The Infrared Spectrograph on Spitzer

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Infrared Spectrograph (IRS)

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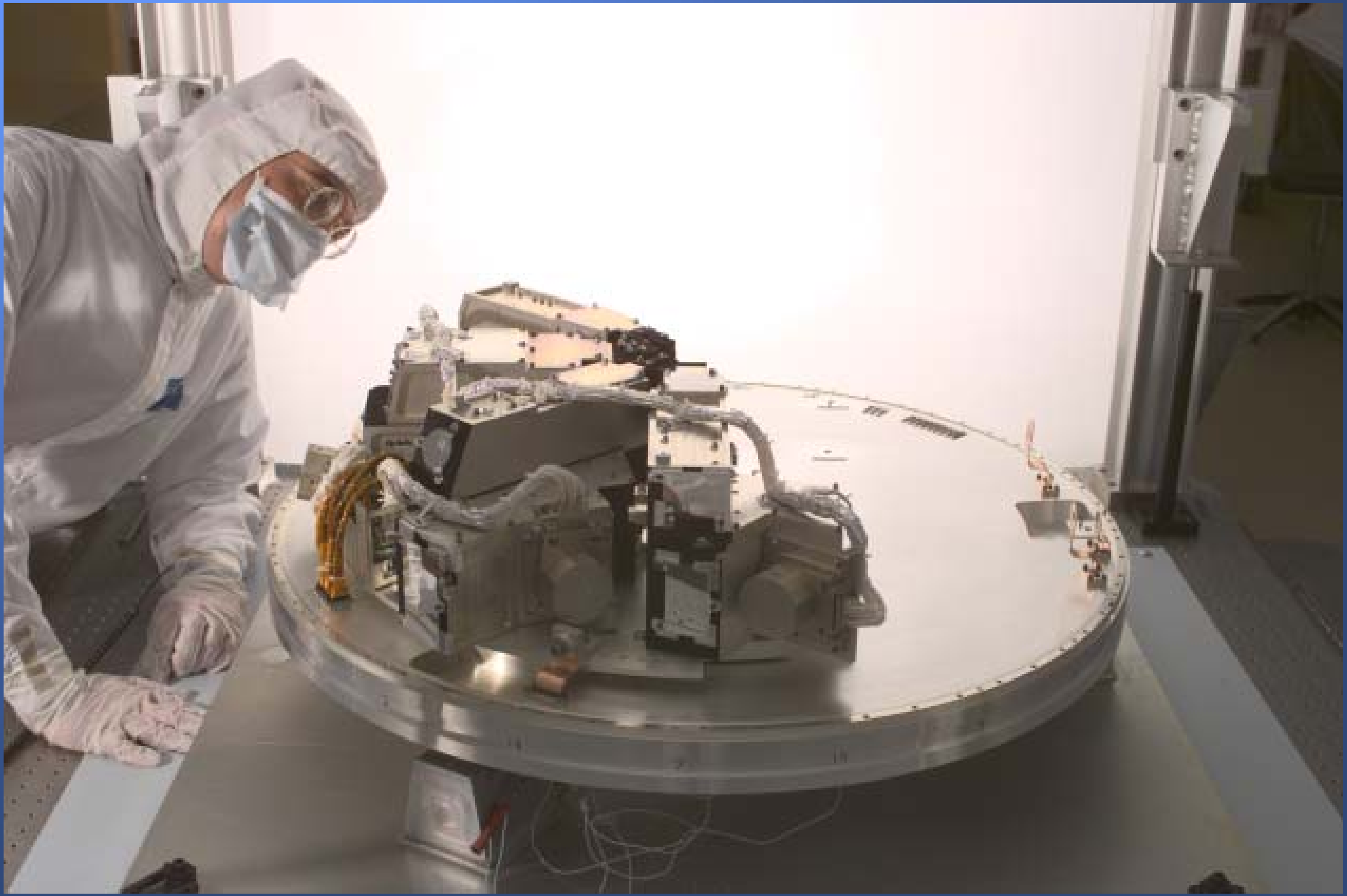
Contractor = Ball Aerospace

Key Features

- Uses 128x128 Boeing Si:As and Si:Sb arrays
- No moving parts
- Two, R~650 echelle modules (10–19.5, 19.3–37 μm)
- Two, R~80 longslit modules (5.3–14.2, 14.2–40 μm)
- Peak-up imaging (13.3–18.7 and 18.5–26 μm)

  Acquisition of sources with poorly known positions over the 1– 350 mJy flux density range. Peak-up on the science target or a nearby offset star whose relative position is accurately known.
- The IRS operates in staring or spectral mapping modes.
- All data arrives in sample up the ramp mode and is fit on the ground.

The IRS on the MIC Baseplate



Basic IRS Capabilities

Module	Array Format (pixels)	Pixel Size (arcsec)	λ (μm)	Resolution	Slit size (arcsec)
Short Low	128 x 128	1.8	5.2 – 14.5	64 –128	3.6x57(x2)
Long Low	128 x 128	5.1	14.0 – 38.0	64 –128	10.5x168(x2)
Short High	128 x 128	2.3	9.9 – 19.6	600	5x11
Long High	128 x 128	4.5	18.7 – 37.2	600	11x22

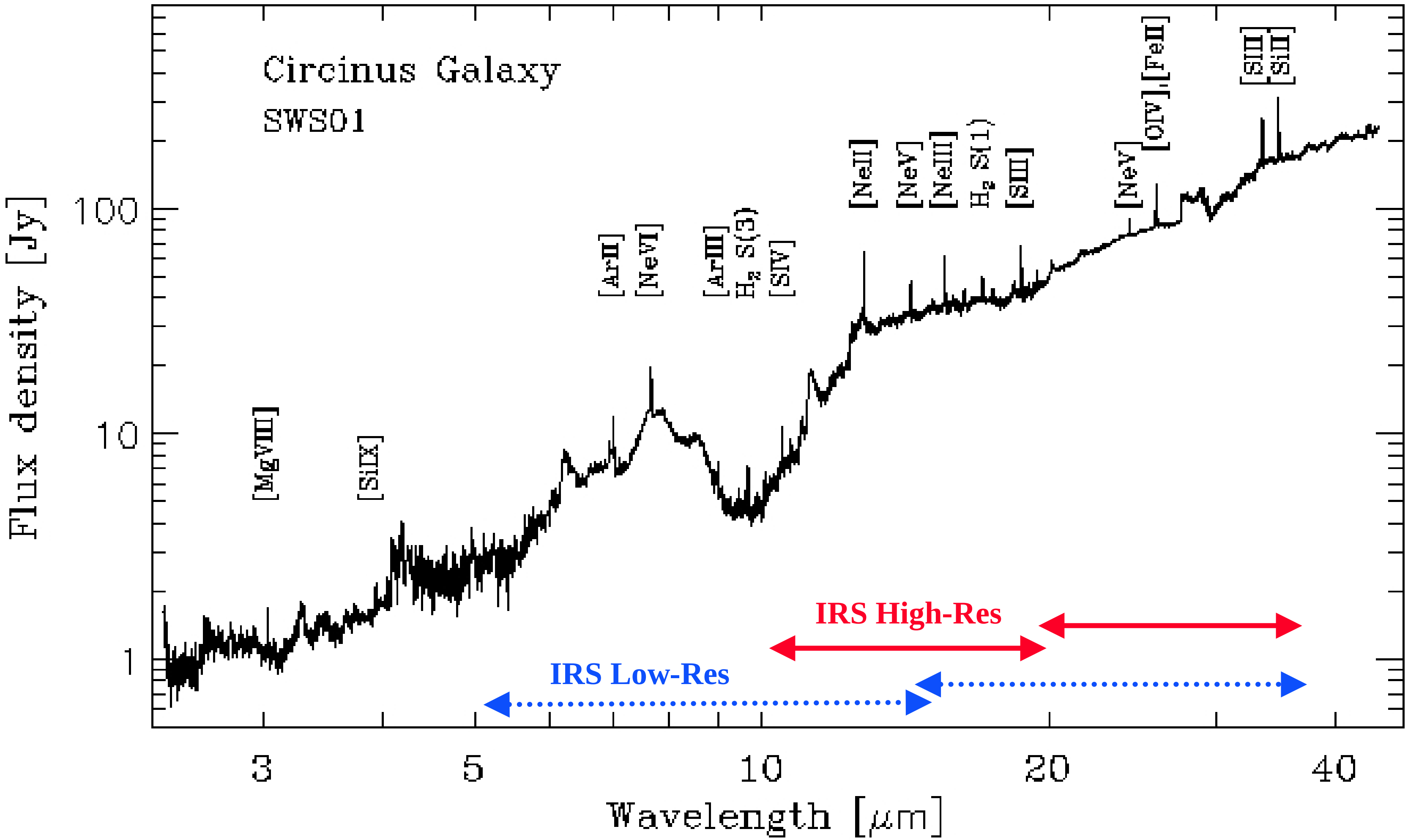
Sensitivity Levels (point source 5σ, 500 seconds)

