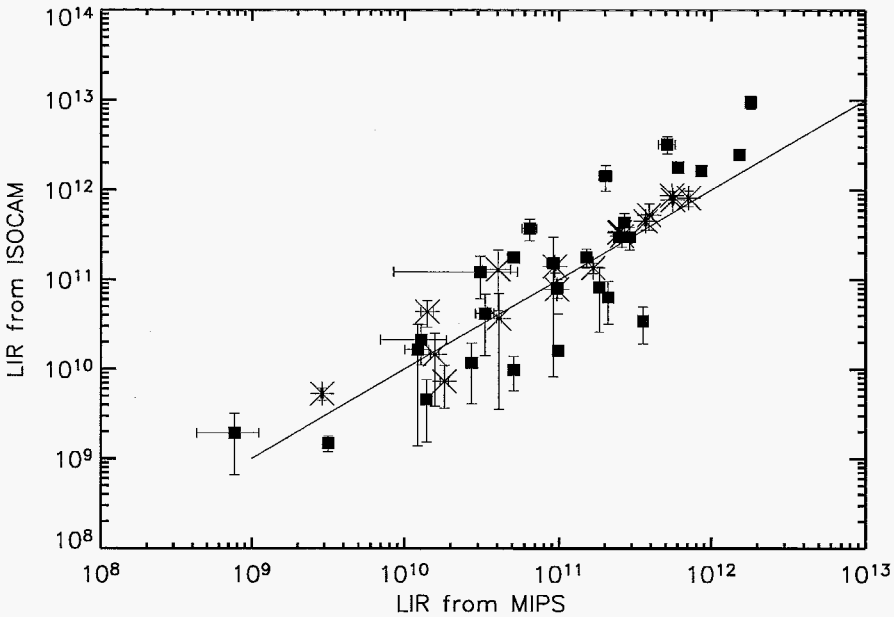
Sensitivities of measurements at different wavelengths to high-z star formation

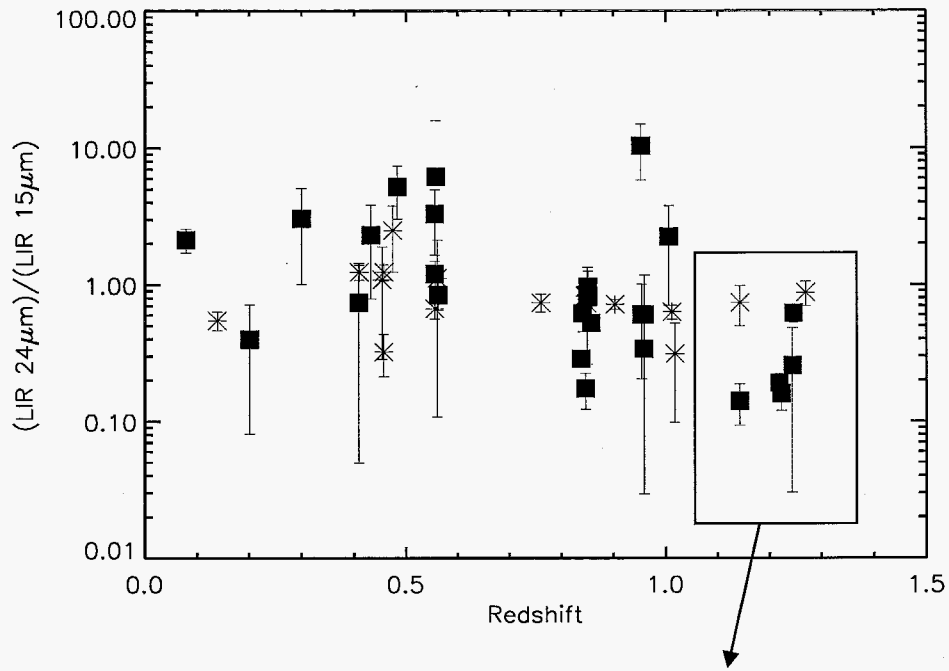


Bolometric Corrections are x10 !



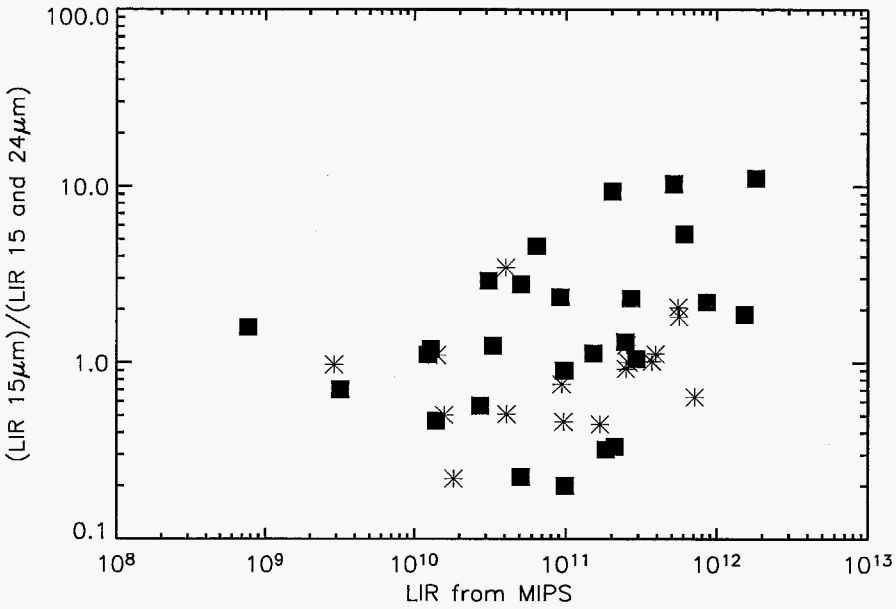
Comparison with z~1 ISOCAM galaxies: General agreement in LIR estimates from mid-infrared

