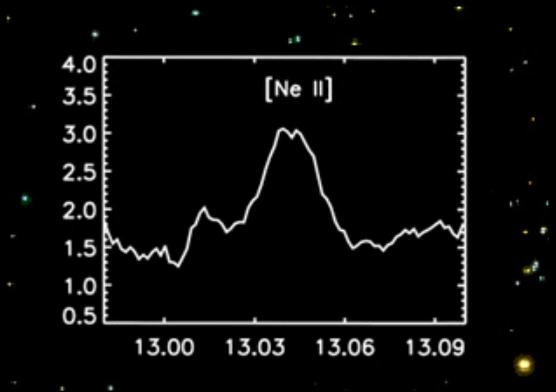
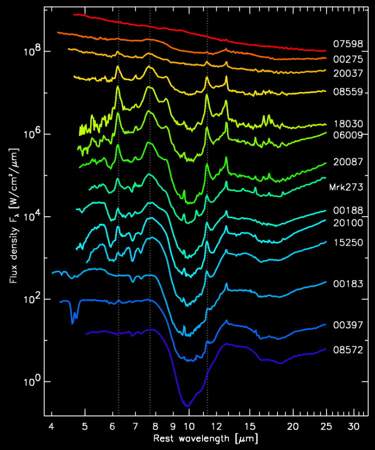
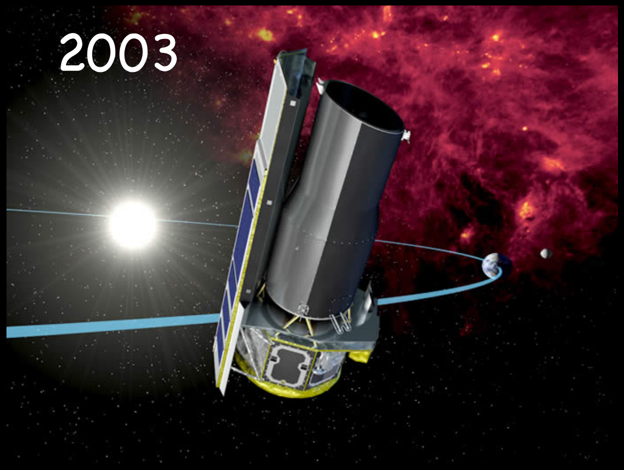
Mid-Infrared Studies of Galaxies from Space



Dimitra Rigopoulou
Univ. of Oxford
& RAL-Space

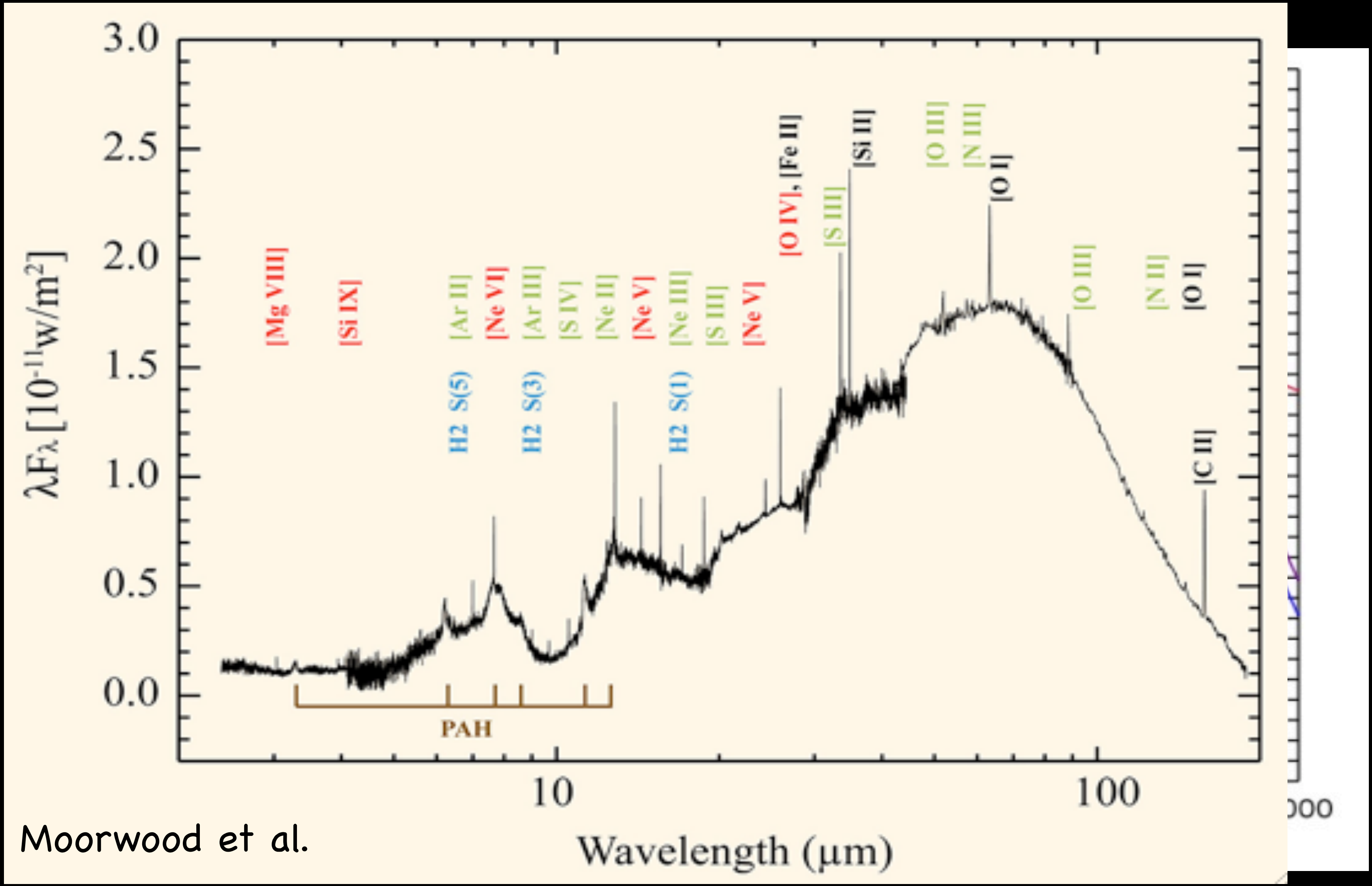




Disclaimer

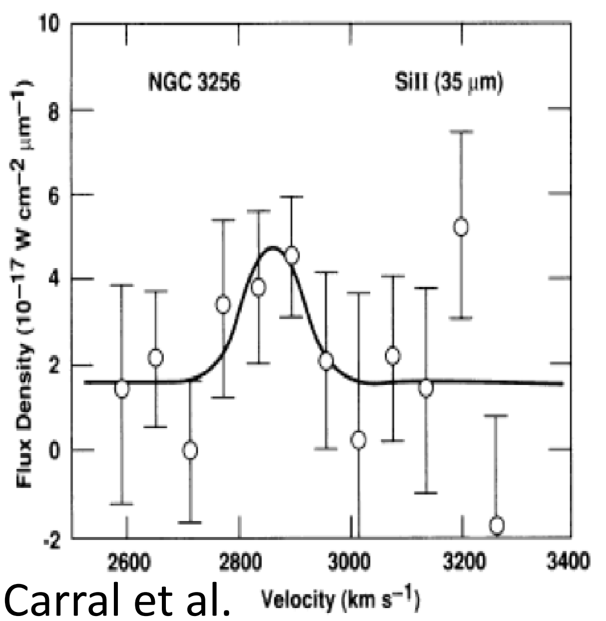
it is impossible to review x100s Spitzer and ISO papers. Instead I focused on selected MIR-spectroscopic studies of galaxies. Apologies if I don't cite your paper!

Why bother with the mid-infrared?

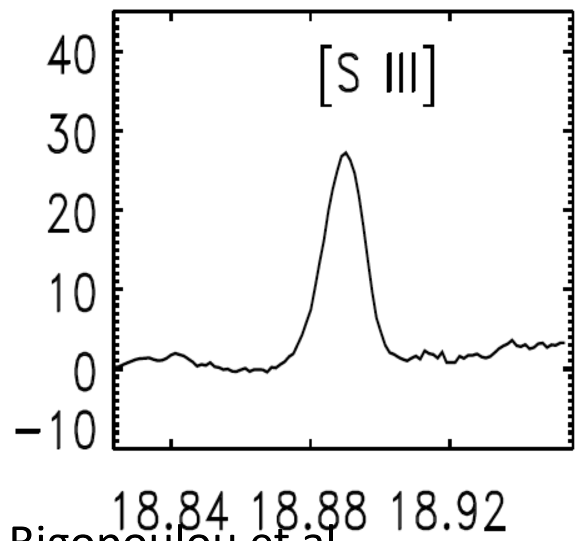


Moorwood et al.

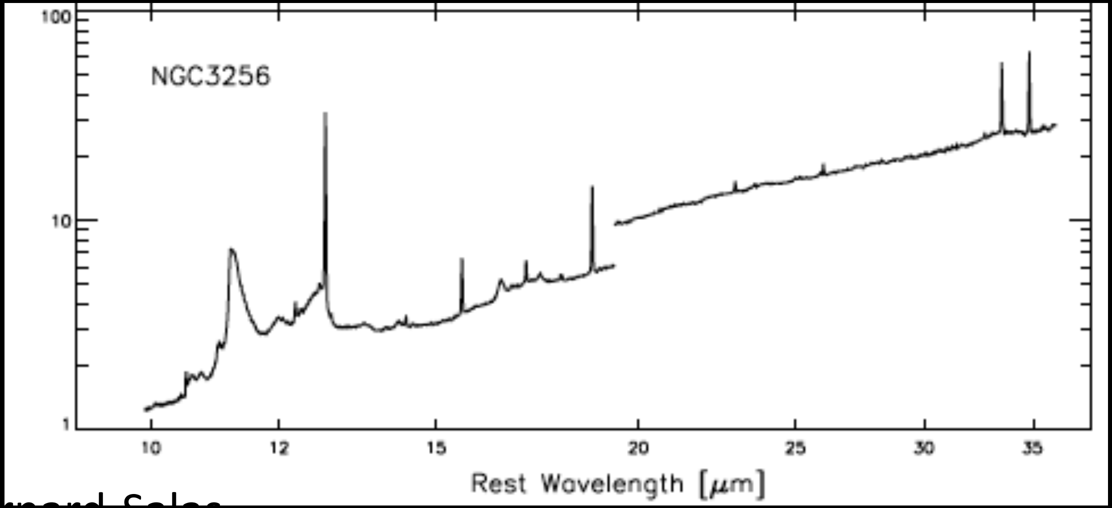
Mid-infrared spectroscopy from space : from KAO to ISO to Spitzer, JWST and beyond



Carral et al.