Low Res: ~ 0.5-1 mJy @10 μm
High Res: ~ 3-5x10^{-18} W m^{-2} @15 μm
Peakup: ~ 0.5 mJy

Saturation Limits (point & extended sources)

Low Res: ~ 5 Jy @10 μm (6 seconds)
or ~ 0.4 Jy $arcsec^{-2}$
High Res: ~ 50 Jy @15 μm (6 seconds)
or ~ 2.1 Jy $arcsec^{-2}$
Peakup: ~ 0.5 Jy (4 seconds)
or ~ 40 mJy $arcsec^{-2}$

IRS Wavelength Coverage



The 2.5 to 45 micron spectrum of the Circinus galaxy

Basic IRS Science

Spectroscopic observations of previously known sources (IRAS, ISO, 2MASS, etc.) and those discovered with Spitzer.

extragalactic examples

- the **physical conditions** of the atomic/molecular gas in dusty galaxies via emission/absorption lines.
- the **redshifts** of optically obscured, distant galaxies.

The IRS will enable spectroscopy at levels that are ~100 times more sensitive than those reached by ISO

Early IRS Results

Low redshift active galaxies

- Three Ultraluminous Infrared Galaxies (ULIRGs): Mrk 1014, Mrk 463, and UGC 5101.

Low metallicity starburst galaxy

- The Blue Compact Dwarf (BCD) SBSS 0335-052.

High redshift QSO

- The = 3.91 lensed QSO APM 08279+5255.

ULIRG Basics

Properties

- $L_{IR} \geq 10^{12} L_{\odot}$; $L_{bol} \sim L_{IR}$; $L_{opt} < 0.1 L_{IR}$
- 90 – 95% are interacting or in merging systems
- very strong OIR emission lines (atomic, molecular, PAH)
- NIR stellar CO absorption from young stars
- large, compact reservoirs of molecular gas (> 10^9 - 10^{10} $M_{\odot}$ over $\leq$ 1 Kpc) in their nuclei
- drive "superwinds" of hot, enriched gas into the IGM
- rare in the local Universe - only ~3% of galaxies in BGS
- Fraction of AGN appears to rise from 20 – 25% at L < $2 \times 10^{12} L_{\odot}$ to ~35 – 50% at L > 2 – $6 \times 10^{12} L_{\odot}$.

What Powers most ULIRG's ??

A **starburst** (SFR ~ 50 – 500 $M_{\odot} yr^{-1}$), an **AGN**

……. or **both** ?

Rest Frame Mid-IR Spectroscopy

Clear benefits of MIR spectroscopy for ULIRG studies

- The extinction is much lower ($A_{15} \sim 0.025\ A_V$)
- Atomic, fine-structure lines (e.g. [NeV] or [OIV]) can be effective diagnostics of the radiation field.
  - *The ionization potential of [NeIV] is 97 eV. In an integrated galactic spectrum this line indicates the presence of an AGN.*
- Aromatic features (PAHs) are abundant.
  - *Typically very strong in starbursts, but weak in AGN.*
- Pure rotational H_2 lines are available as warm gas probes.

Key Mid-IR diagnostic features

			Short-Hi		Long-Hi	
Line	λ_{rest}	Ion Pot. (eV)	z_{in}	z_{out}	z_{in}	z_{out}
NeVI	7.6	126	0.31	1.61	1.61	3.97
SIV	10.5	35	0	0.90	0.90	2.62
NeII	12.8	22	0	0.52	0.52	1.97
NeV	14.3	97	0	0.36	0.36	1.66
NeIII	15.6	41	0	0.25	0.25	1.44
SIII	18.7	23	0	0.04	0.04	1.03
NeV	24.3	97			0	0.57
OIV	25.9	55			0	0.47
SIII	33.5	23			0	0.13
SiII	34.8	8			0	0.09

The IRS ULIRG Program

A Sampling of ULIRGs

- 110 ULIRGs chosen predominantly from the BGS, 1 Jy, 2Jy, and FIRST/ IRAS samples*
- $\leq 0.04 < S_{25} < 8.66$ and $0.14 < S_{60} < 103.33$ Jy
- $0.02 < z < 0.93$
- $11.7 < \log L_{FIR} (L_{\odot}) < 13.1$
- mix of warm ($S_{25} / S_{60} > 0.2$) and cold FIR sources
- the total time for the program, including overheads, is ~82 hours.

We will observe all 110 with SL and LL (R~80)
and 56 with SH and LH (R~650)

* (Soifer, et al. 1987; Kim & Sanders 1998; Strauss, et al. 1992; Stanford, et al. 2000)

IRS ULIRG Spectroscopy

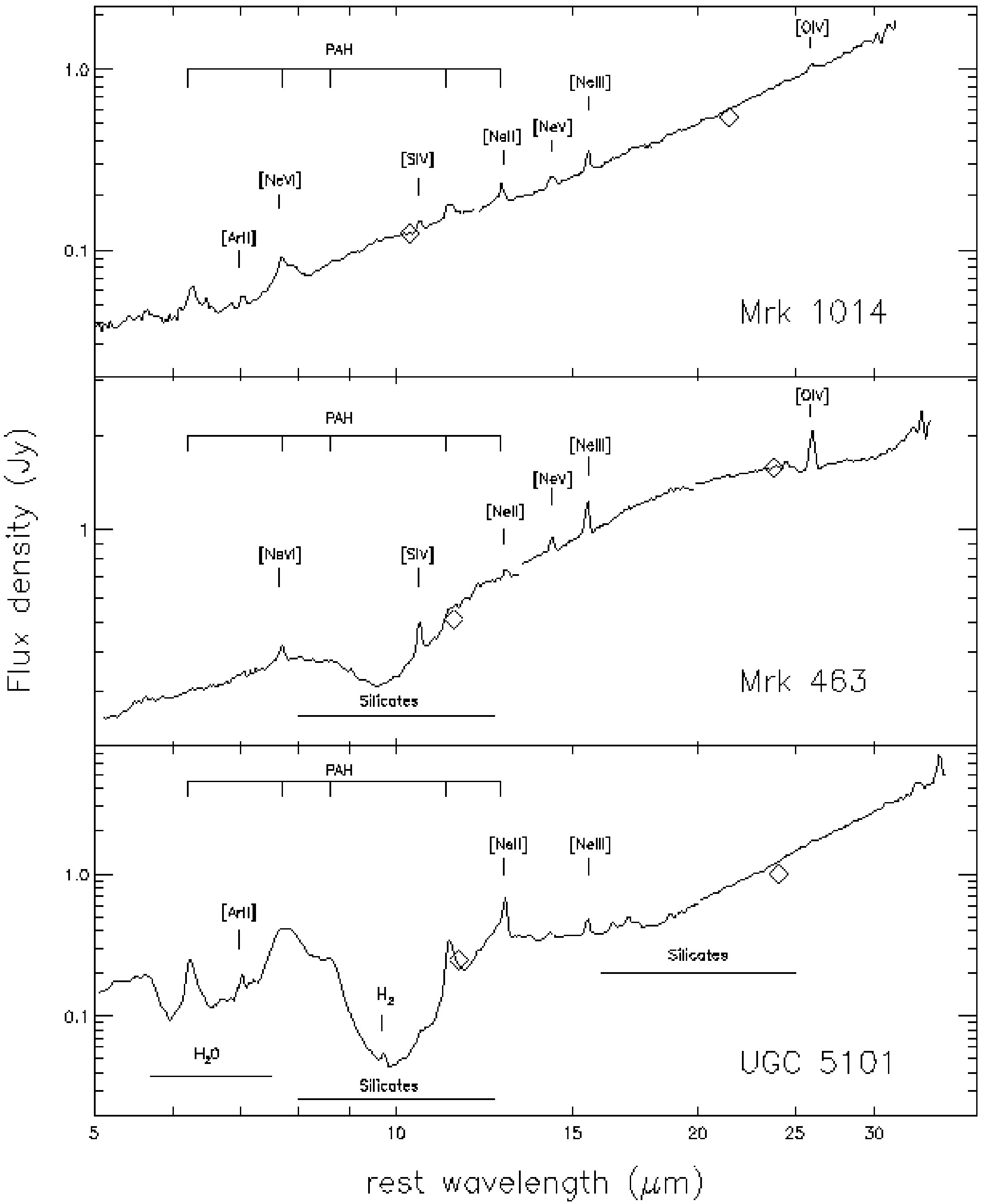
We observed three ULIRGs in SV, IRS-2, IRS-5