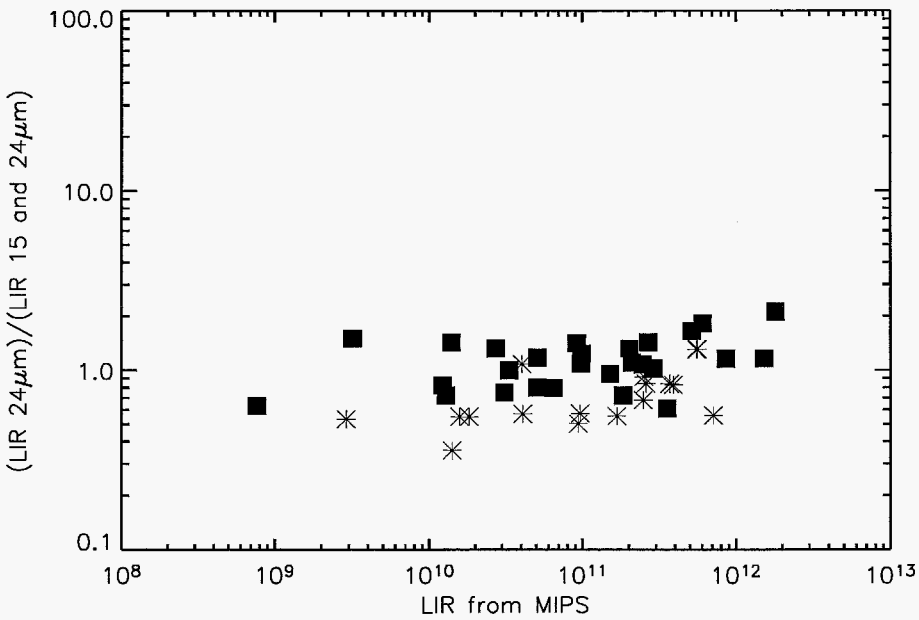


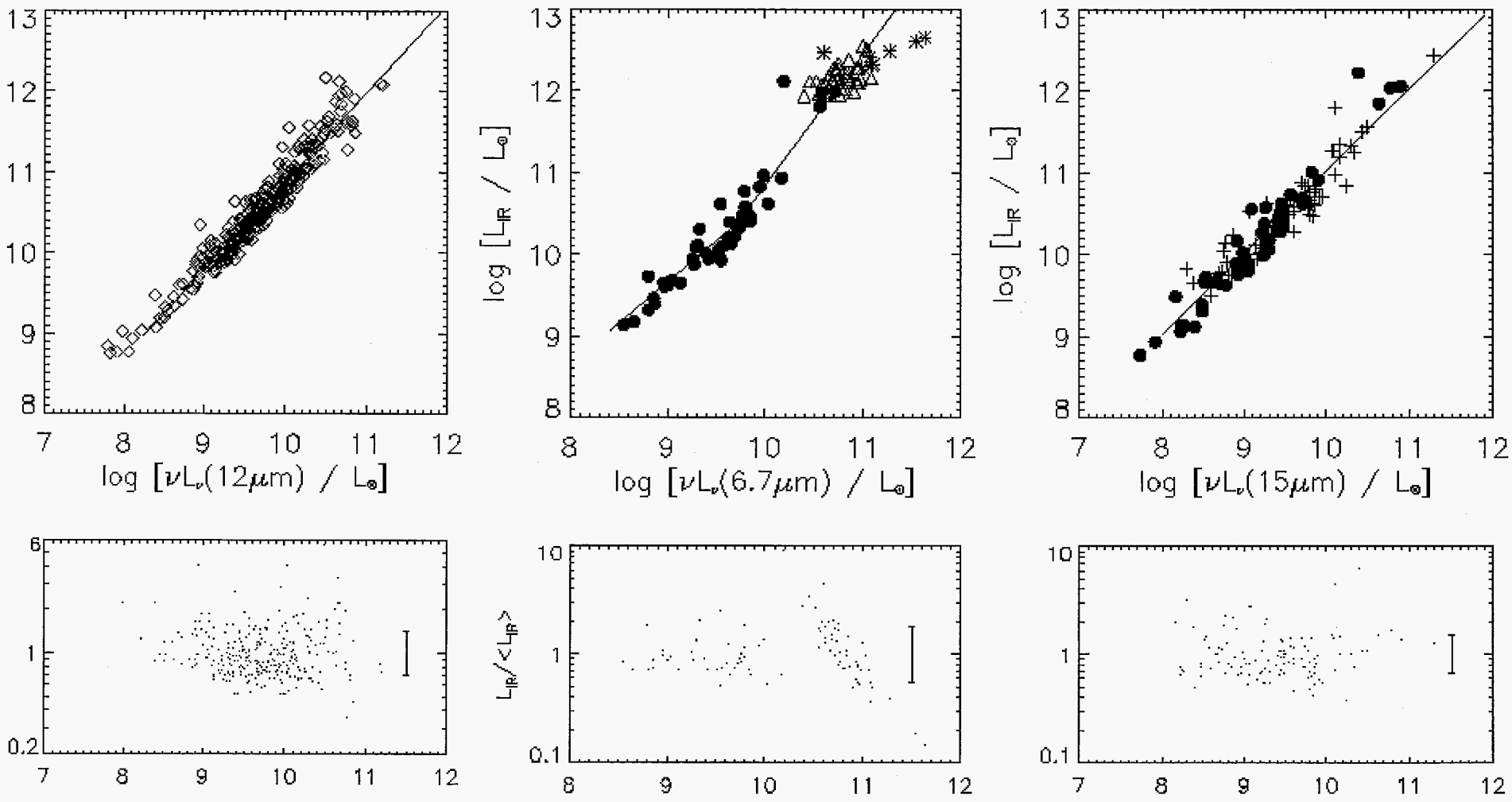


6.2μm PAH emission feature redshifted out of 15μm passband
9.7μm Silicate absorption feature into 24μm filter