Rigopoulou et al.



rnard Salas

Studying Galaxy Evolution in the MIR

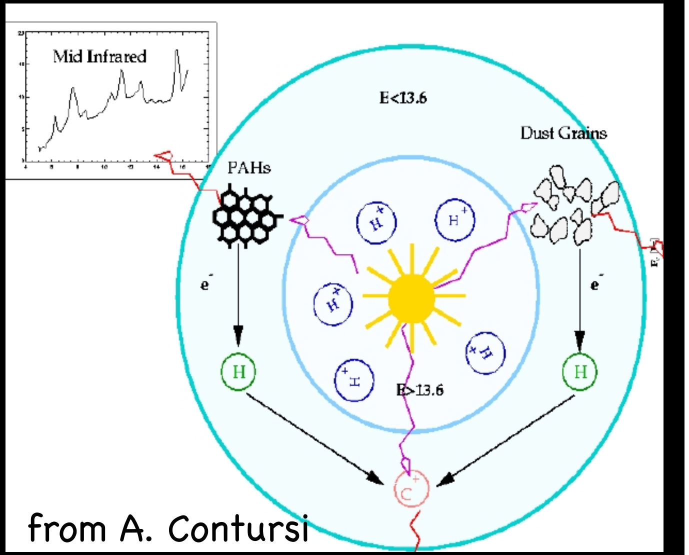
Pure rotational H_2 lines

H_2 rotational transitions in the mid-infrared (excitation energies 5-10 times smaller), probe gas T~ 100-1000 K up to 30% of total H_2 (norm)

PAHs & silicate absorption

PAHs used as diagnostics of SB and AGN

Crystalline silicates (forsterite=Mg_2SiO_4 found in 12 ULIRGs)



from A. Contursi

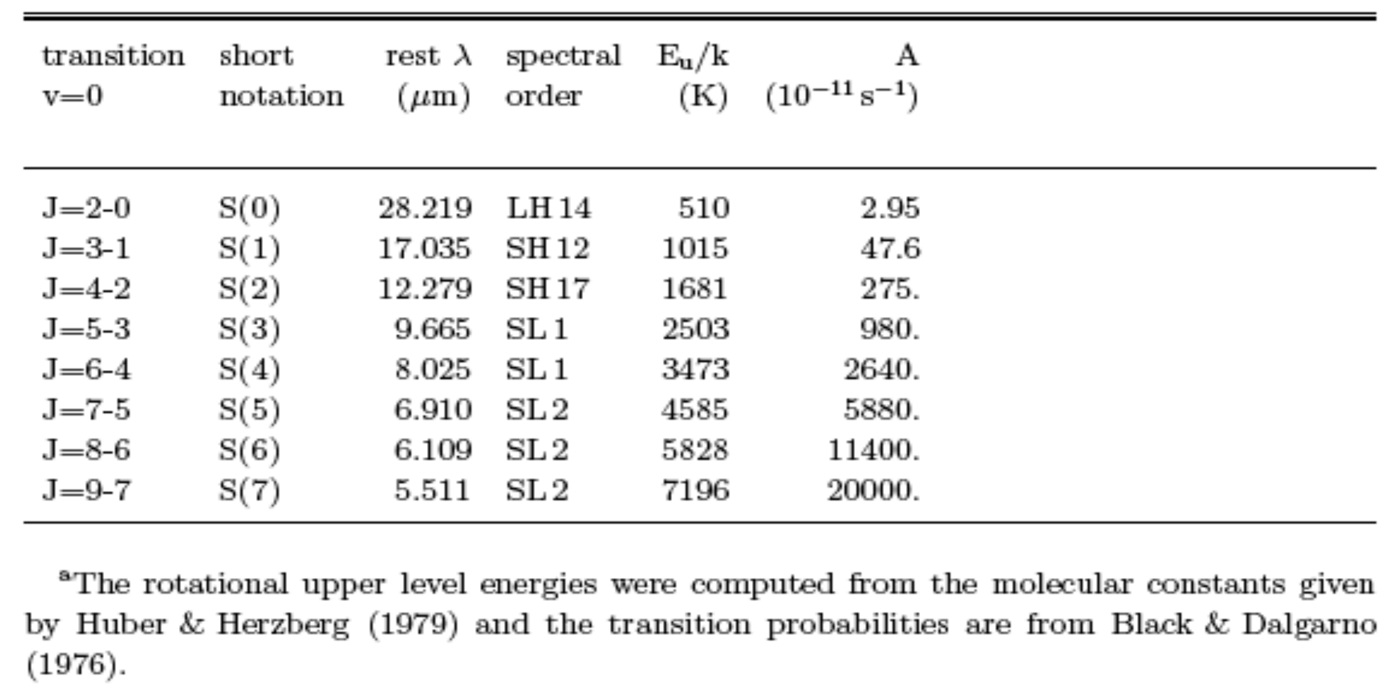
Fine Structure lines

A host of mid-infrared fine structure lines with a wide variety of ionization potential : [NeII] 12.8 µm [NeV] 14.3 µm, [OIV] 25.9µm, [SIII] 18 & 32 µm, [SiII] 34 µm

H_2 rotational / vibrational lines

H_2 vibrational transitions in the near-IR arise from gas at T > 1000 K, small fraction (10^{-6}) of total molecular H_2 gas

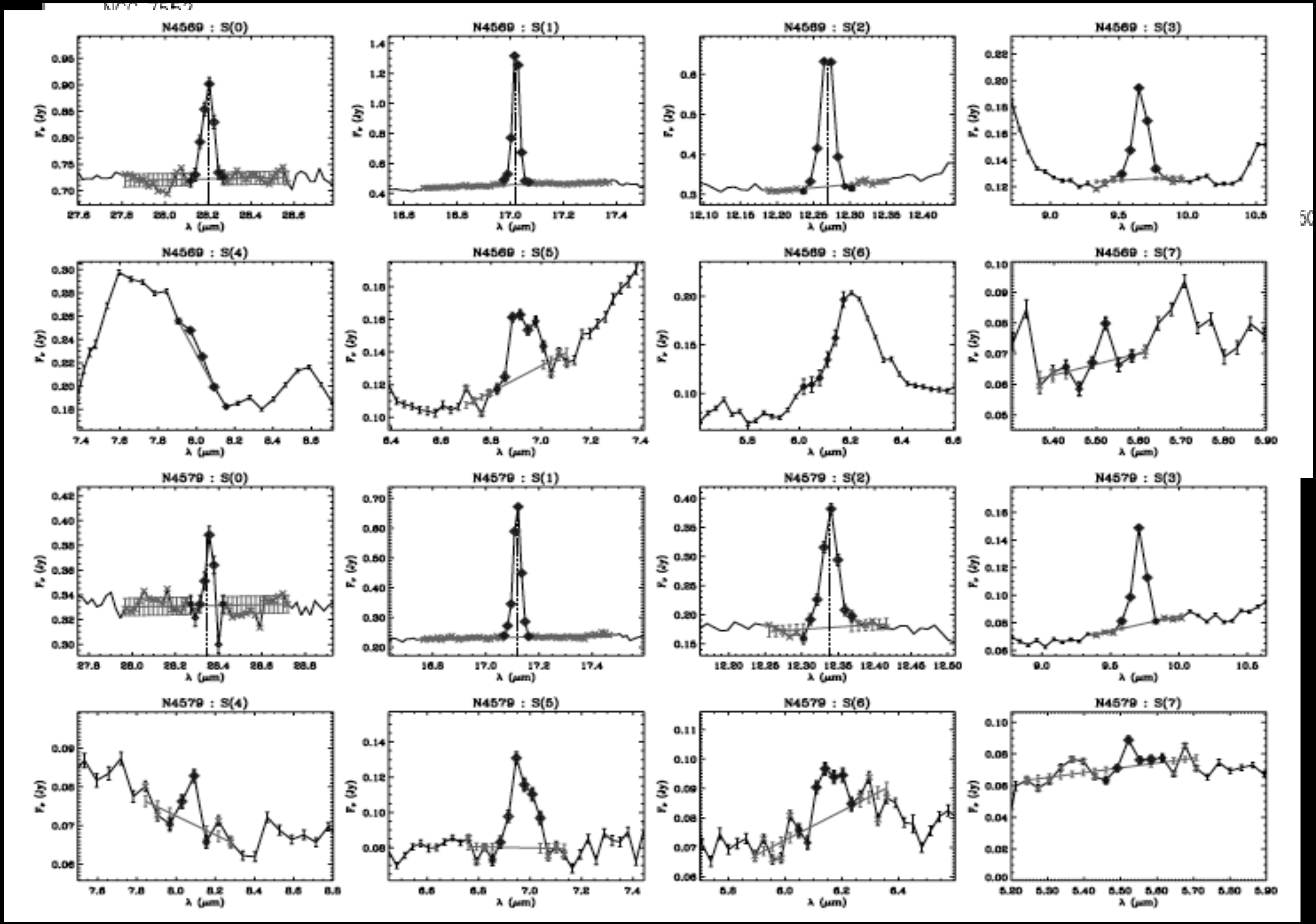
H_2 rotational transitions in the mid-infrared (excitation energies 5-10 times smaller), probe gas T~ 100-1000 K up to 30% of total H_2 (norm)



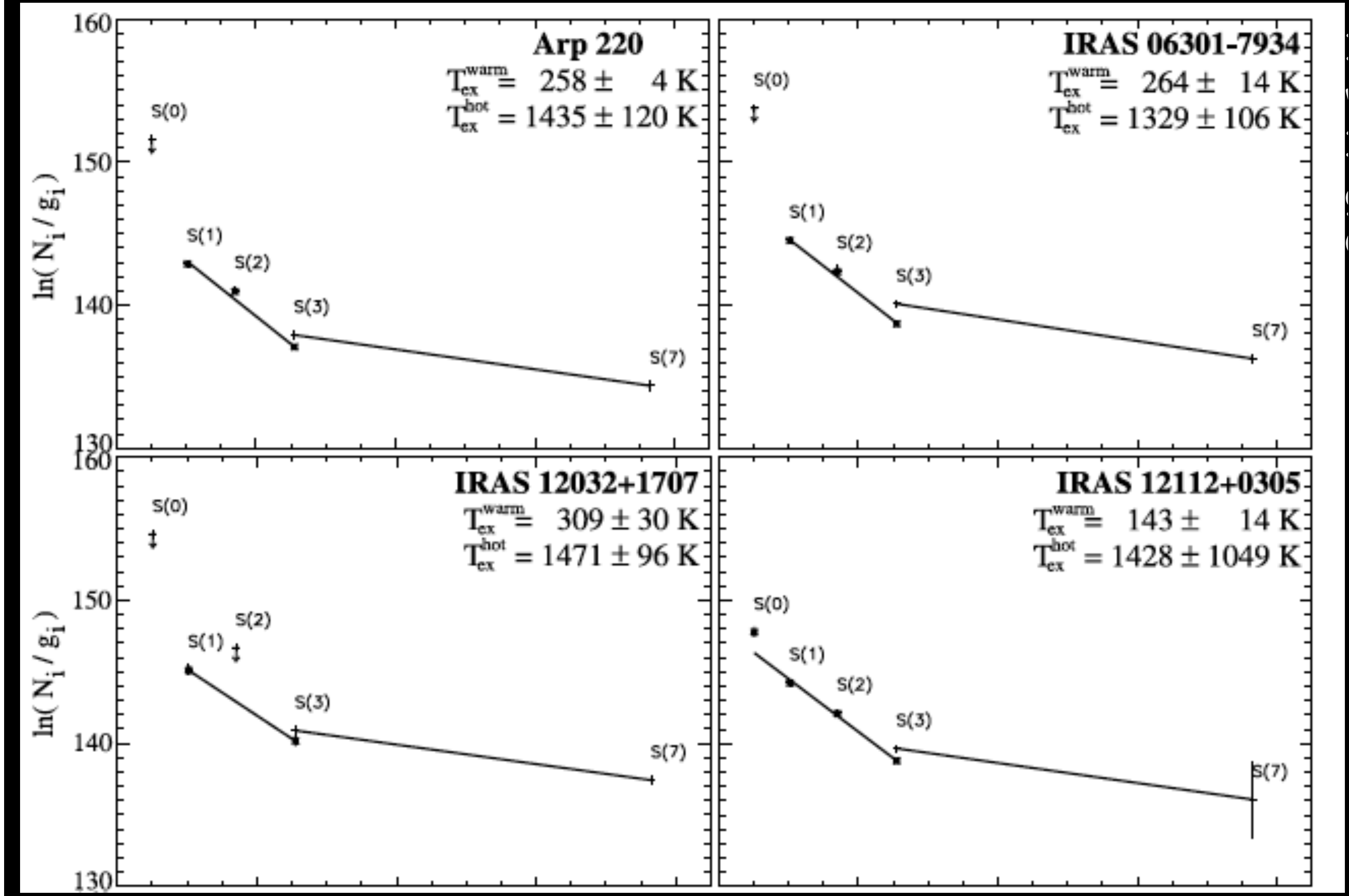
transition v=0	short notation	rest λ (μm)	spectral order	E_u/k (K)	A ($10^{-11}\,s^{-1}$)
J=2-0	S(0)	28.219	LH 14	510	2.95
J=3-1	S(1)	17.035	SH 12	1015	47.6
J=4-2	S(2)	12.279	SH 17	1681	275.
J=5-3	S(3)	9.665	SL 1	2503	980.
J=6-4	S(4)	8.025	SL 1	3473	2640.
J=7-5	S(5)	6.910	SL 2	4585	5880.
J=8-6	S(6)	6.109	SL 2	5828	11400.
J=9-7	S(7)	5.511	SL 2	7196	20000.