- Mrk 1014 (z=0.163; $L_{IR} \sim 4.2 \times 10^{12}\, L_{\odot}$)
  Radio quiet, broad-line, dusty QSO with twin tidal tails.
- Mrk 463 (z=0.051; $L_{IR} \sim 6.4 \times 10^{11}\, L_{\odot}$)
  Merging, twin Seyfert 2 nuclei. Mrk 463e dominates in IR.
- UGC 5101 (z=0.039; $L_{IR} \sim 9.5 \times 10^{11}\, L_{\odot}$)
  Post-merger, LINER nucleus with a circum-nuclear starburst.
  XMM and Chandra data suggest a buried AGN behind $N_H \sim 10^{24}$ cm^{-2}.

(Veilleux, et al. 1995; Genzel, et al. 1998; Mazzarella, et al. 1991; Miller & Goodrich 1990; MacKenty & Stockton 1984; Shuder & Osterbrock 1981; Imanishi, et al. 2003)

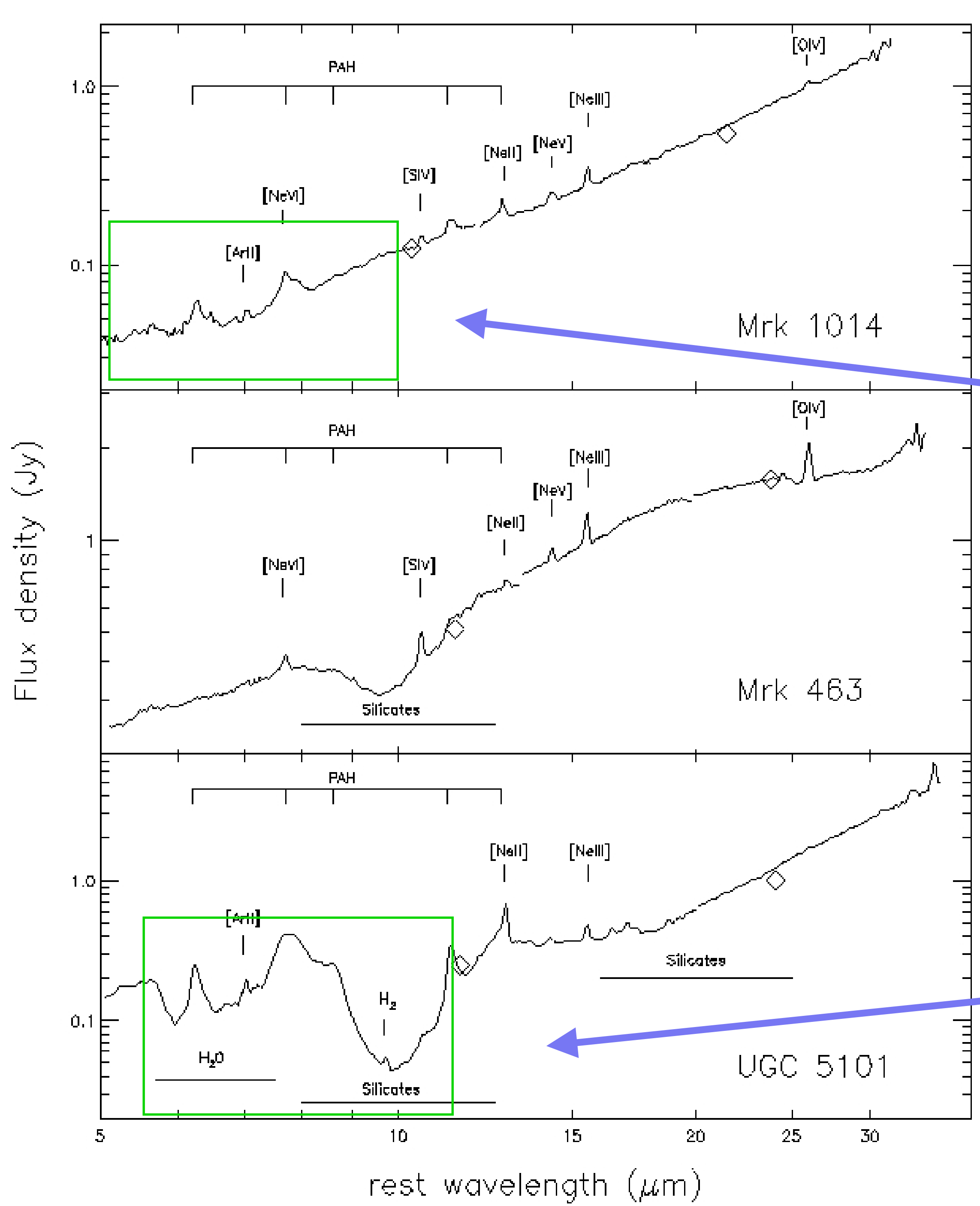
Integration Times

- Mrk 1014: SL ~ 170s, LL ~ 240s, SH ~360s, LH ~480s
- Mrk 463: SL ~ 170s, LL ~ 170s, SH ~360s, LH ~ 480s
- UGC 5101: SL ~ 170s, LL ~ 240s, SH ~60s, LH ~ 120s