However, large scatter possibly associated with variation of PAH strength with redshift: but already seen in local Universe

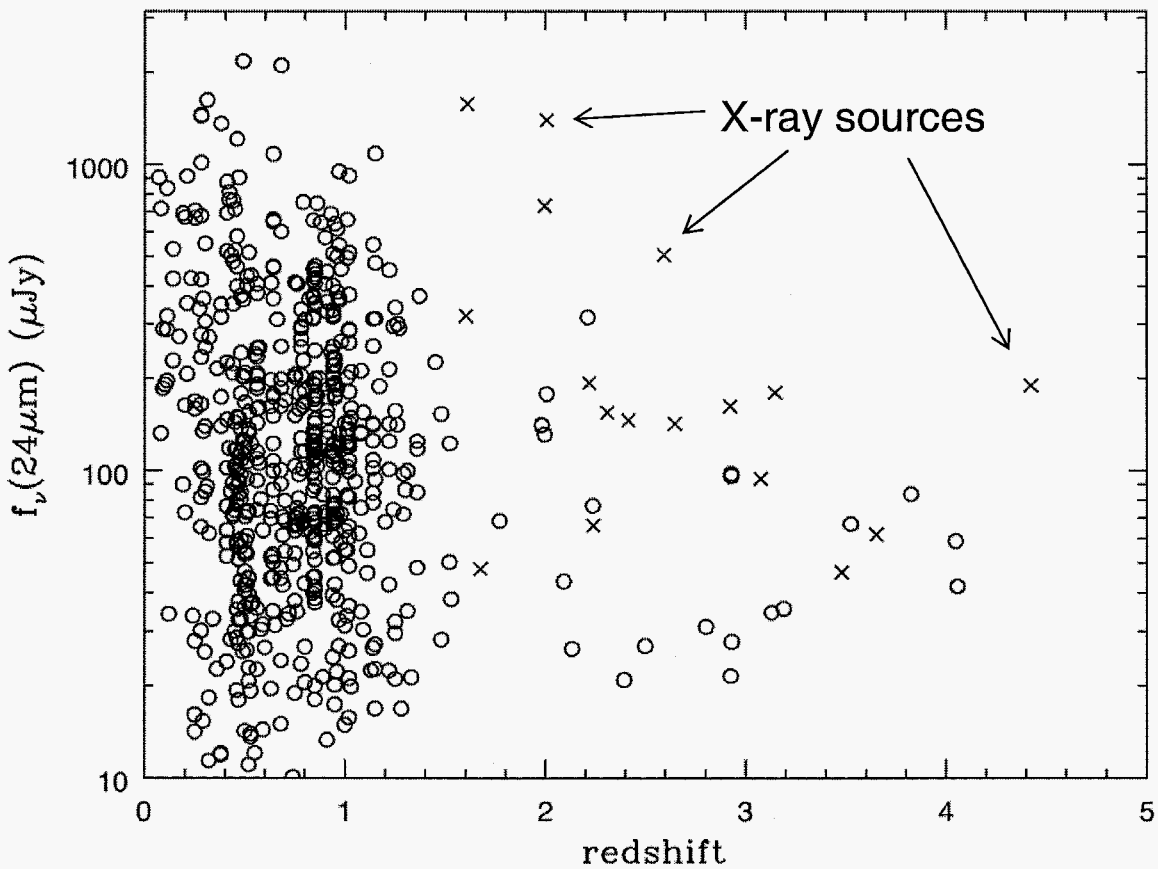