[a] The rotational upper level energies were computed from the molecular constants given by Huber & Herzberg (1979) and the transition probabilities are from Black & Dalgarno (1976).

H_2 observations: from ISO to SPITZER



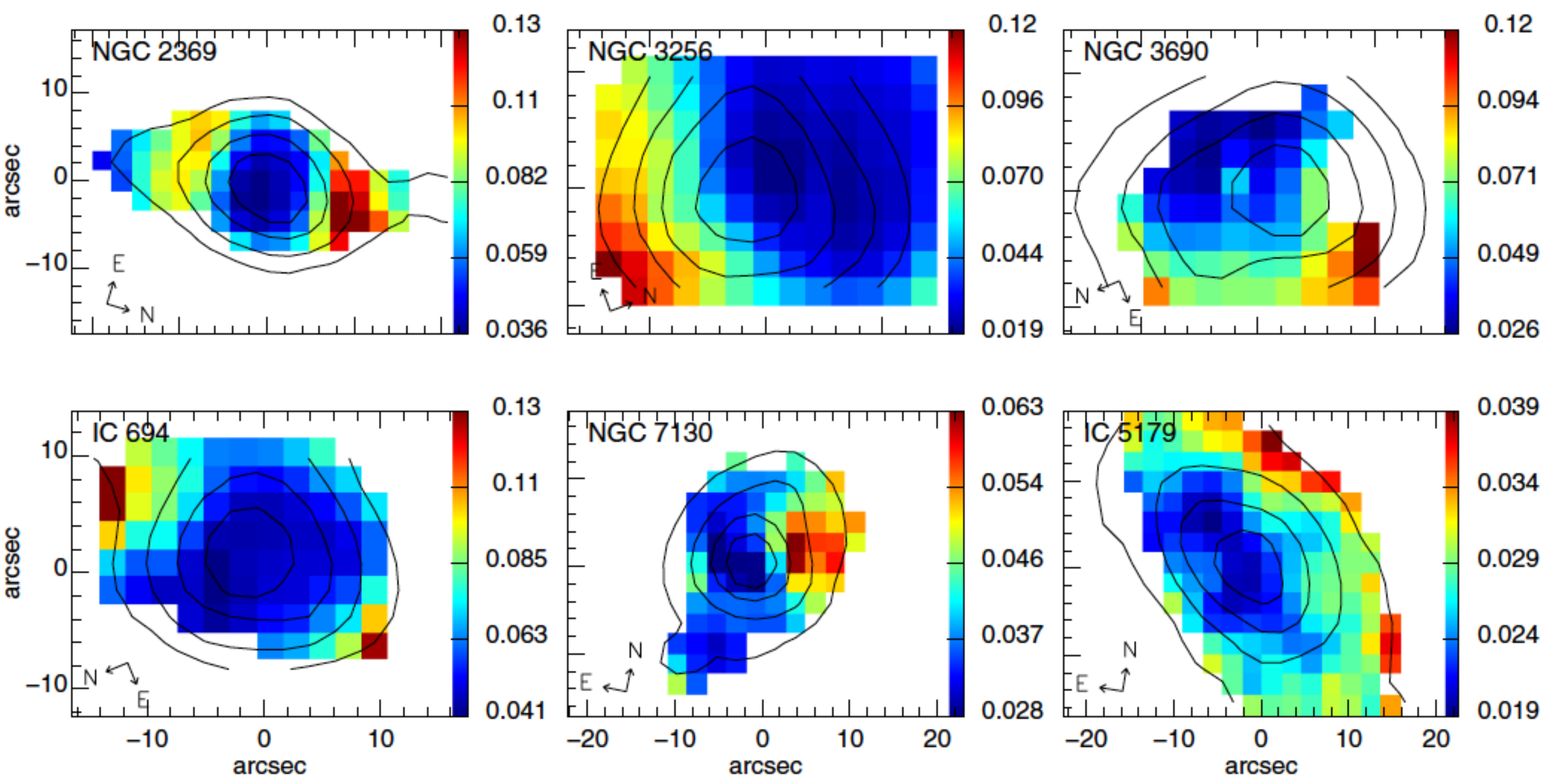
Excitation temperatures & Masses



ULIRGs show 3x more H2 emission than that expected from their SFR. Additional source of heating in shocks? (Hill+14)

Higdon et al. 06

Spatially resolved H_2 measurments in LIRGs

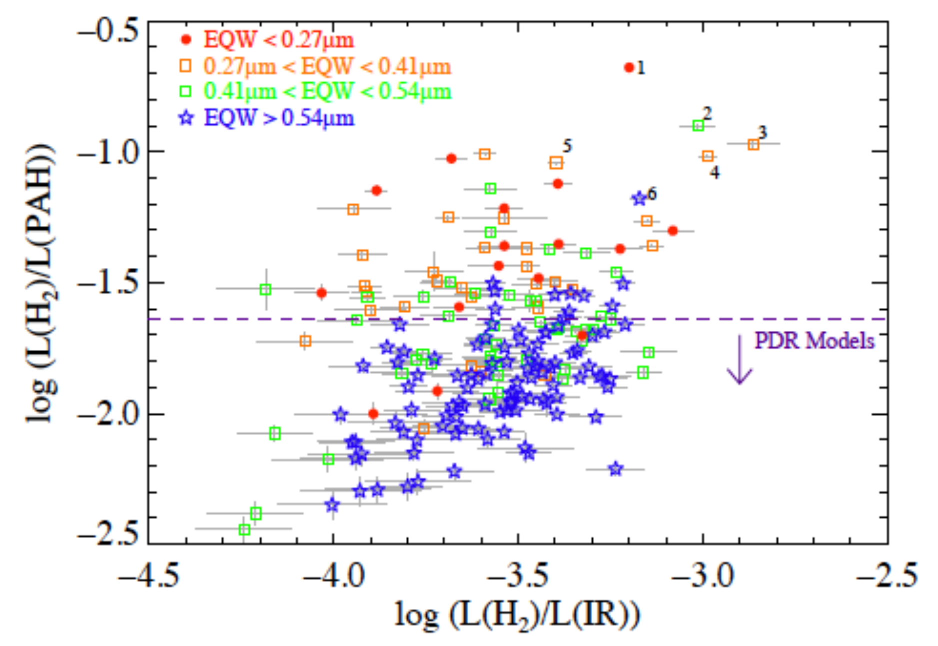


Pereira-Santaella et al. 2010

Broad agreement between spatial extent of H2 and PAHs:
Common origin (in PDRs?)
What about shocks?

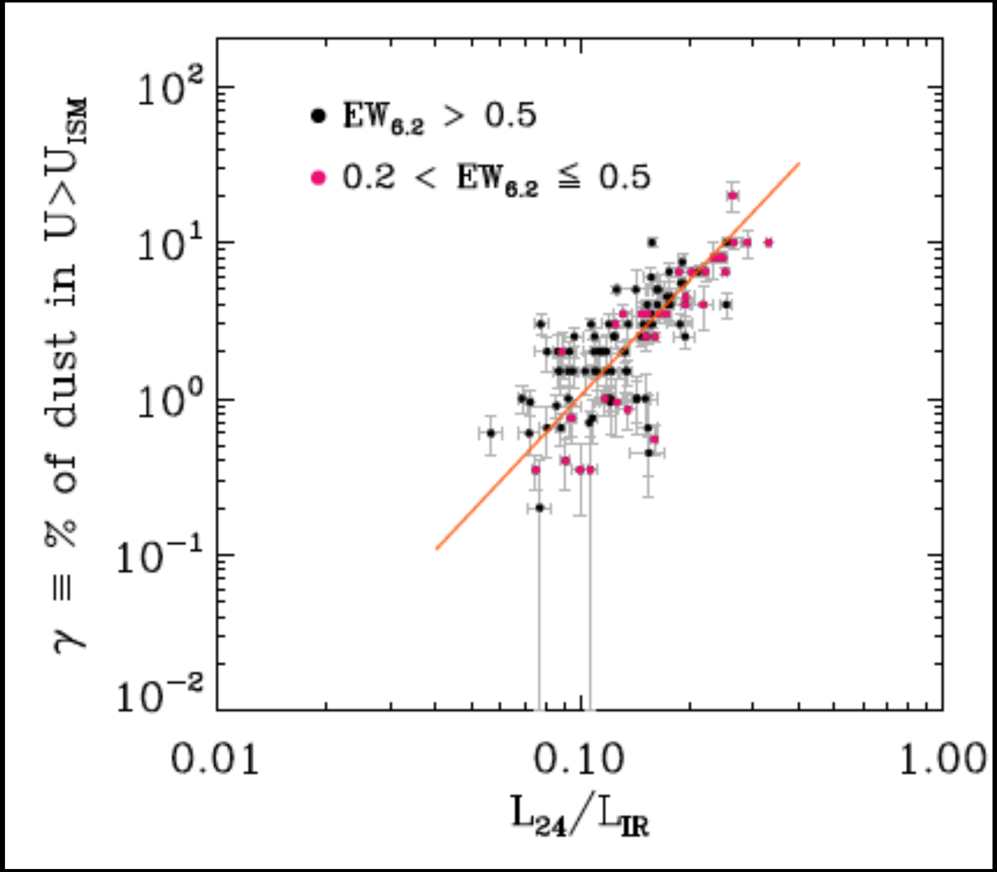
H2 origin

Excess H2 emission: evidence for shocks/ outflows?



GOALS sample, Stierwalt +14

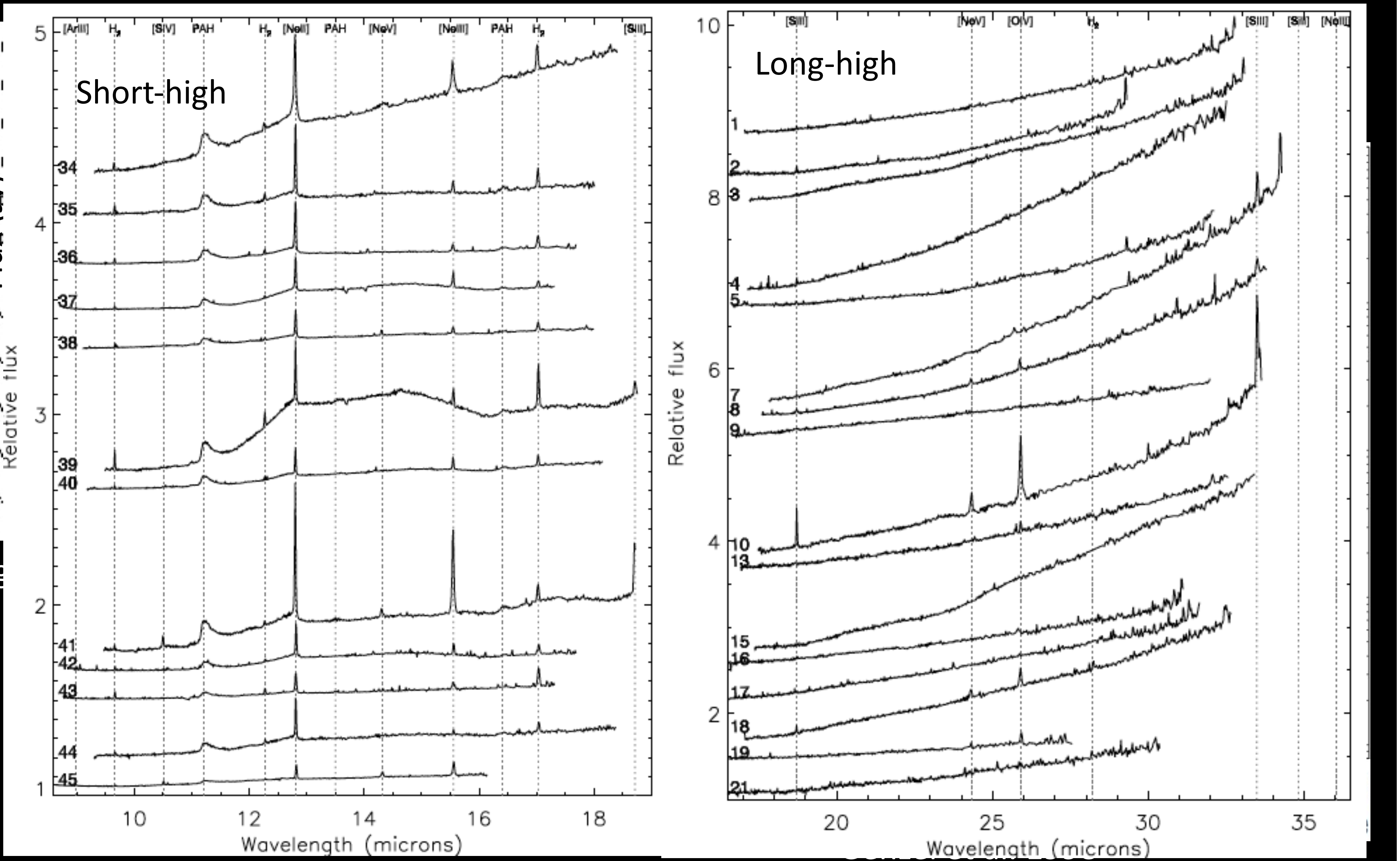
Fraction of Mdust heated by radiation fields stronger than diffuse ISM (incl PDRs, based on Draine+Lee '07 models