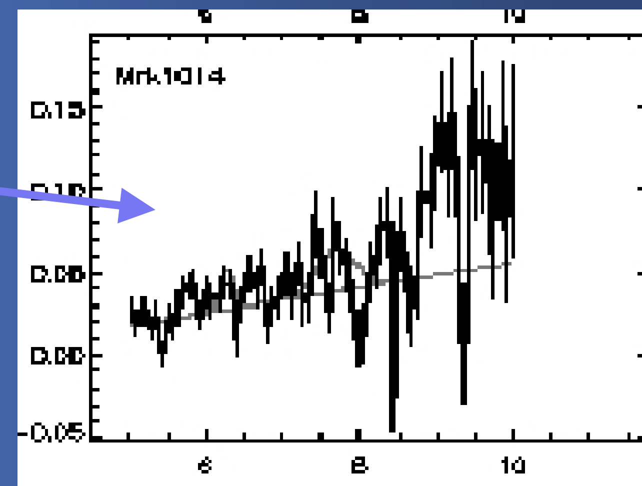
IRS SL and LL Spectra

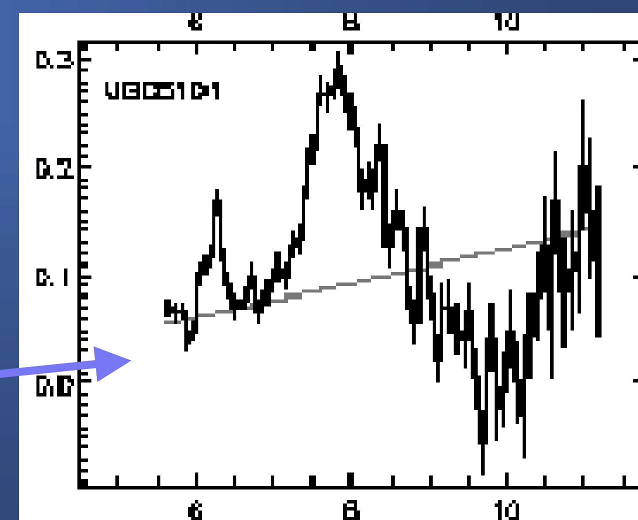
- No silicate absorption in Mrk 1014, yet obvious PAH emission.
- Silicate abs. toward Mrk 463e but no PAH.
- Strong silicates and PAH in UGC 5101. Continuum fit to UGC 5101 suggests A_V > 15–35 mag toward nucleus.
- Water ice and hydrocarbon absorption at 5-7.5 µm in UGC 5101. Water ice greatly affects apparent 6.2 µm PAH strength.
- 16.4 µm PAH detected in UGC 5101