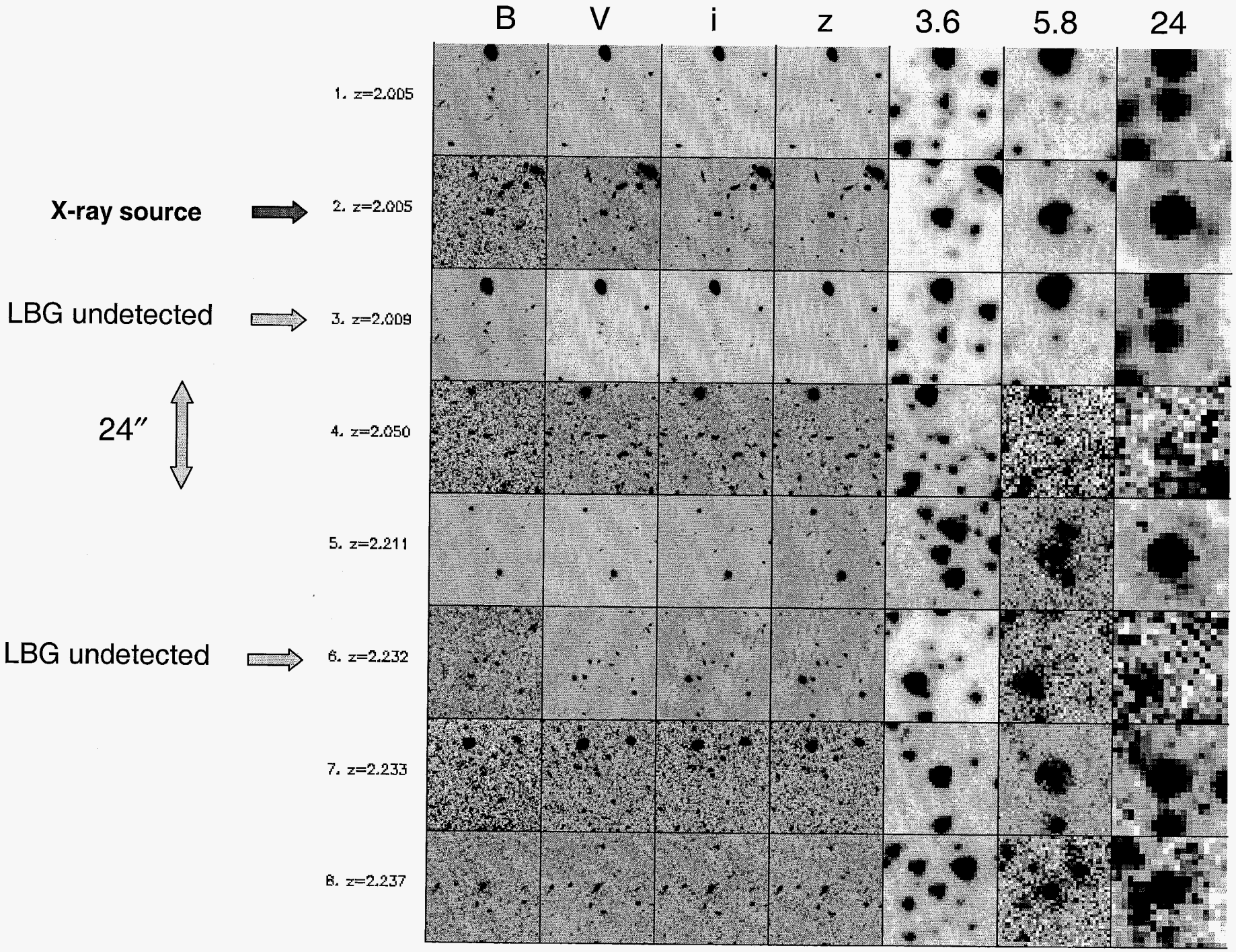




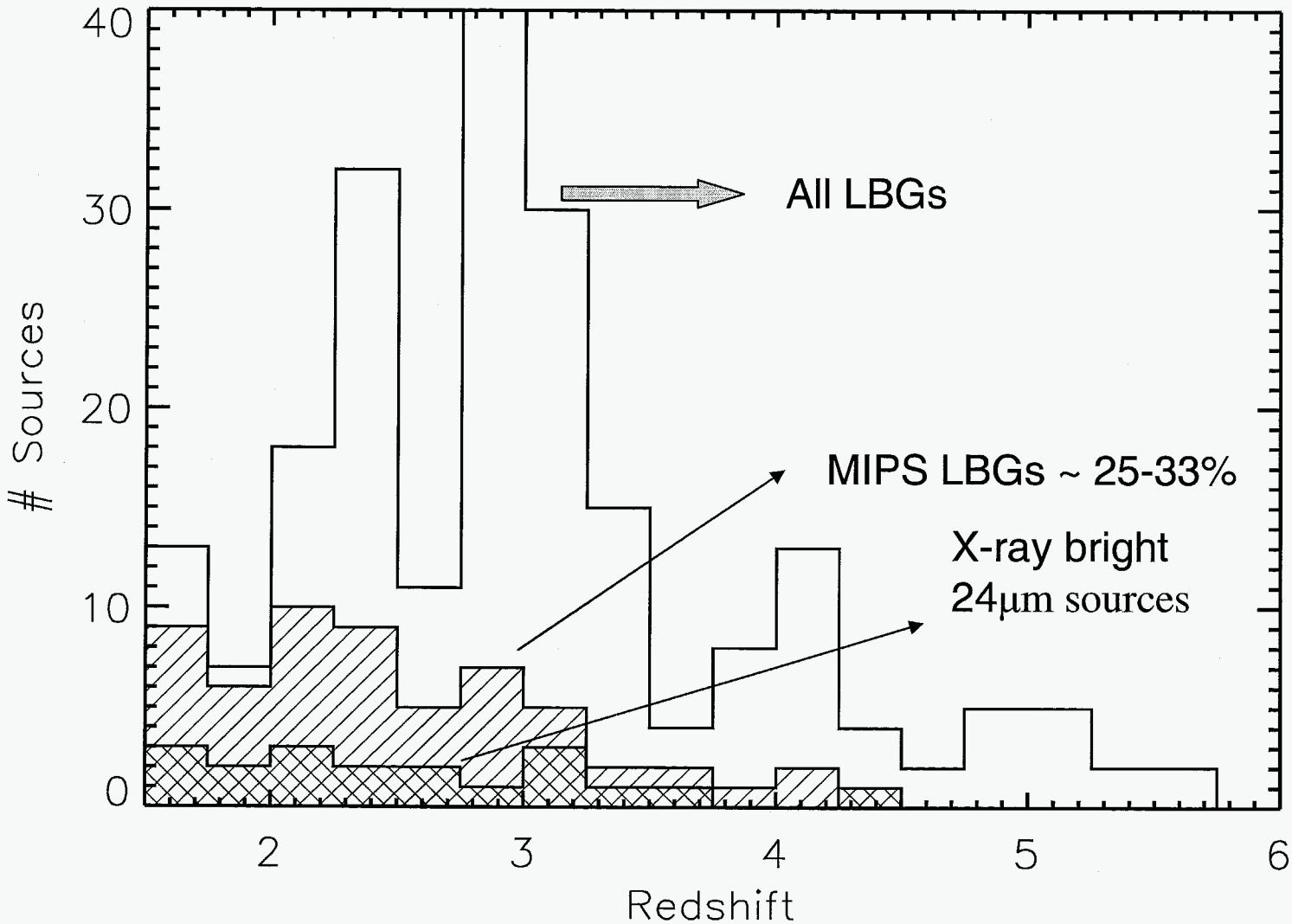
But this scatter in deriving LIR from the PAH is seen in the local Universe already !