Magdis, Rigopoulou +13

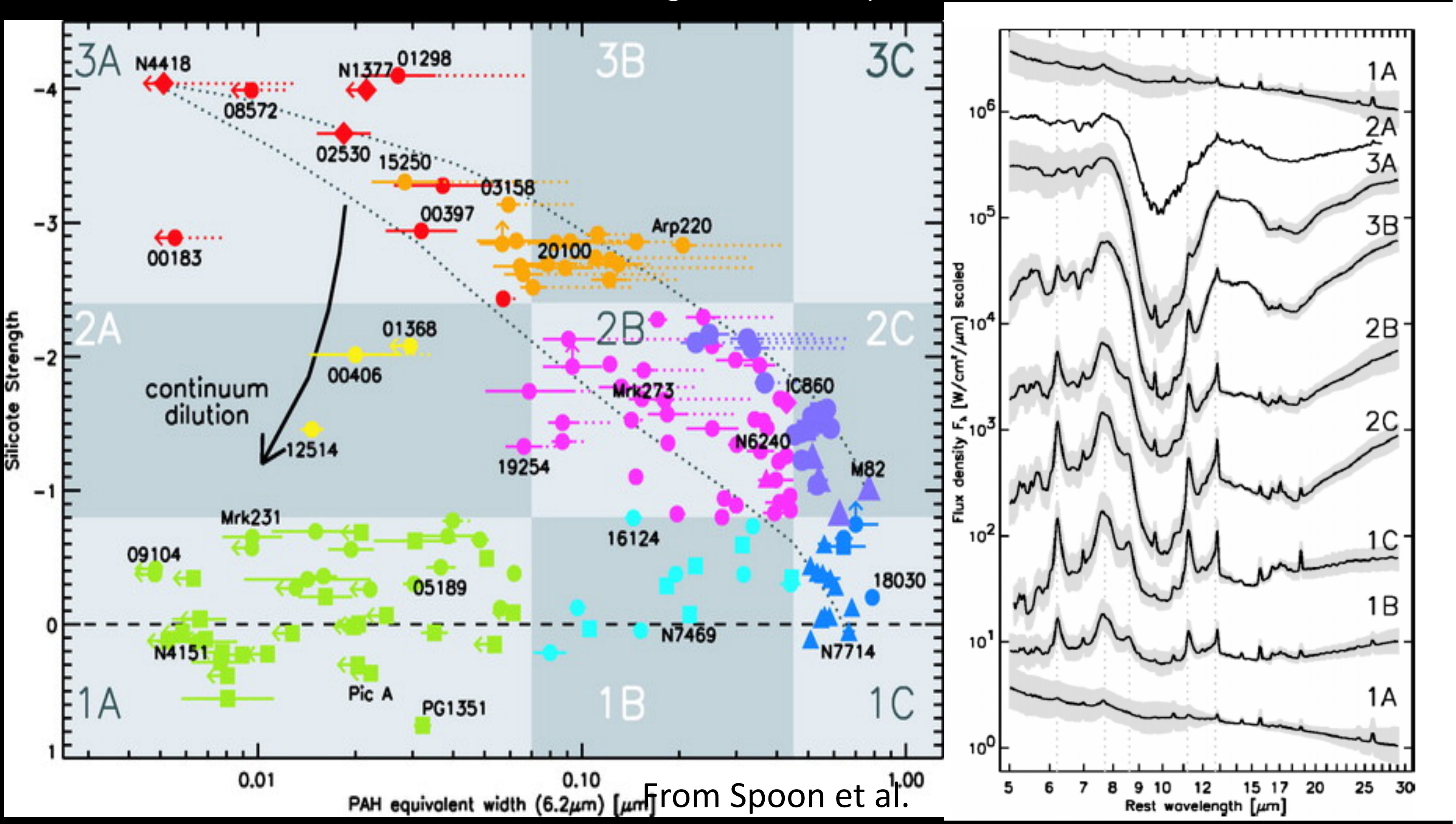
ULIRGs

Mid-infrared spectroscopy: from ISO to Spitzer



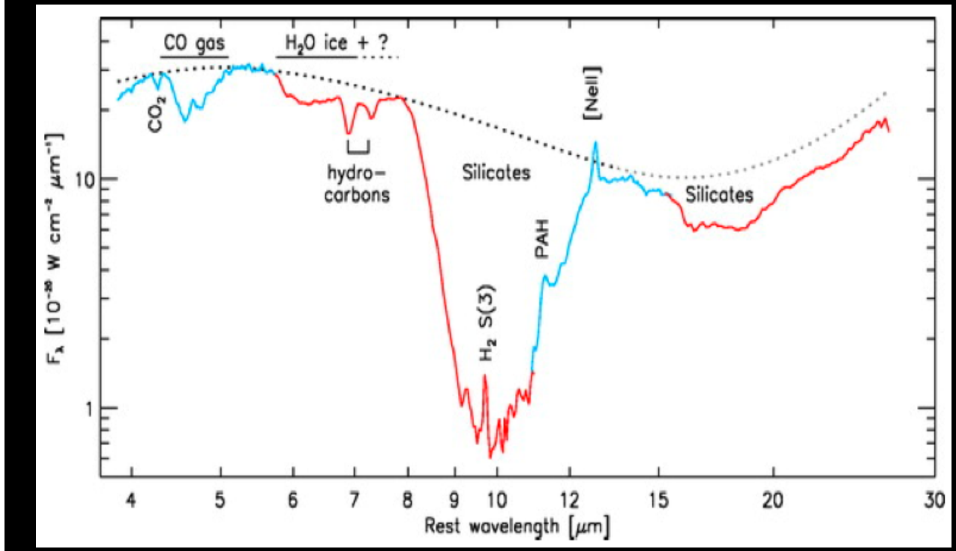
Farrah et al.

Refined diagnostic plots

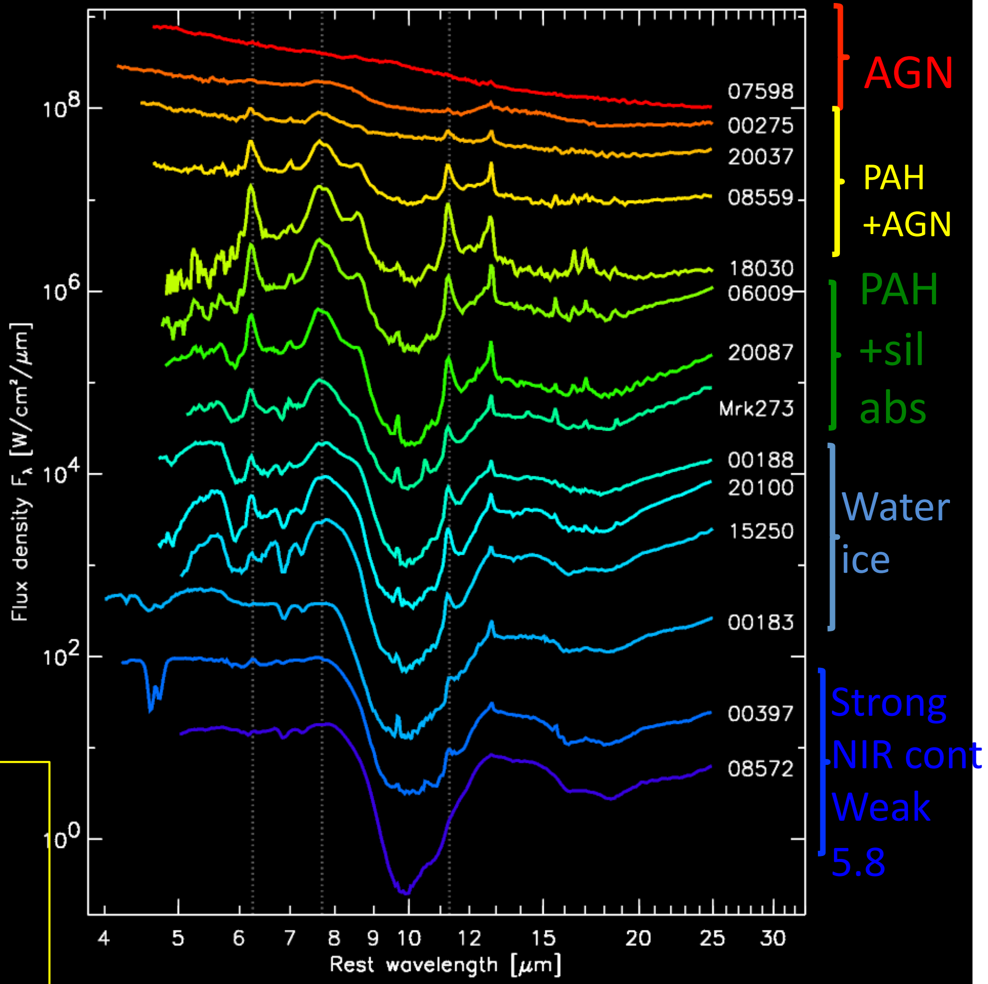


From Spoon et al.