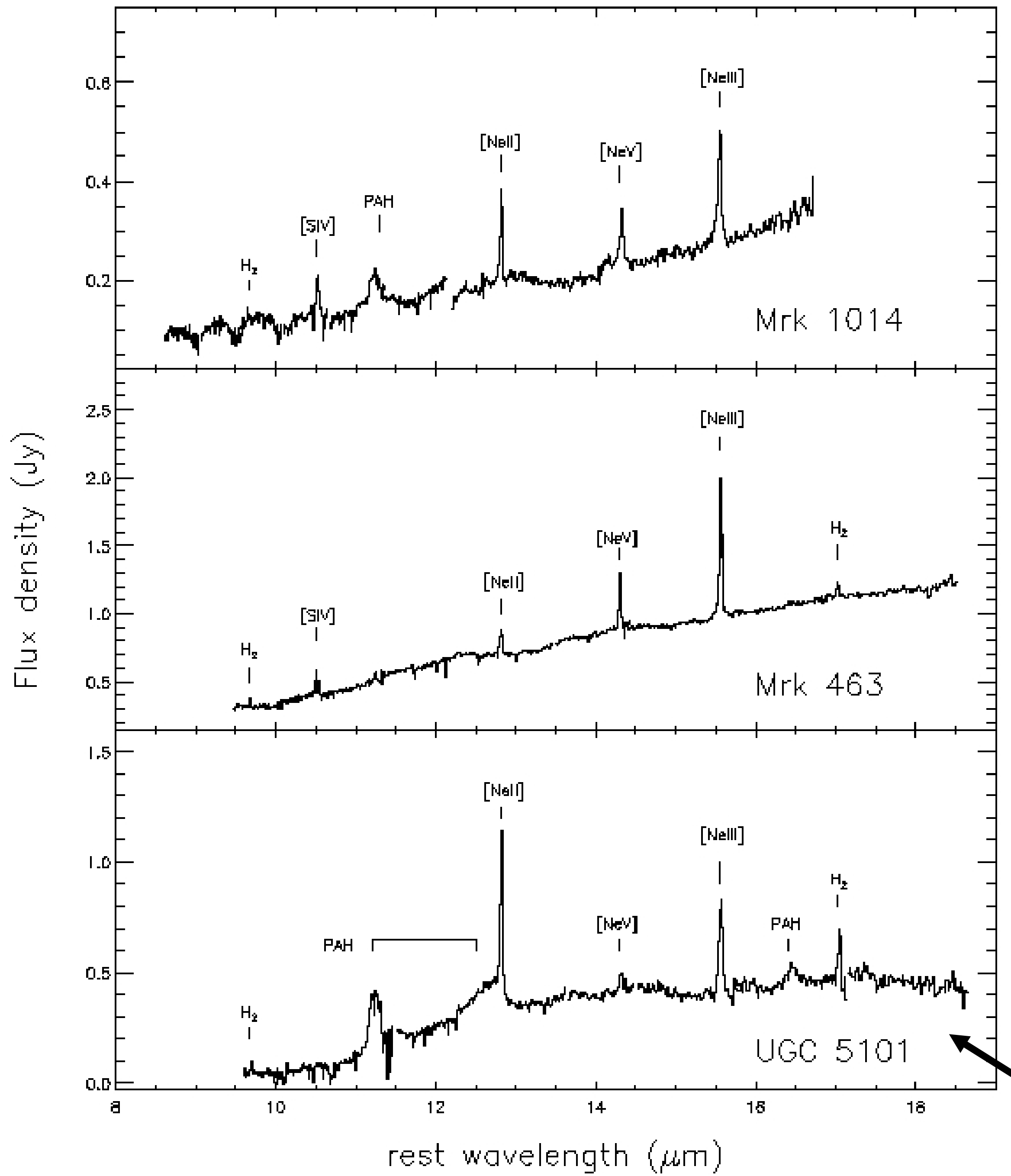


PHT-S spectra

Rigopoulou, et al. 1999



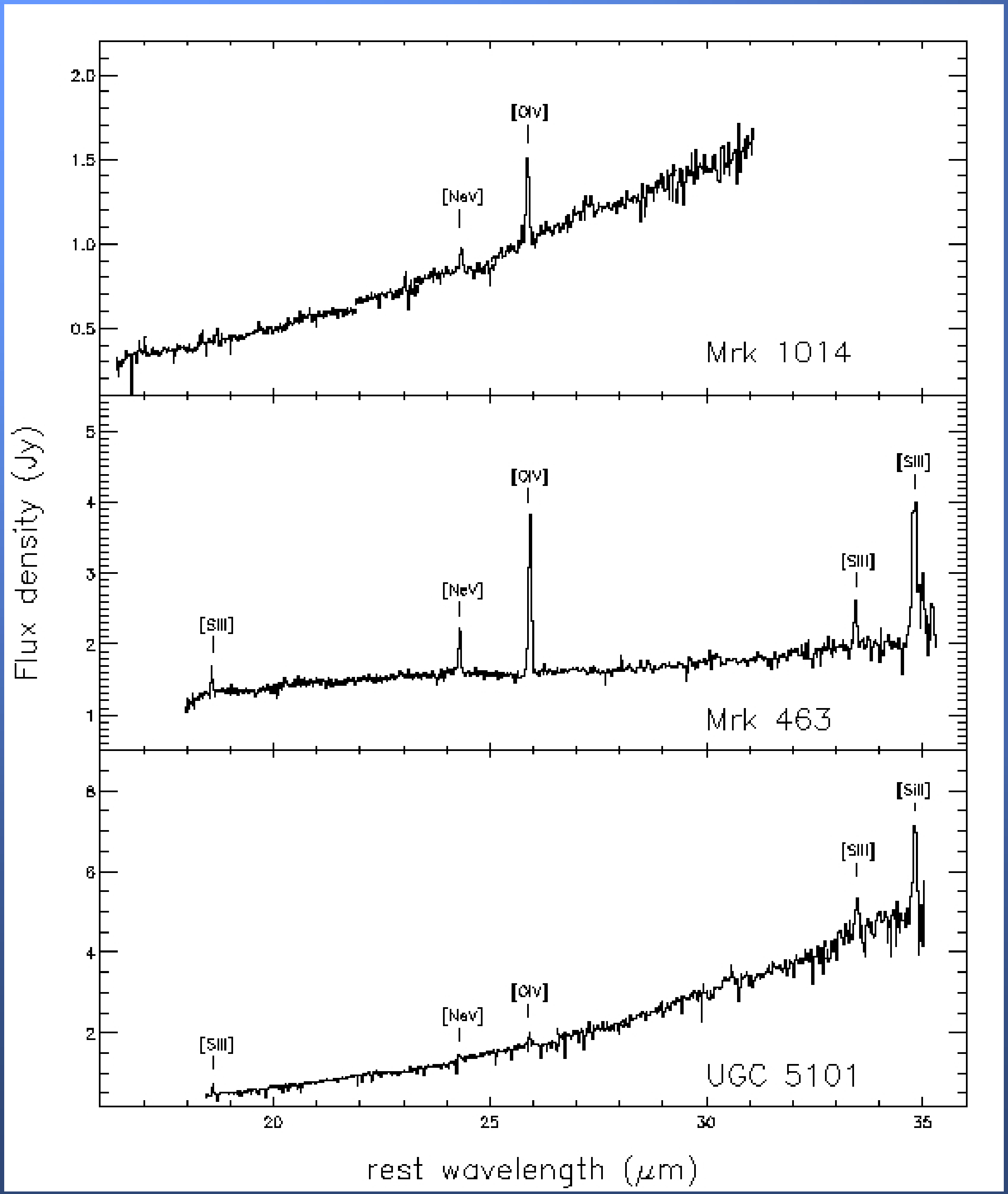




IRS SH Spectra

- [NeV], [NeII], PAH, and [OIV] line flux ratios in Mrk 1014 and Mrk 463e suggest 80-90% of energy from AGN.
- First detection of [NeV] in UGC 5101. Line ratios suggest < 10% of energy from buried AGN. (Sturm, et al. 2002)
- H_2 9.66 and 17.0 μm rotational lines suggest large warm (300-400K) molecular gas reservoirs in UGC 5101 and Mrk 463.

Two, 30sec integrations



IRS LH Spectra

- Strong [NeV] and [OIV] in Mrk 1014 and Mrk 463.
- Weak detection of [OIV] in UGC 5101. [NeIII/[NeII] line ratio at high end of starburst range, close to WR galaxies. (Verma et al. 2003)
- [SIII] 18.7/33.4 flux ratio consistent with ionized gas in low density limit ($n_e < 10^2$ cm^{-3})

SBS 0335-052

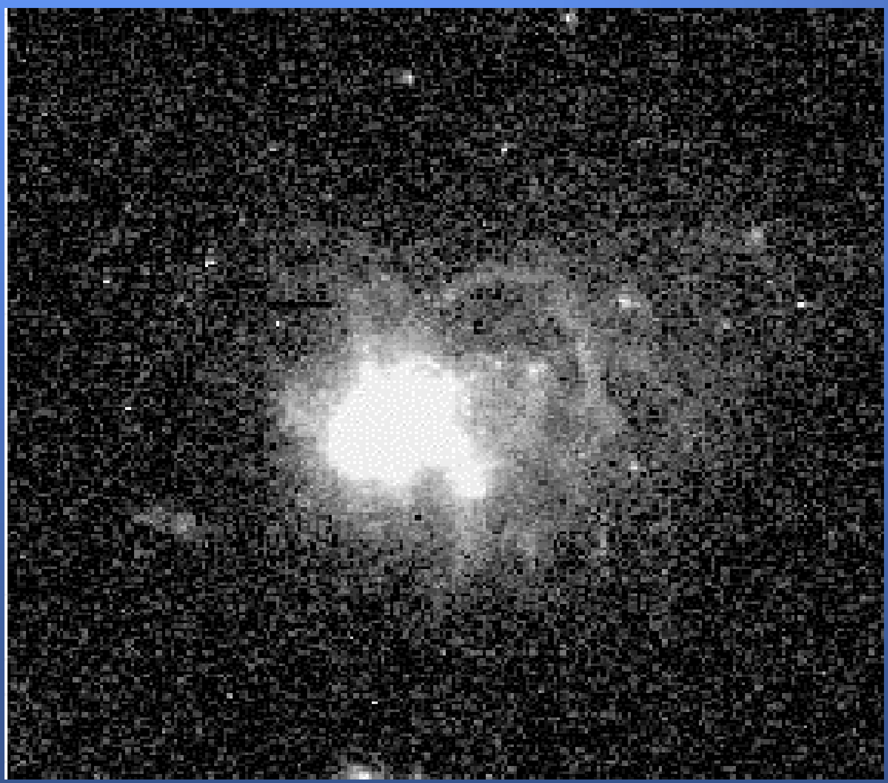
Properties

- $z = 0.0136$; $S_{25} \sim 0.06$ Jy
- Blue Compact Dwarf (BCD) with $Z \sim Z_{\odot} / 41$
  - *In a class with IZw 18 which has $Z \sim Z_{\odot} / 50$*
- Six regions of massive star formation – five visible and one obscured. All six are within a region of ~ 500 pc.
- $L_{bol} \sim 10^9 L_{\odot}$ - about 75% emitted in the mid-IR.

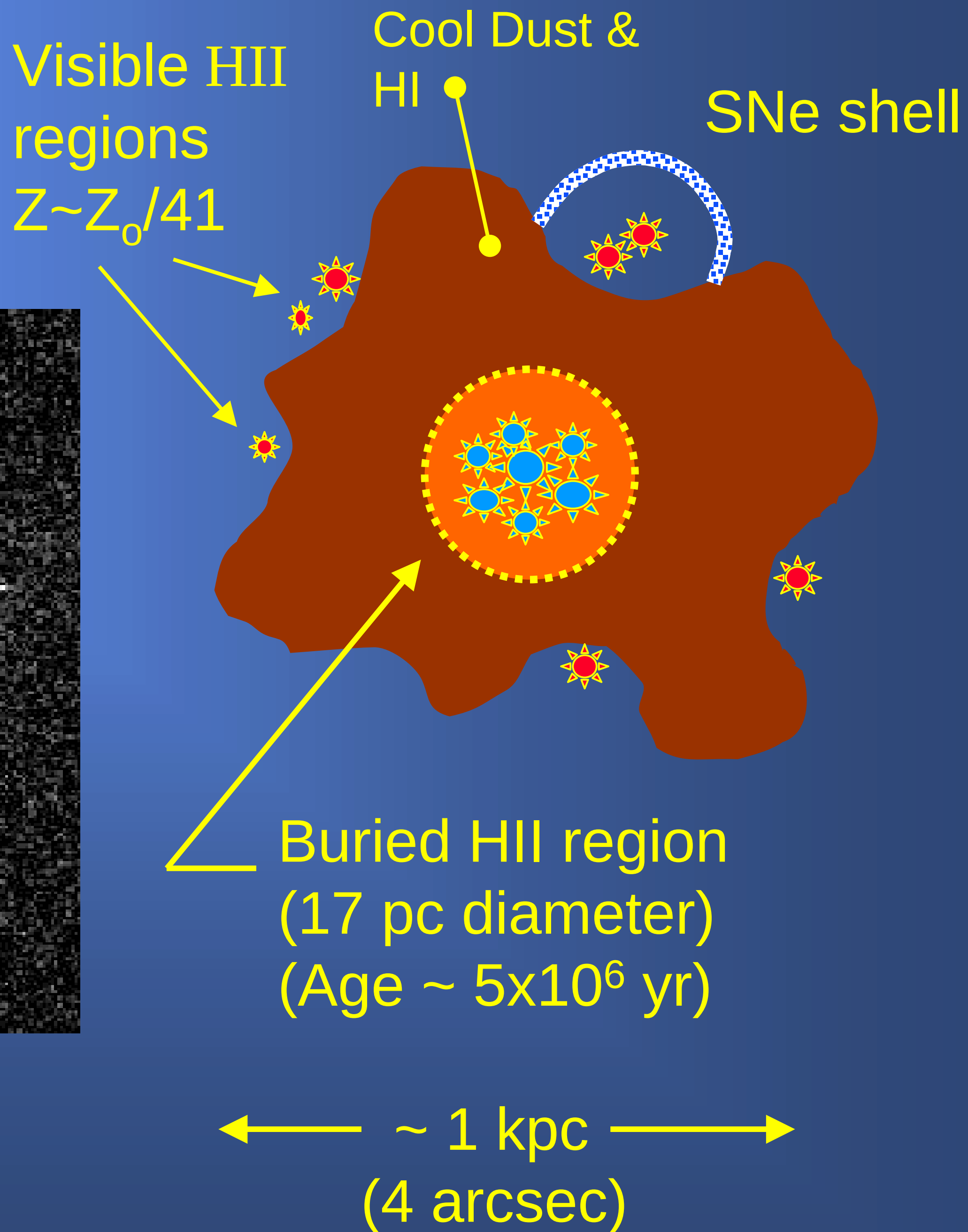
- *Use the IRS to study the MIR properties of the dust and gas in a sample of 20, low-metallicty BCDs. Are these analogs to high-redshift, star-forming galaxies ??*