Moving on to z~2

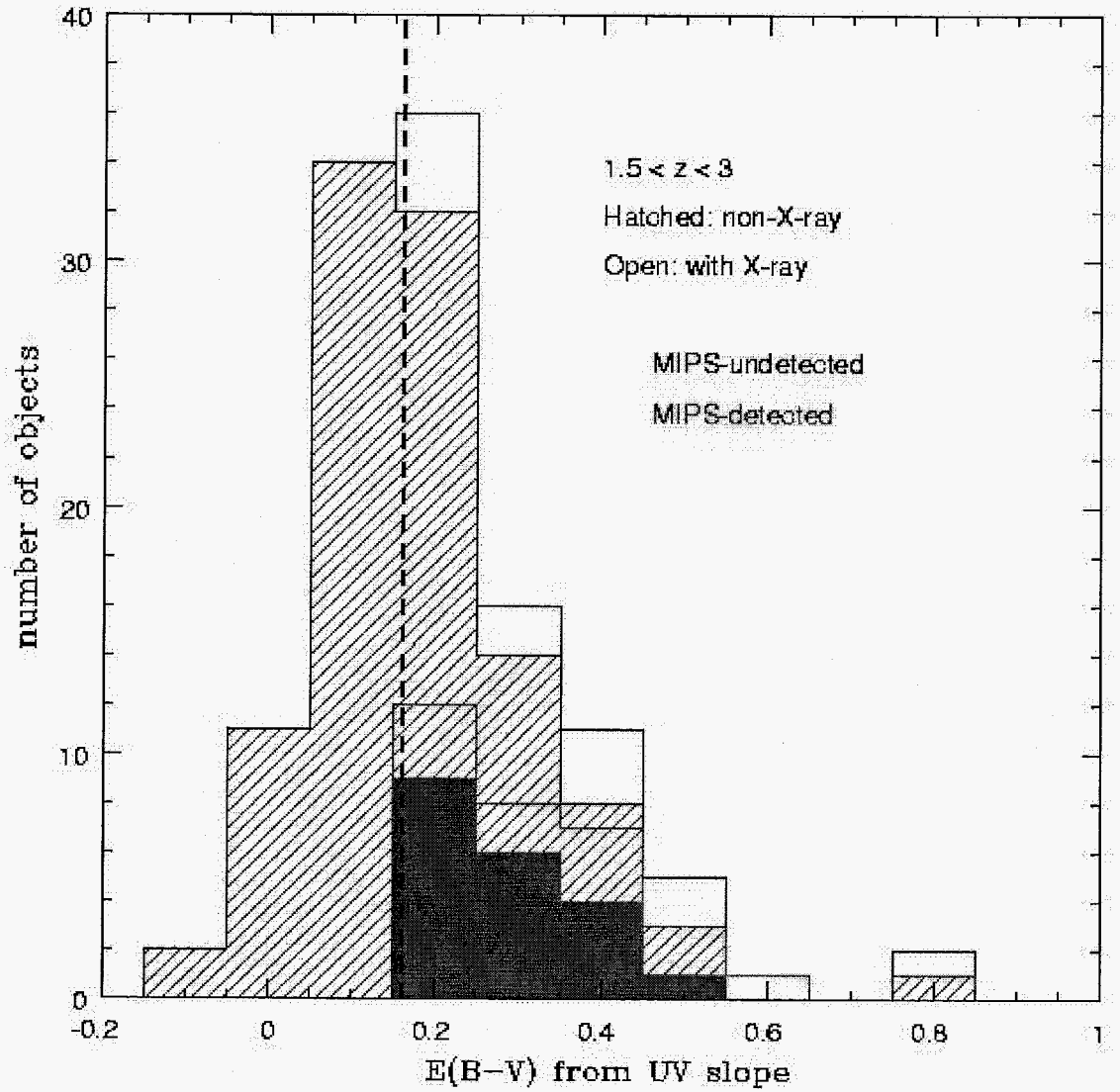



B
V
i
z
3.6
5.8
24
1. z=2.005
2. z=2.005
3. z=2.009
4. z=2.050
5. z=2.211
6. z=2.232
7. z=2.233
8. z=2.237
X-ray source
LBG undetected
24″
LBG undetected