Penetrating through the obscuring material



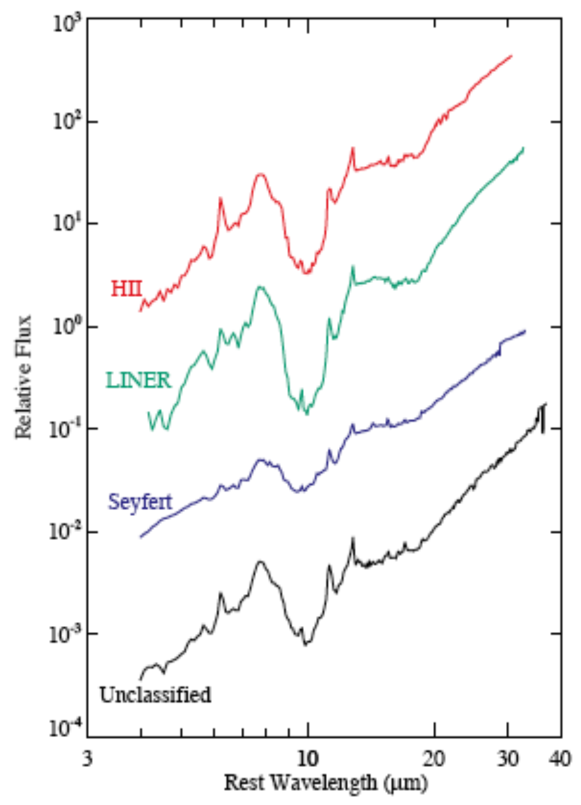
IRASF00183-7111: strong abs bands, water-ice, hydrocarbons (Spoon 2004)

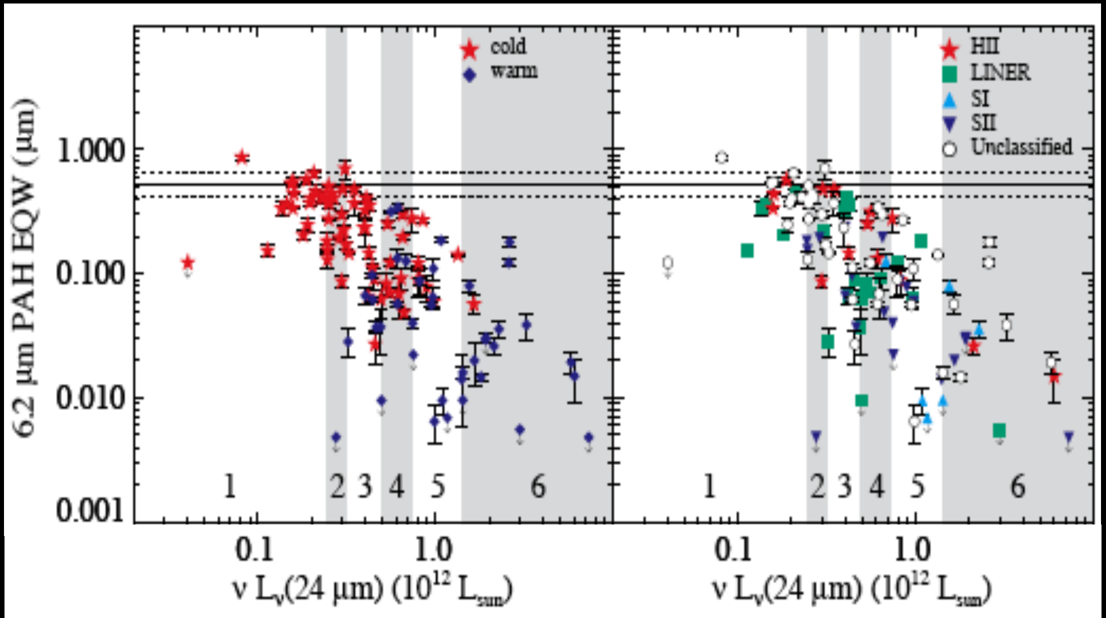


- Large variation in MIR spectra driven by PAH, H_2O ice, hydrocarbon & silicate absorption
- 30-40% of the power of a typical ULIRG comes from an AGN. This rises with luminosity, dust temp, merger stage, etc.

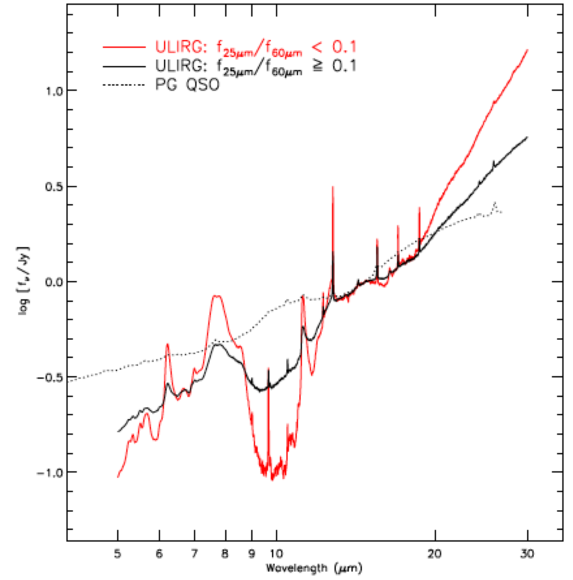
Spoon +(2007), Armus +(2006,2007), Desai +(2007), Hao +(2007), Imanishi +(2007), Schweitzer +(2008), Lutz +(2008), Veilleux +(2009)

AGN contribution increases with increasing LIR





Desai +2007



- 30-40% of the power of a typical ULIRG comes from an AGN. This rises with luminosity, dust temp, merger stage, etc.
- detection of SB signatures (PAH + cold dust) in QSOs strengthened evidence for rapid BH and bulge growth in dusty, merging galaxies.

Veilleux +2009

The Starburst – AGN connection

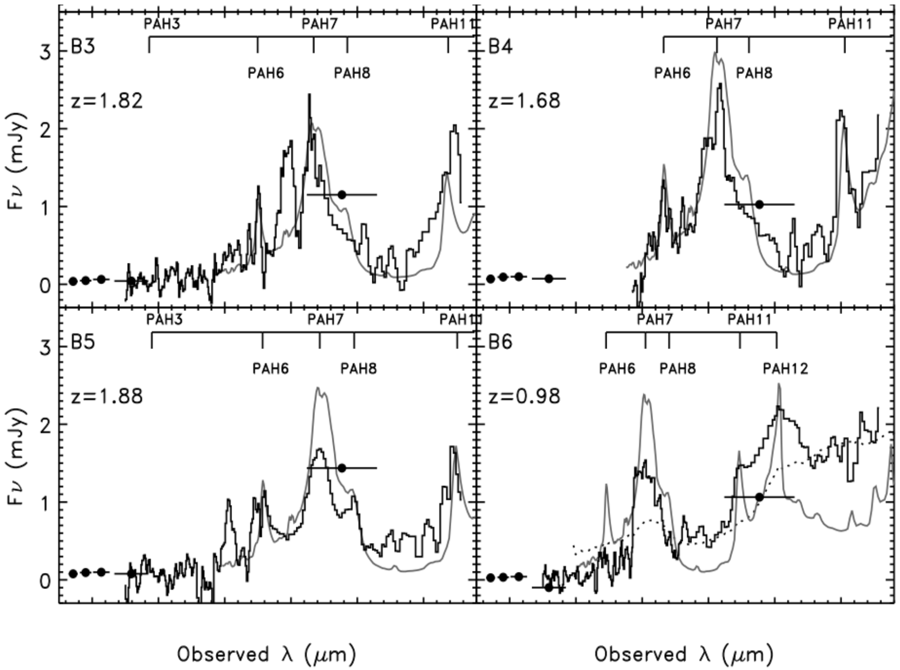
The mid-IR SED is composed of two main components:

Starburst:

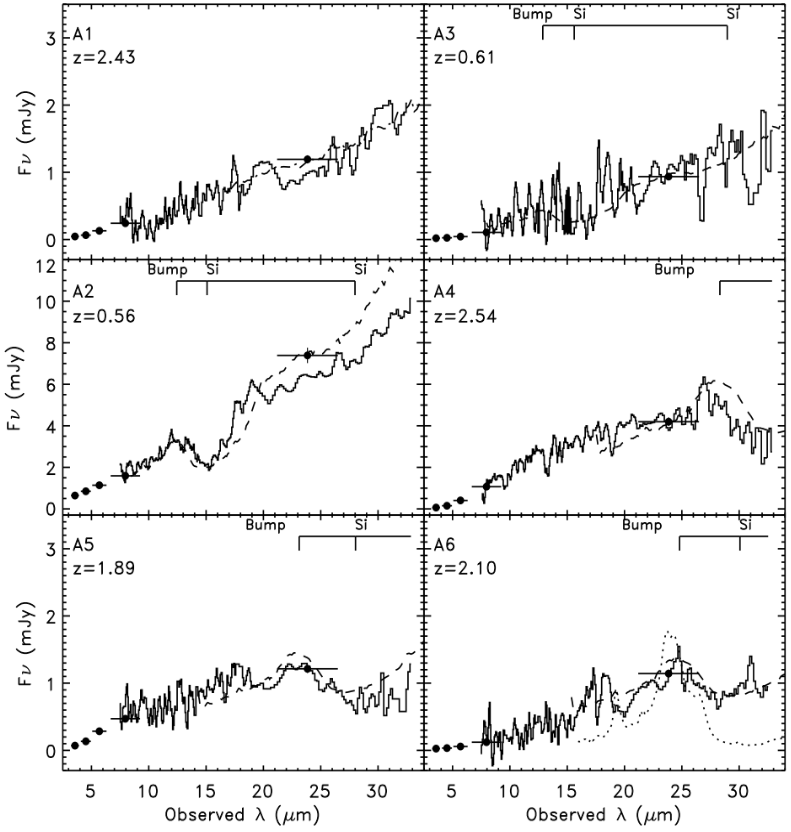
Polycyclic aromatic hydrocarbons (PAH) emission lines + extinction