IRS Observations: Feb 2004
SL = 28 mins, LL = 14 mins

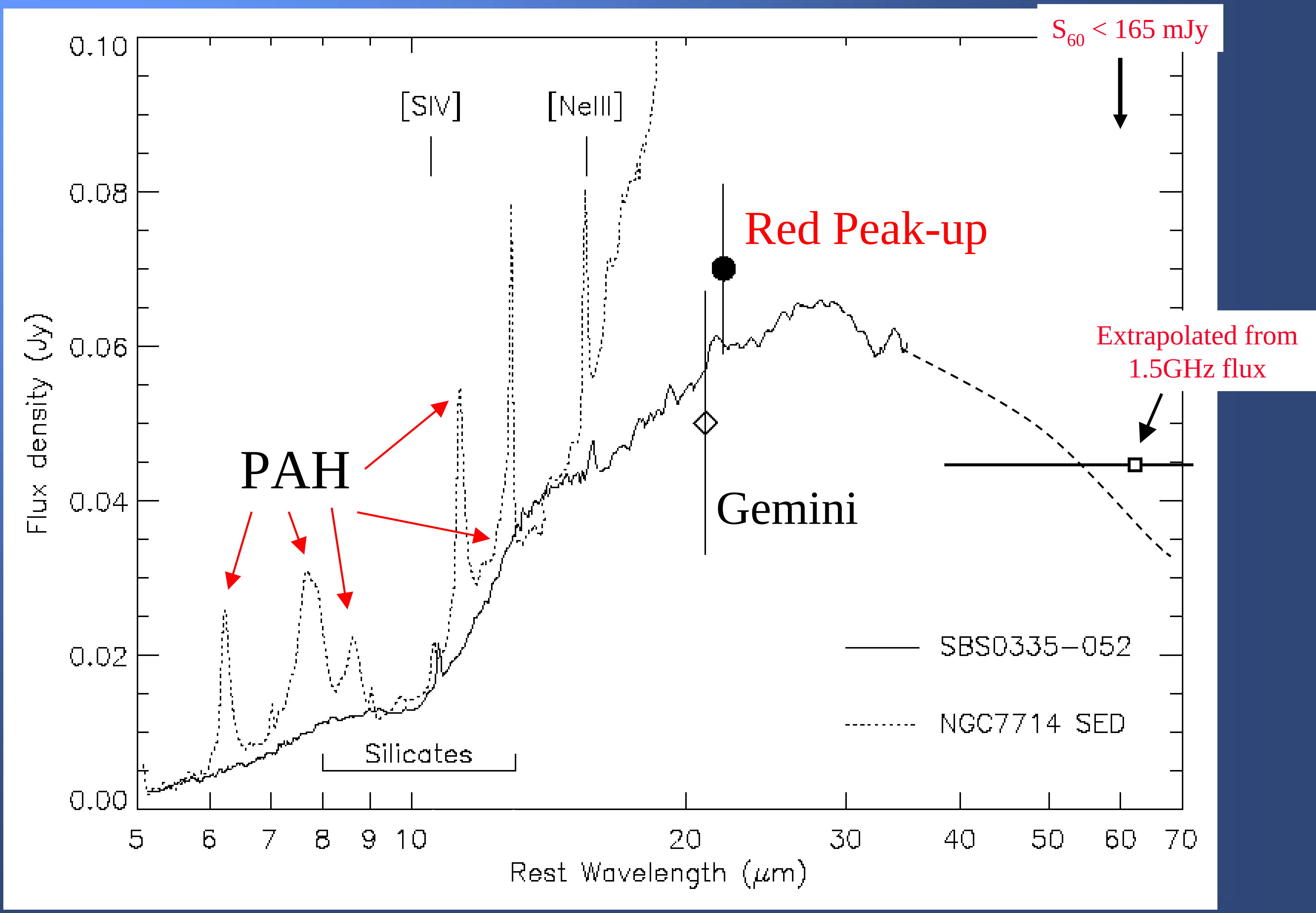
(Searle & Sargent 1972; Izotov, et al. 1997; Plante & Sauvage 2002; Thuan, et al. 1997; Dale, et al. 2001)



HST: Thuan, et al. 1997



IRS Spectra of SBS0335-052 & NGC7714



SBS 0335-052

IRS Results

- The spectrum shows silicate absorption ($A_{9.7}$ > 0.5 mag) but no PAH emission.
- The spectrum peaks at λ~28 μm. A two temp. BB fit (65 and 150K) implies a much smaller mass of cold dust than estimated from the ISO data (1.5 vs. 6×10^3 $M_\odot$). The Plante & Sauvage detection of 112 mJy at 65 μm seems inconsistent with the IRS spectrum by more than 2x.
- [SIV] 10.51 and [NeIII] 15.55 are clearly detected. The [SIV] / [SIII] and [NeIII] / [NeII] line flux ratios indicate a hard radiation field (T_{eff} > 4×10^4 K).
- Using the free-free 5GHz radio flux from Hunt, et al. (2004) and the He abundance from Izotov (1997), the MIR lines imply abundances which are higher (by 2-5x) than the optical values. The imbedded SC may be more enriched.