Redshift distribution of z>1.5 Sources

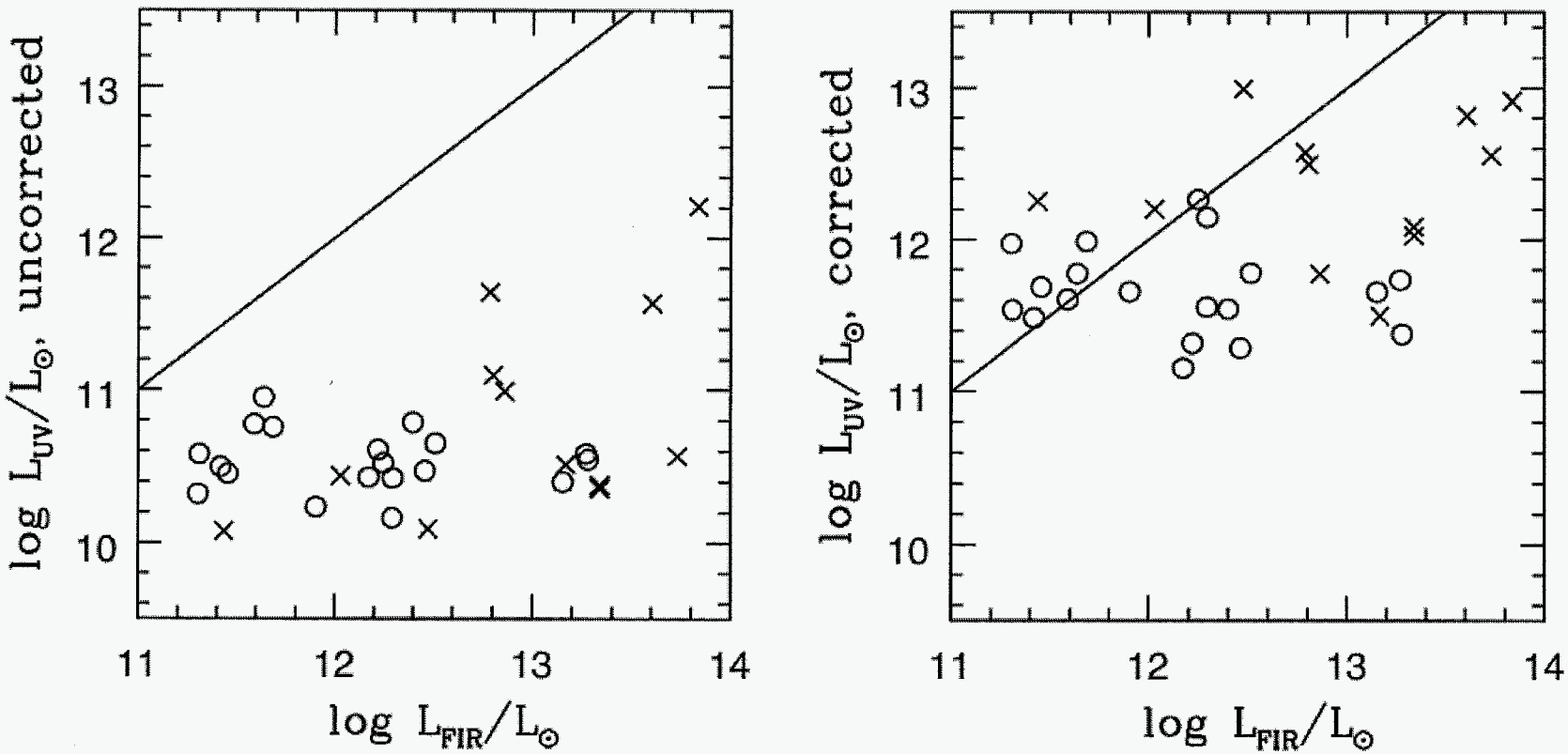


Colors of MIPS detected z~2 sources



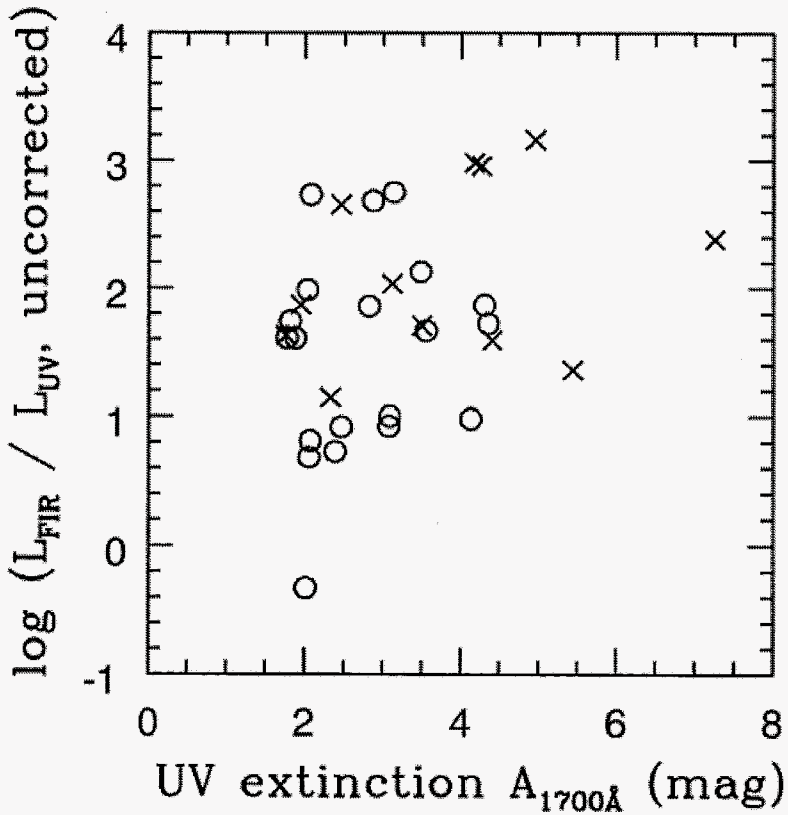
Comparing mid-IR vs. UV luminosities at 1.5 < z < 3

L_{FIR} always exceeds uncorrected LUV.
This remains true at $L_{FIR} > 10^{12}\ L_{sun}$ even when nominal UV extinction corrections have been applied.