Main lines at 6.2, 7.7, 8.6 and 11.3μm

2. **AGN**: power-law + extinction

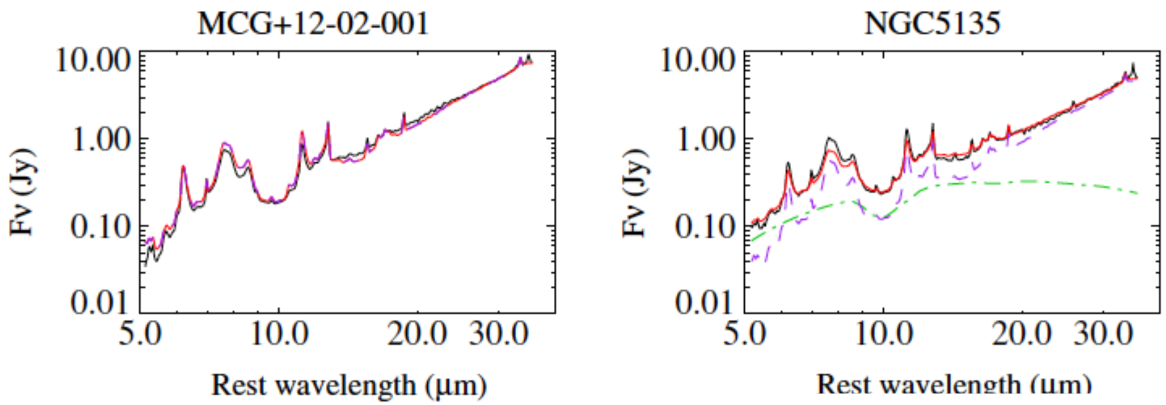


Bernard-Salas +09

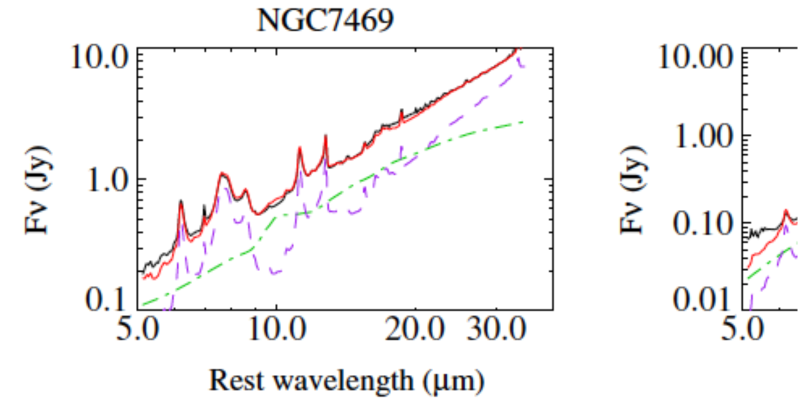


Weedman et al. 2006

The Starburst – AGN connection: spectral decomposition



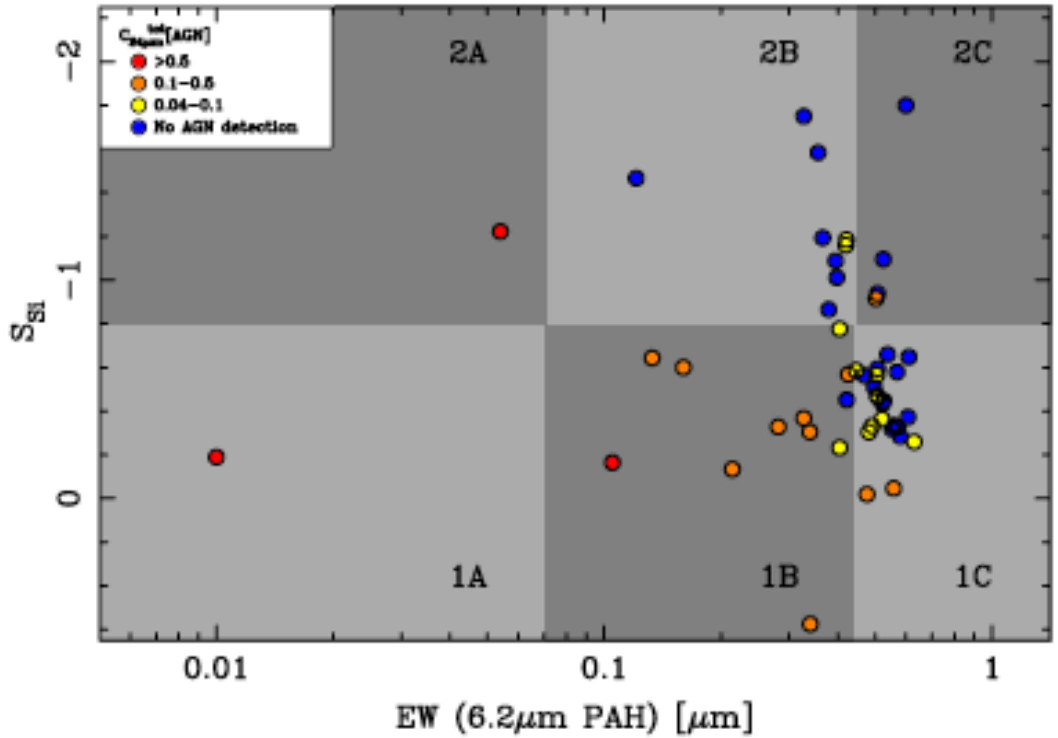
Fit the entire 5–38μm range using Nenkova clumpy dusty torus & empirical SB templates



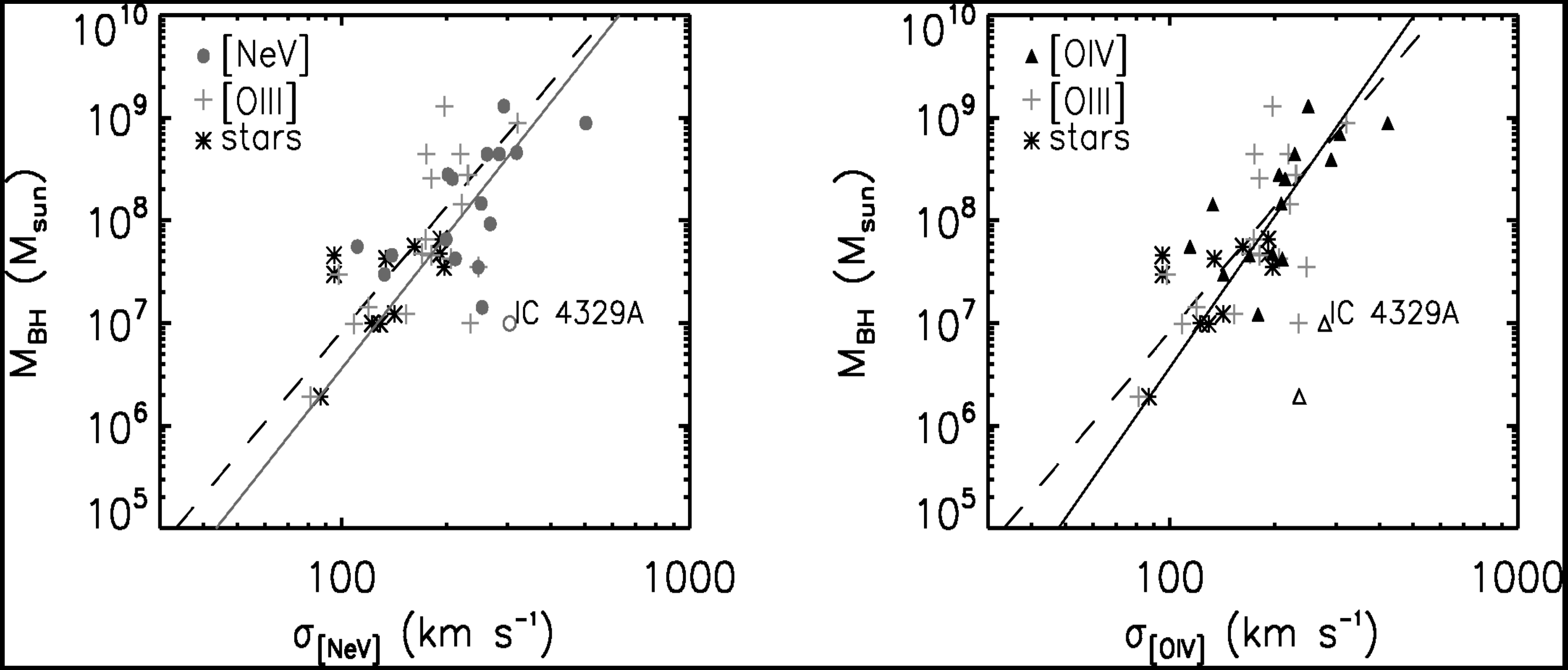
Alonso-Herrero +2012

Most LIRGs are powered by star-formation

The Spoon 3007 diagram



Mid-IR lines as probes of the central AGN



Ho et al. 07, Dasyra et al 08

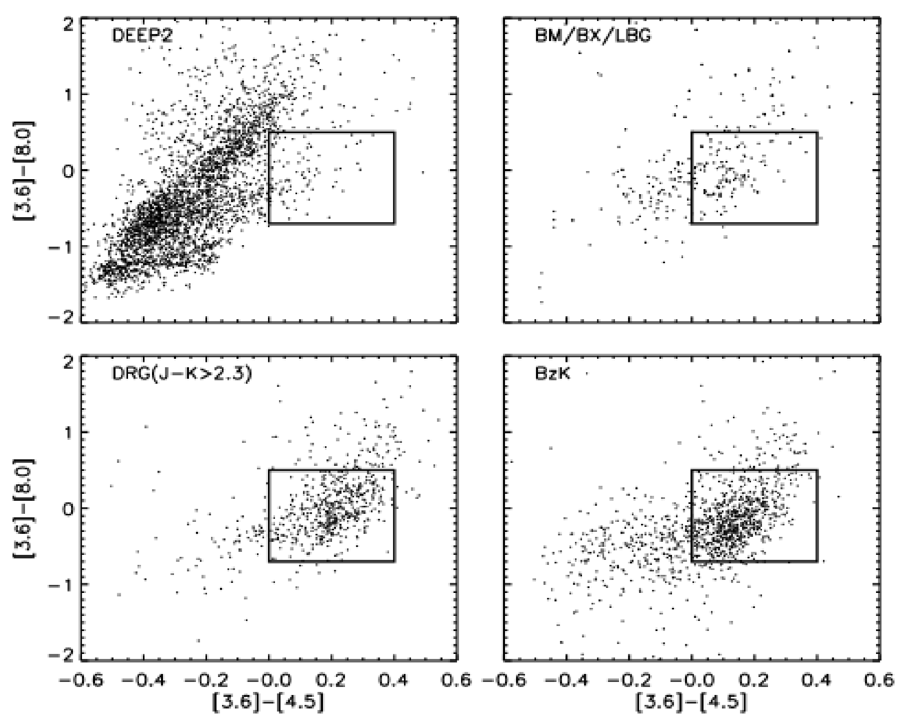
Relation between M(BH) and the velocity dispersion using [NeV] and [OIV] for dusty AGN

MIR spectra of high redshift galaxies

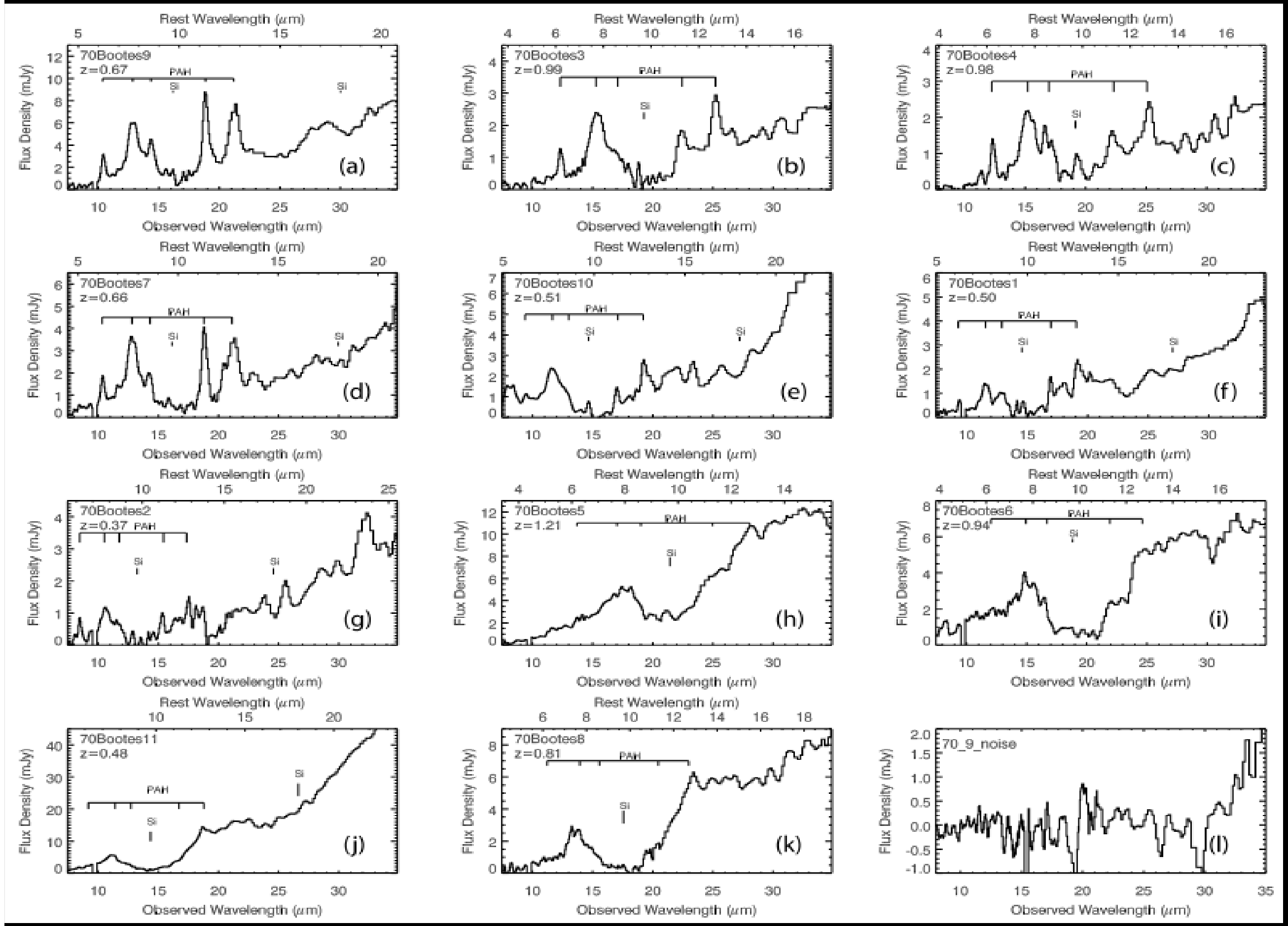
MIR colours effective in selecting z>1 galaxies

At z~2, 24 μm rest-frame 8 μm (PAHs)
Samples selected based on different colour cuts but in most cases including 24 μm and being faint in the optical (Yan +07, Weedman+06, Hernan-Caballero+09)