APM 08279+5255

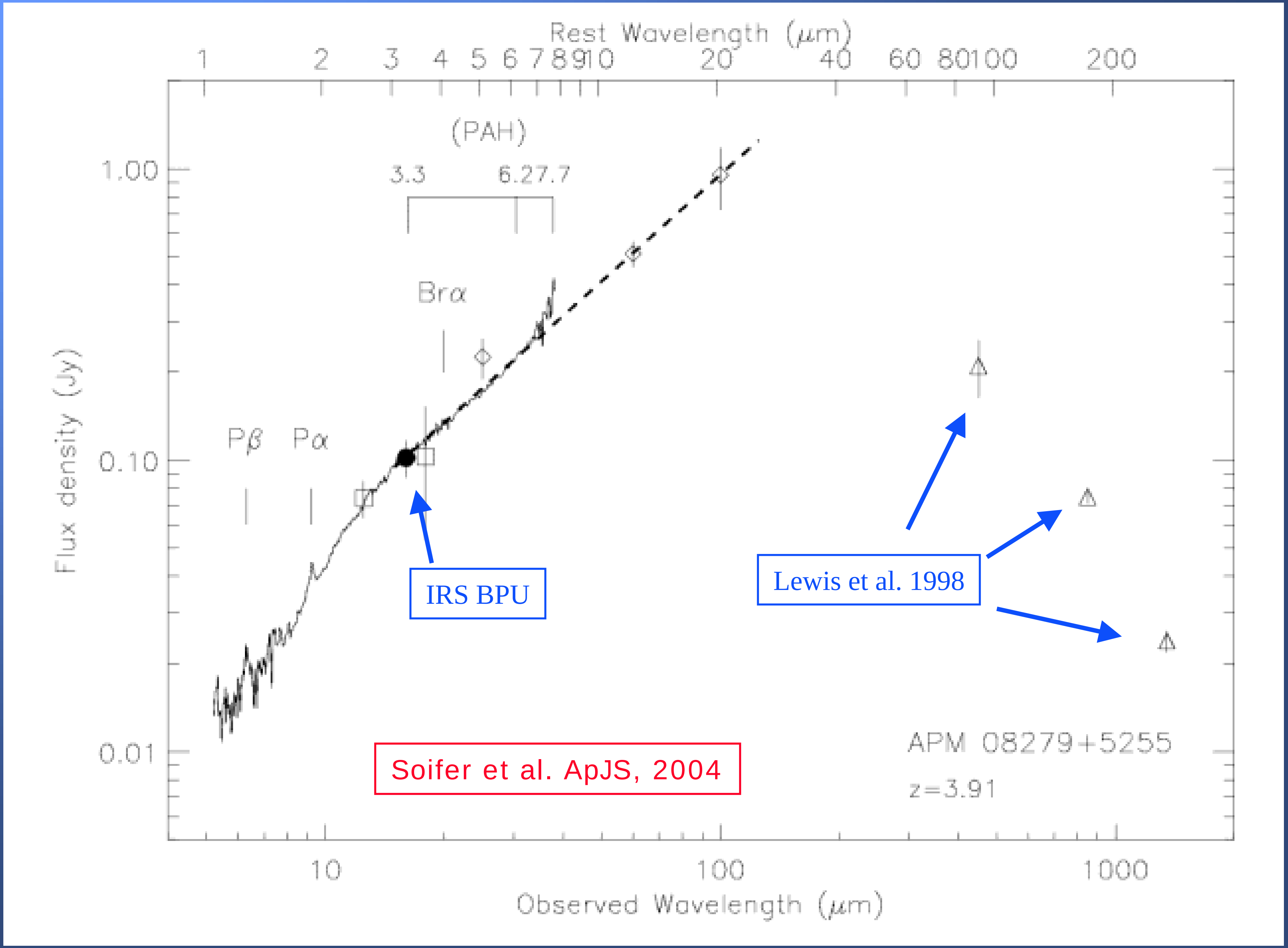
Properties

- $z = 3.91$; $S_{25} \sim 0.2$ Jy
- $L_{bol} \sim 5 \times 10^{13}\ L_{\odot}$ (after correcting for a magnification of ~100)
- Detected in mm, sub-mm and CO ($1\text{-}10 \times 10^{9}\ M_{\odot}$)
- FIR, sub-mm SED well fit by BB with T ~ 220 K

➢ *Since the QSO is gas and dust rich, can we use the IRS to measure the 3.3 and 6.2 PAH emission features or organic absorption features (e.g. water or hydrocarbons) and compare to low-z AGN and ULIRGs ??*

IRS Observations: Oct, Nov 2003
SL = 112 sec, LL = 168sec

(Irwin, et al. 1998; Downs, et al. 1999; Ibata, et al. 1999; Egami, et al. 2000; Lewis, et al. 2002)


Rest Wavelength (μm)
1 2 3 4 5 6 7 8 9 10 20 40 60 80 100 200
(PAH)
3.3 6.2 7.7
Brα
Pβ Pα
1.00
0.10
0.01
Flux density (Jy)
10 100 1000
Observed Wavelength (μm)
IRS BPU
Lewis et al. 1998
Soifer et al. ApJS, 2004
APM 08279+5255
z=3.91

APM 08279+5255

IRS Results

- The spectrum is very smooth with $f_\nu \sim \nu^{-1.2}$ for $\lambda_{rest} > 2.9$ µm, steepening to $f_\nu \sim \nu^{-2.3}$ for $\lambda_{rest} < 2.9$ µm. This is consistent with a decrease in very hot (T > 1000K) dust perhaps from sublimation of silicate grains in the inner accretion disk.
- No 3.3 or 6.2 PAH emission is detected. The rest-frame EQW of the 6.2 PAH line is < 0.006 µm. This is less than 1/43 (1/8) that seen in the IRS spectra of the ULIRGs UGC 5101 (Mrk 1014).
- Redshifted P-β and P-α are detected, but P-α/ P-β ~ 1.05 +/- 0.2, which is less than case B (2.0) and high density models (1.8) of the BLR (e.g. Drake and Ulrich 1980; Lynch et al. 2000).
- The P-β and P-α lines are resolved in low-res, and have FWHM ~ 9000 km s^{-1}.

IRS Spectroscopy – An Early Prognosis

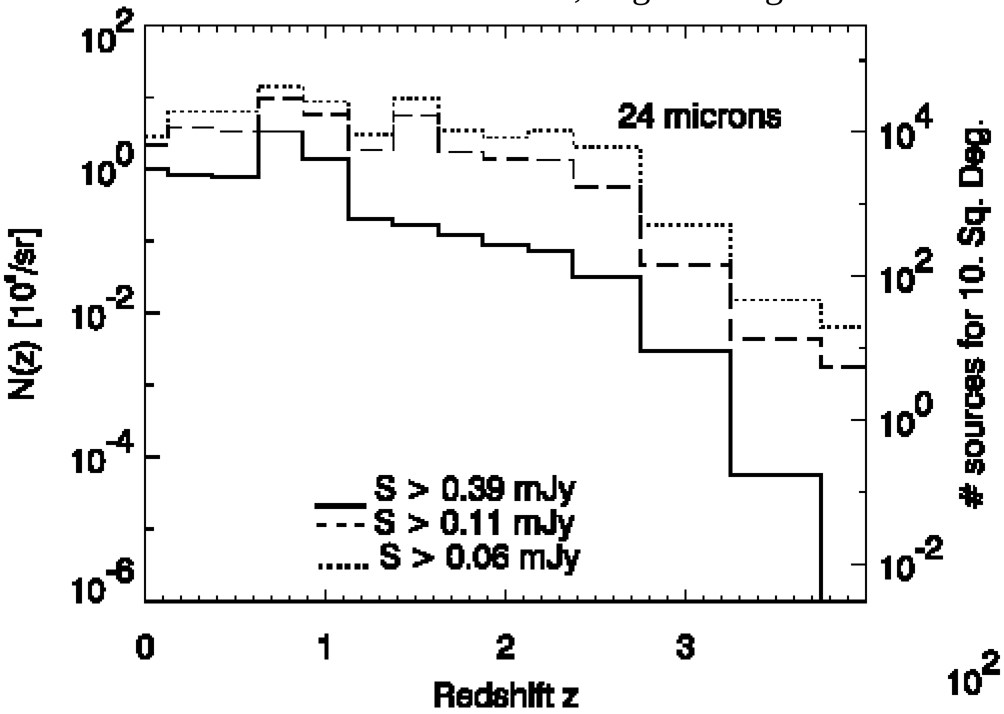
- There are hundreds of low-z and luminous high-z sources that can be measured with the IRS to determine energy sources, dust temperatures, compositions, warm molecular gas masses, etc.

- Most of these sources are already known (e.g. ULIRGs, BCDs, unusual IRAS sources), or will be found in various Spitzer GTO and Legacy surveys (e.g. FLS, SWIRE).