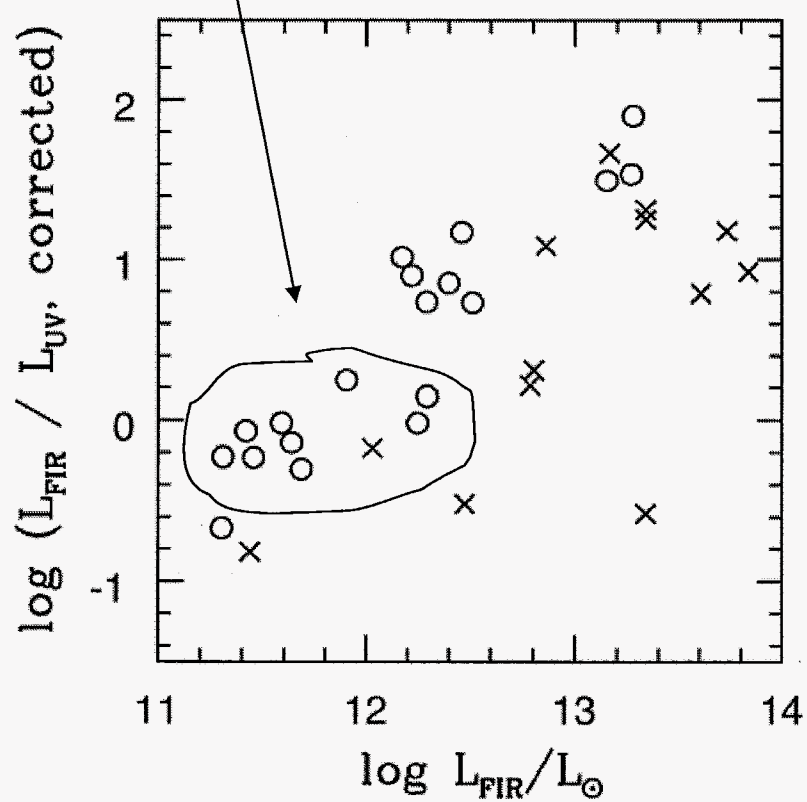


Extinction scaling with L_{IR}

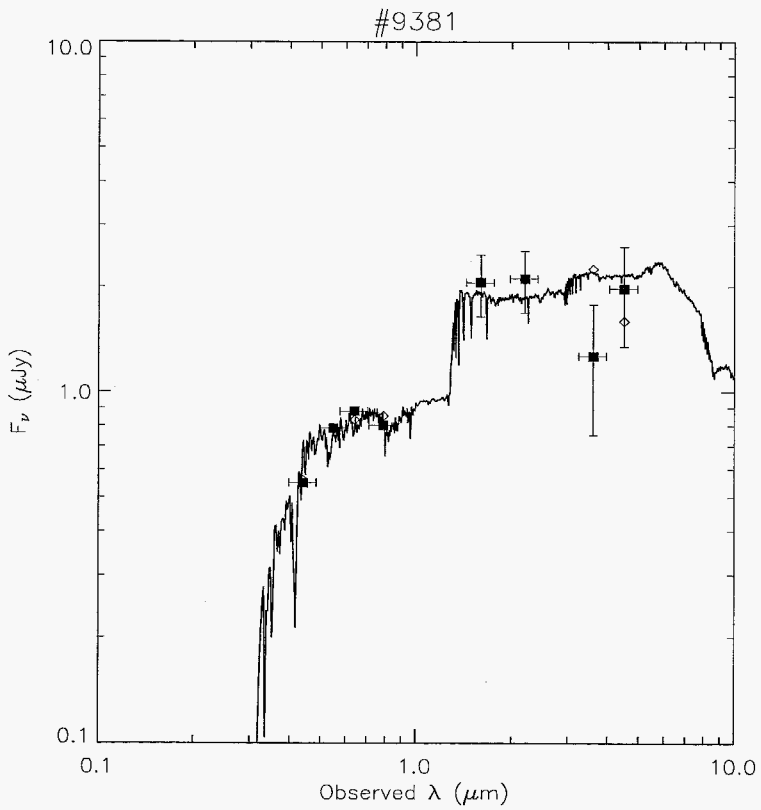
"IRX-β" diagram
(as per Meurer et al.)