Alternatively, selection based on the 1.6 μm bump and IRAC colours (e.g Huang et al 09, Lonsdale et al, Farrah et al)



Spectroscopy of z~1 galaxies : PAHs and FS lines

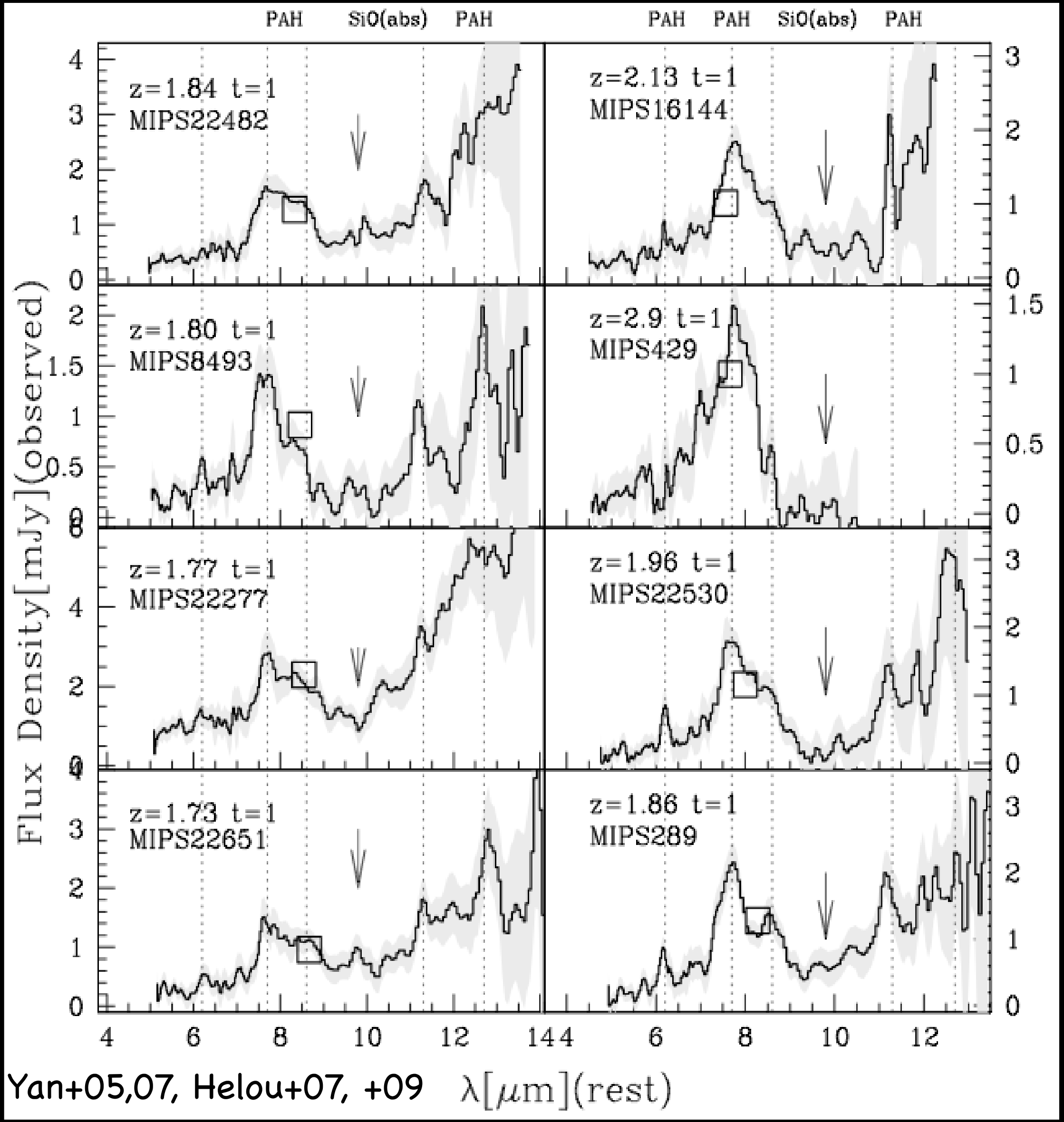


Brand+08, 0.5<z<1, L_{IR} ~ 0.1–2 x 10^{12} $L_{\odot}$,
high L_{PAH},
low $\nu f\nu$ (70)/ $\nu f\nu$(24)
AGN?
Also, Weedman+06
Yan+05,09

24 μm selection criteria seems to pick out z~1 systems with sizeable AGN contribution

z~2 spectra of galaxies selected based on 24/8μm ratio

A large sample of 50+ galaxies based on 24/8 ratio and faint R magnitudes.



Yan+05,07, Helou+07, +09

33% strong PAH
SB dominated

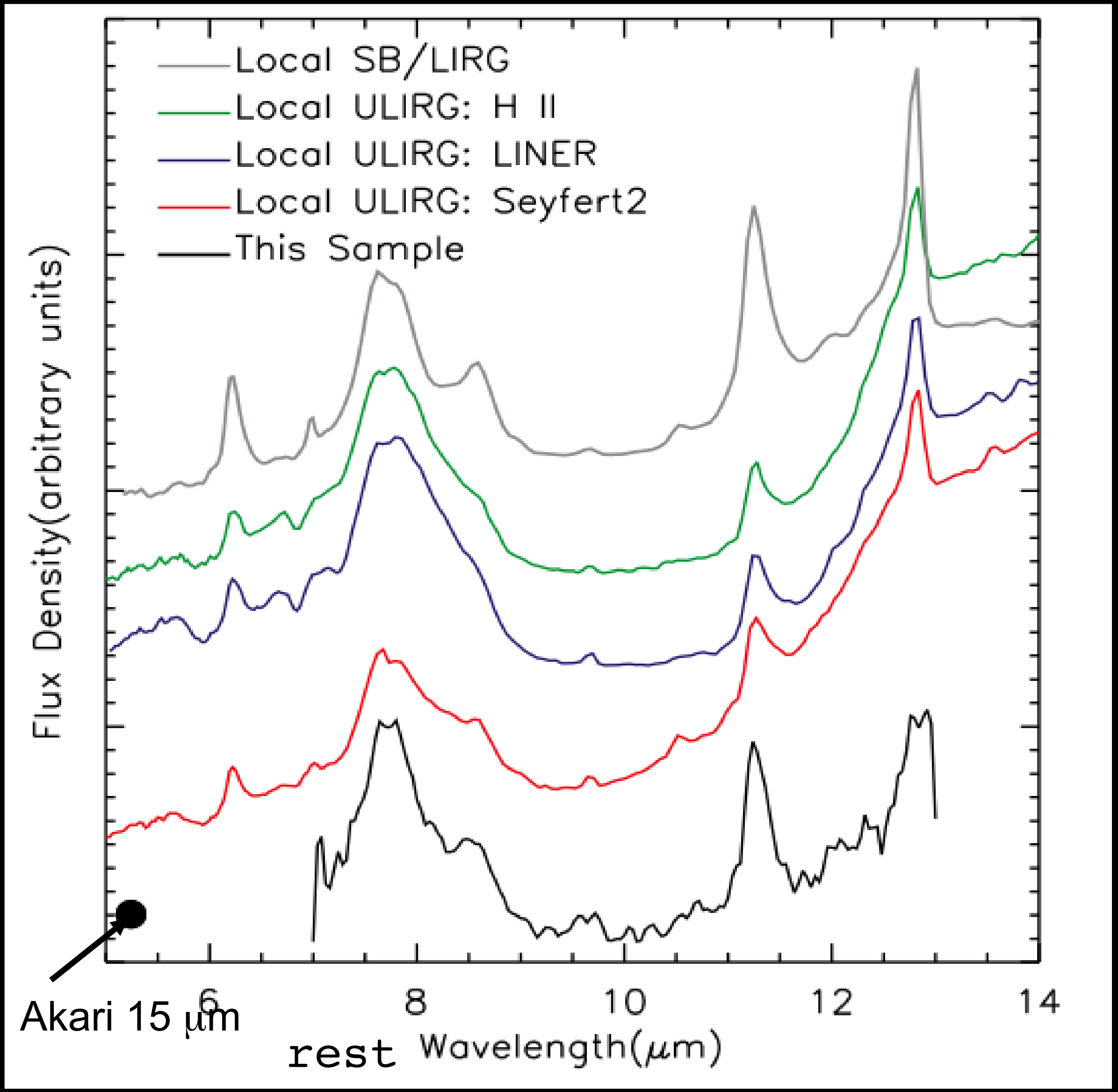
33% deep silicate absorption
deeply embedded sources

34% weak PAH, steep continuum
most likely AGN dominated

Dust enshrouded z~2 galaxies with L_{bol}~ L_{bol} quasar

An alternative way to select z>1.5 galaxies based on IRAC colours

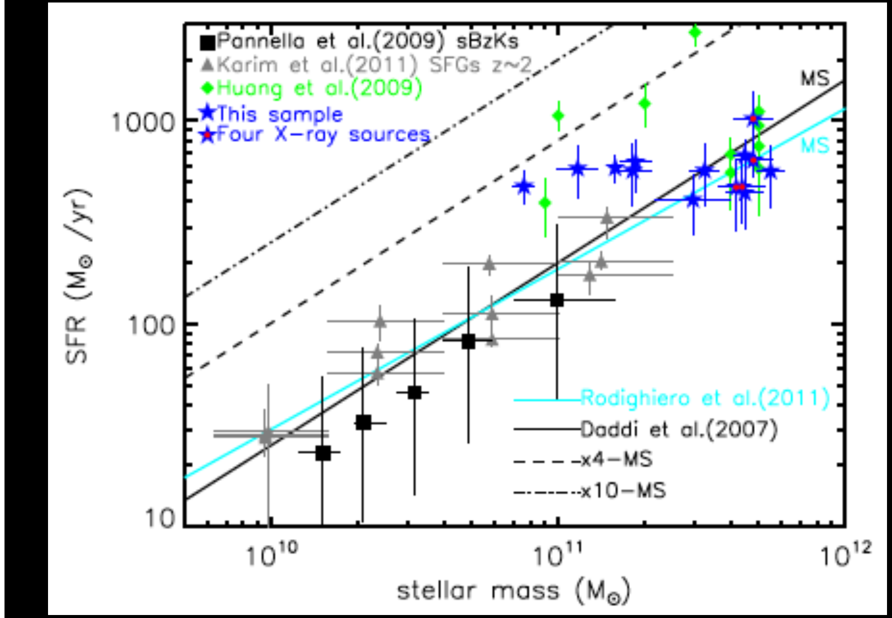
Stacked spectrum of the 19 z~2 SBs is similar to that of local ULIRG HII and local ULIRG LINER.