…However,

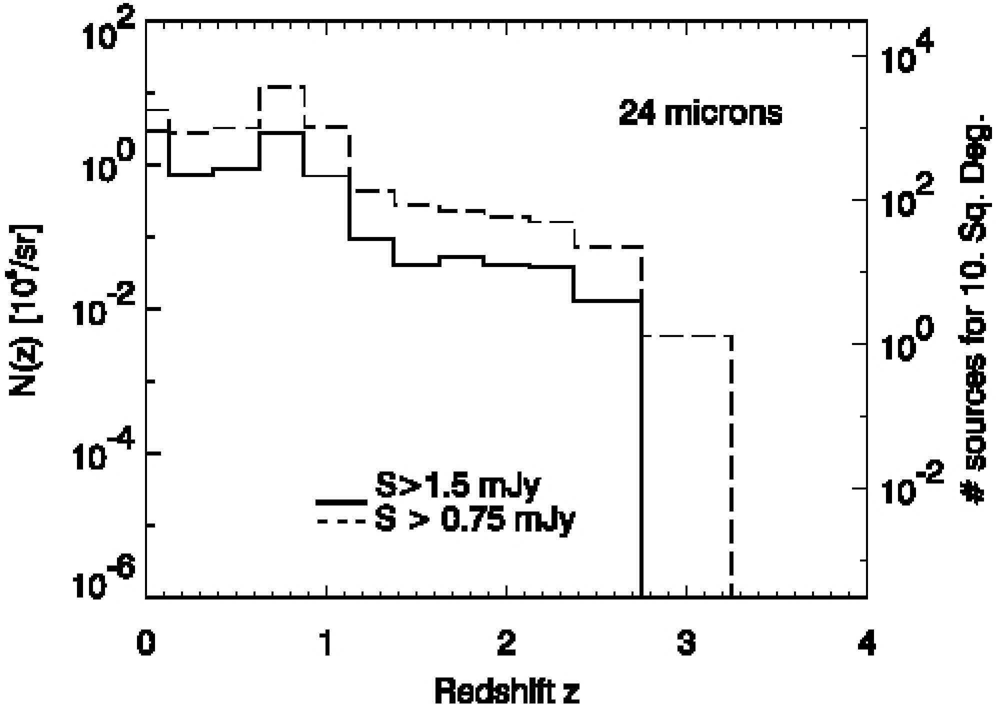
- the majority of the sources found with Spitzer (even in the shallow surveys), especially those at z > 2 (where the luminous optical QSOs and the sub-mm sources peak), will be very difficult to study with the IRS. Broad band techinques (e.g. IRAC-MIPS colors) must be used until future spectroscopic missions are available.
- Spitzer detections will be biased (at many redshifts) to warm dust sources (AGN).
- The dust obscuration in many sources (e.g. some ULIRGs) is so high ($N_H > 10^{23}$ -10^{24} or $A_V >> 100$ mag) that even the MIR cannot penetrate to the nucleus.

Dole, Puget & Lagache 2003

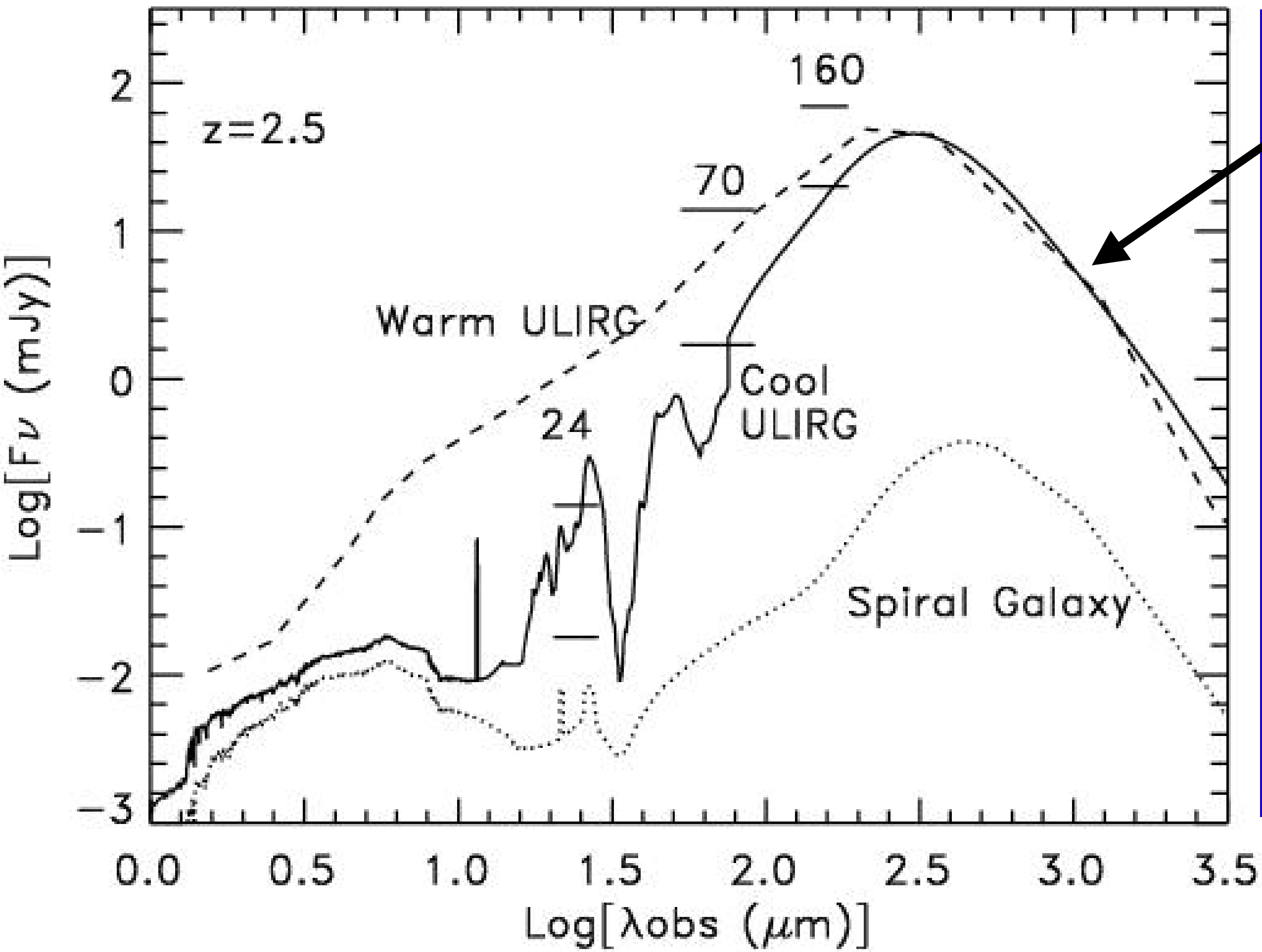


There should be ~20000 sources in the MIPS shallow and SWIRE surveys with z > 2 and S_{24} > 0.2-0.3 mJy (the 5σ survey limits) .

About 1% of these (~200) are observable with IRS low-res in t ~ 0.3-0.5 hr/order (~1-2 hrs for a full SL+LL spectrum).



Can IRS Measure the Sub-mm Population ?



Normalized at 850 μm to match bright SCUBA sample.

Cool source has L_{IR} ~ 5×10^{12} $L_{\odot}$ and S_{24} ~ 0.2-0.3 mJy

Would take ~3 hrs (per order) to get a 5σ detection with the IRS.

Courtesy David Frayer

Beyond the IRS

- Sensitive, long wavelength spectroscopic missions will be needed to explore the densest environments at low redshifts, as well as star-forming galaxies at high redshifts that have luminosities well below 10^{12-13} $L_{\odot}$. The Spitzer IRAC and MIPS Legacy and GTO surveys will lay the groundwork for these missions.