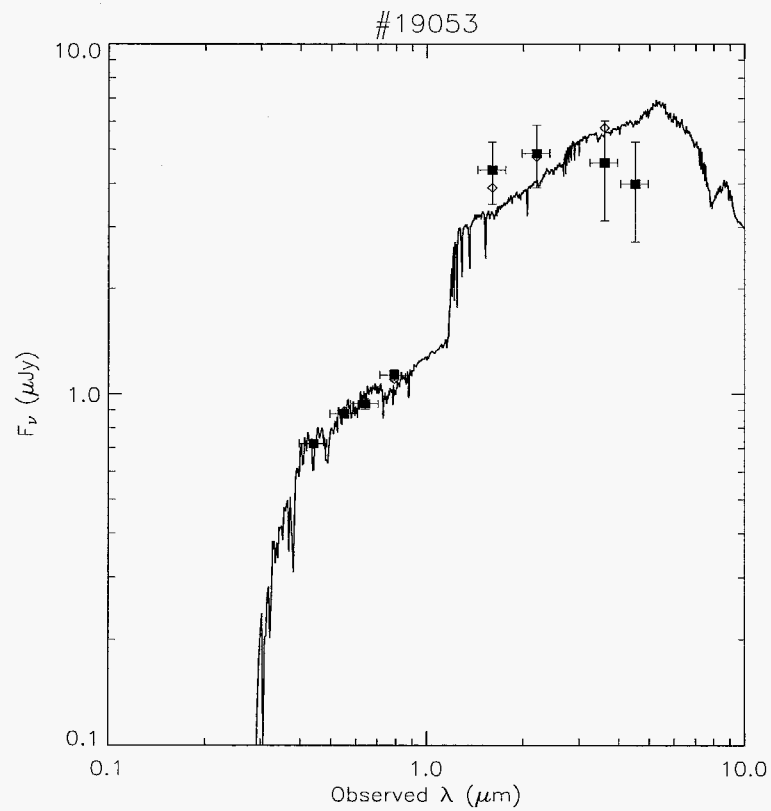
L_{FIR}/L_{UV}(corr.) ~ 1 for many objects at $L_{FIR} < 10^{12}\ L_{sun}$, but >>1 at higher L_{FIR}



Stellar population fitting for LBGs

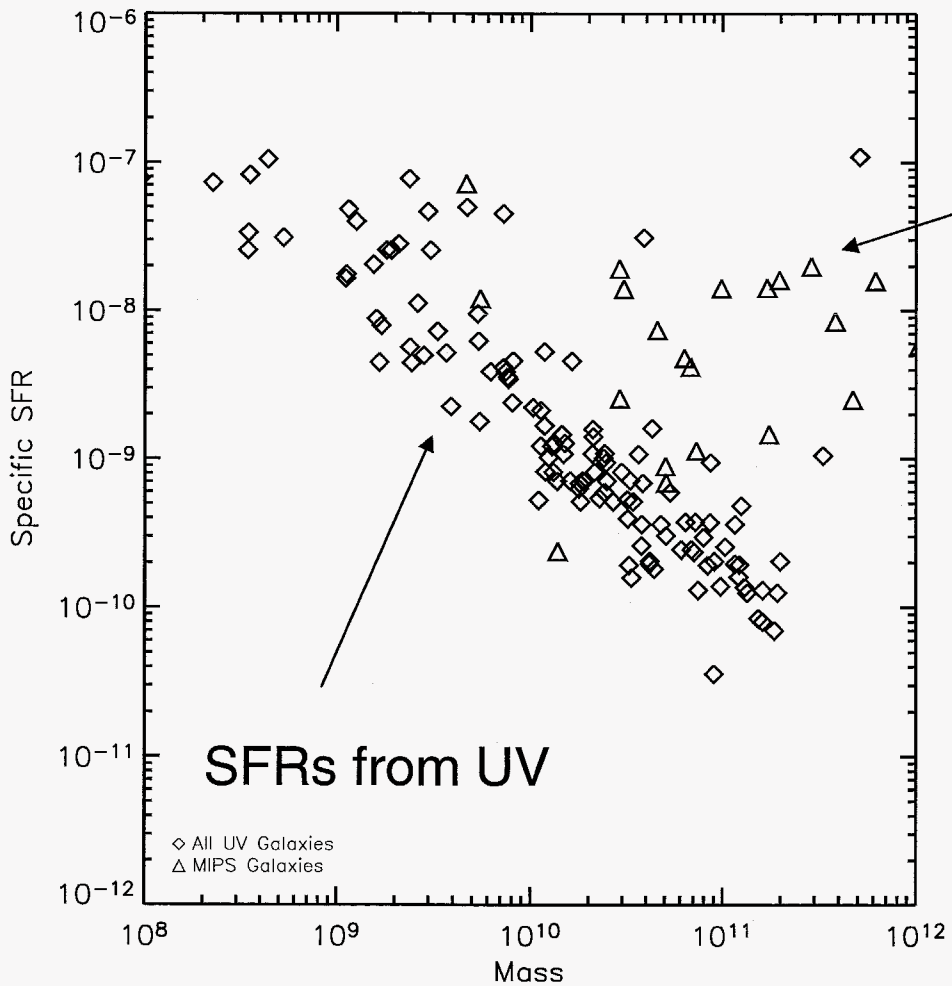


z=2.4, 1.3E11 $M_\odot$, 180 MYr old SB,
A_V~0.1, SFR~20 $M_\odot$/yr



z=2.1, 5E10 M⊙, 450 MYr old SB,
A_V~0.6, SFR(IR)~35, SFR(UV)~10

Specific SFRs vs. stellar mass



SFRs from MIPS

Objects with high 24μm SFRs tend to be among the more massive galaxies

Summary

- There seems to be an unresolved fraction of the near-infrared background. Isotropic zodiacal light or population III stars ?
- Strong evolution of IR luminosity function between z~0 and 1 is confirmed.
- High SFR in ISOCAM galaxies but large scatter in bolometric correction due to variation in strength of PAH
- Dusty star-formation reasonably well traced in the LIG range from UV but fails at higher bolometric luminosities.
- 24μm detected galaxies appear to be more massive – is there a bias or are massive galaxies more likely to have violent star-formation ?
- A wealth of results forthcoming !