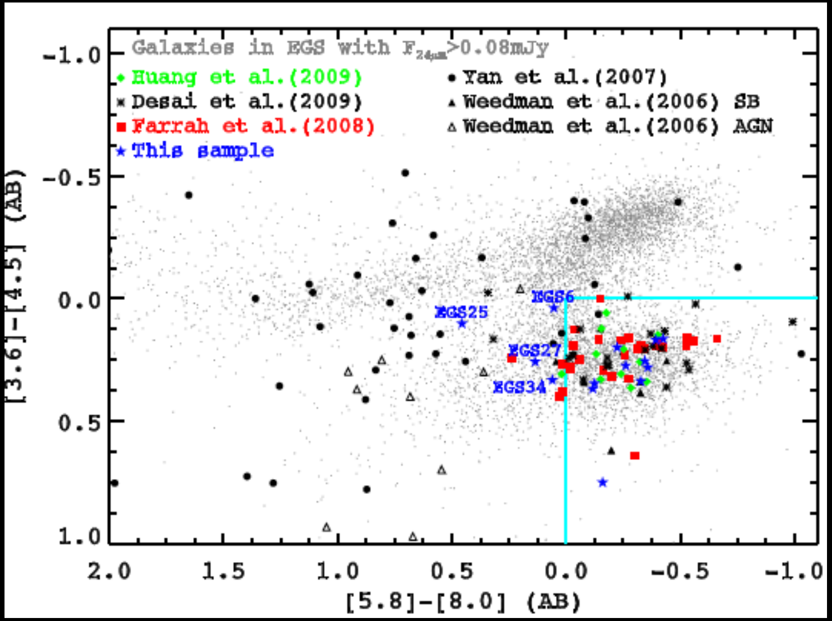


Colour selection based on IRAC colour indices picks Mostly SB-dominated ULIRGs In narrow z-range z~<1.95>

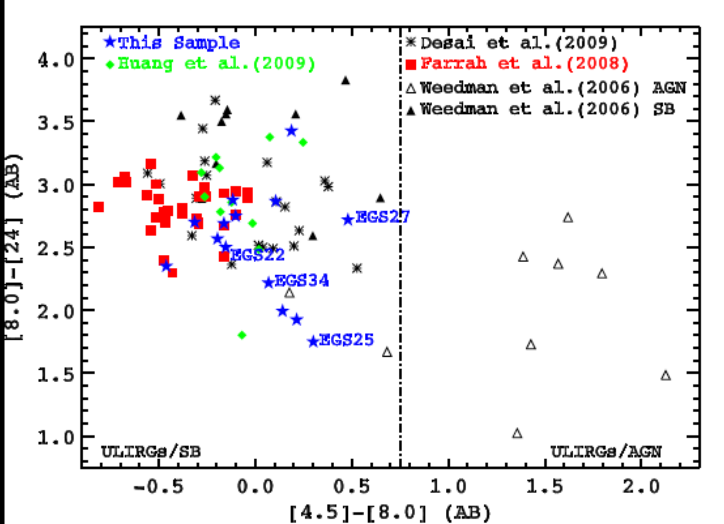
Huang+ 2009, S24>0.6 mJy
Fang +2014, S24>0.11 mJy

IRAC colour selection picks massive ($M>10^{11}\ M_{\odot}$) systems



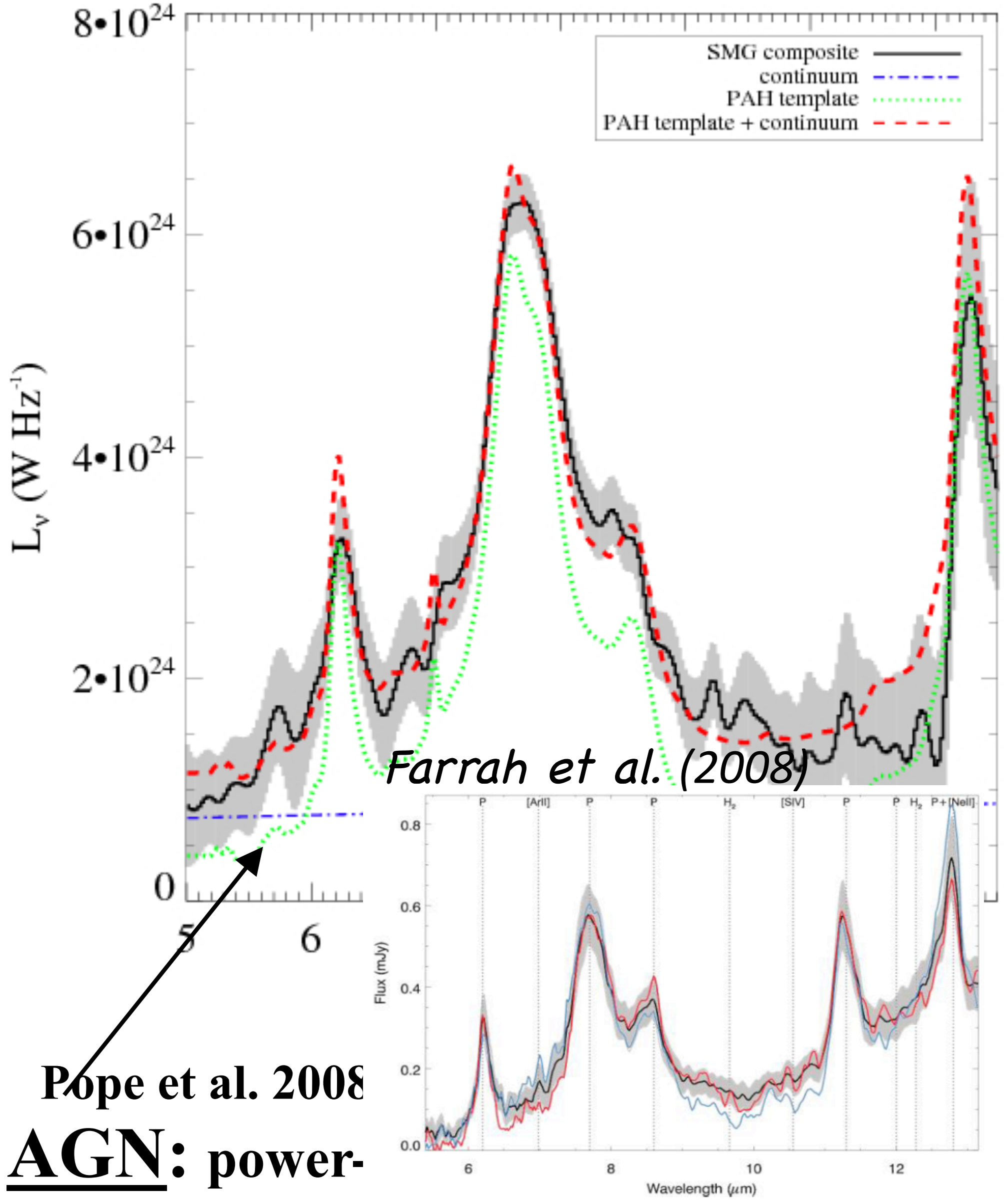


Small fraction of AGN:
Less than 20%
IRAC colour selection effective in picking out massive SBs in narrow z-range



Fang+14
Pope+08

SMG Spectra: Polycyclic aromatic hydrocarbons (PAH) + extinction



Farrah et al. (2008)

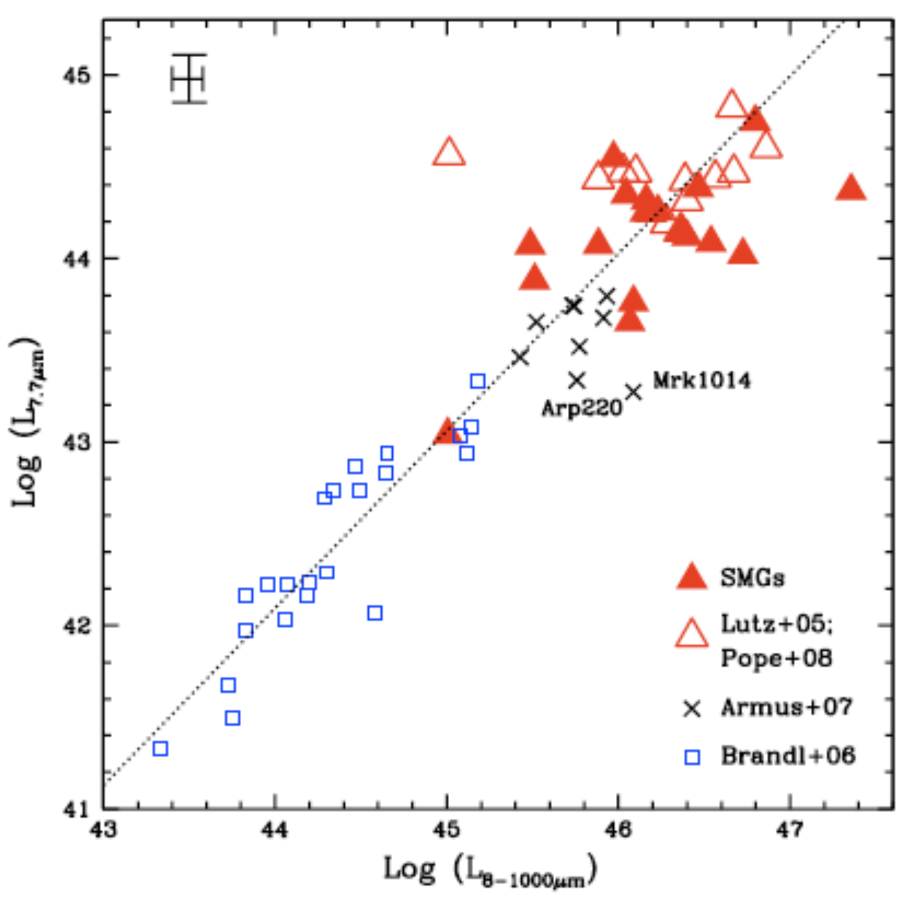
Pope et al. 2008

AGN: power-

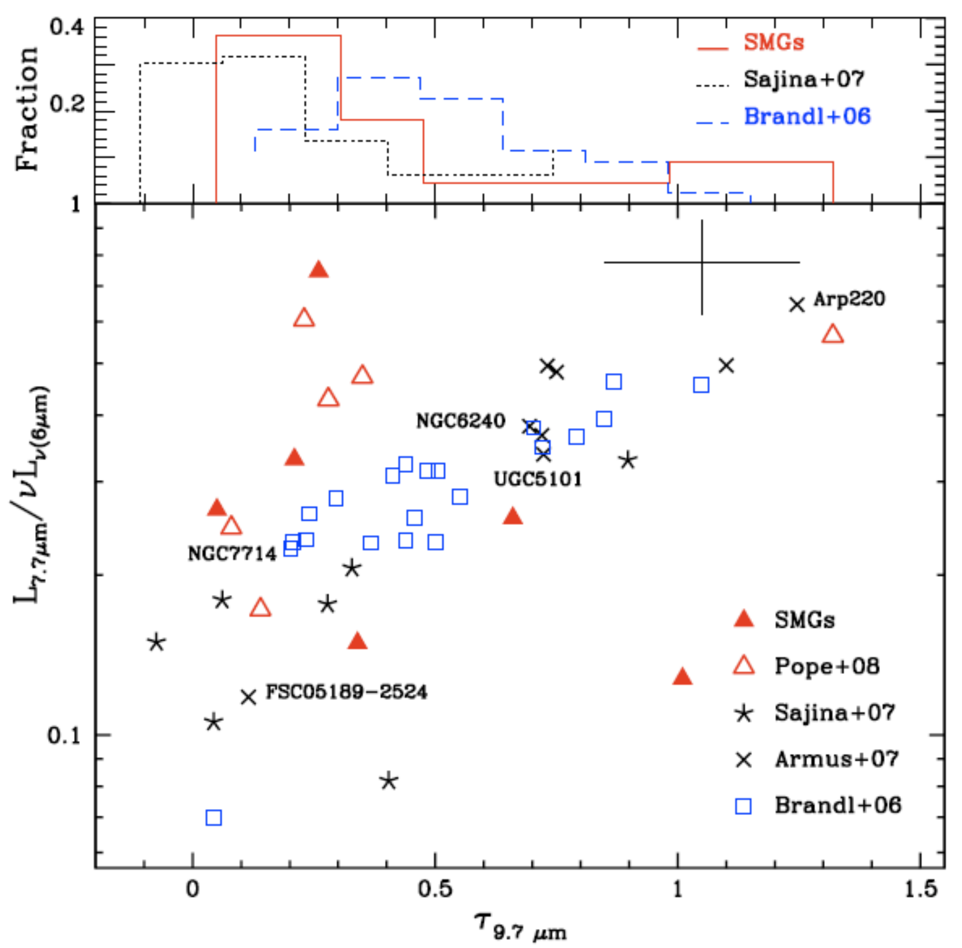
Mid-IR SED of SMGs is starburst dominated : small contribution from AGN (<30% at these wavelengths)

Scaled up M82 – not like local ULIRGs (e.g. Arp220)

See also Valiante et al. 2007, Menendez-Delmestre et al. 2009



Menendez-Delmestre et al. (2009)



- z=2 SMG's have similar PAH/LIR as local starbursts

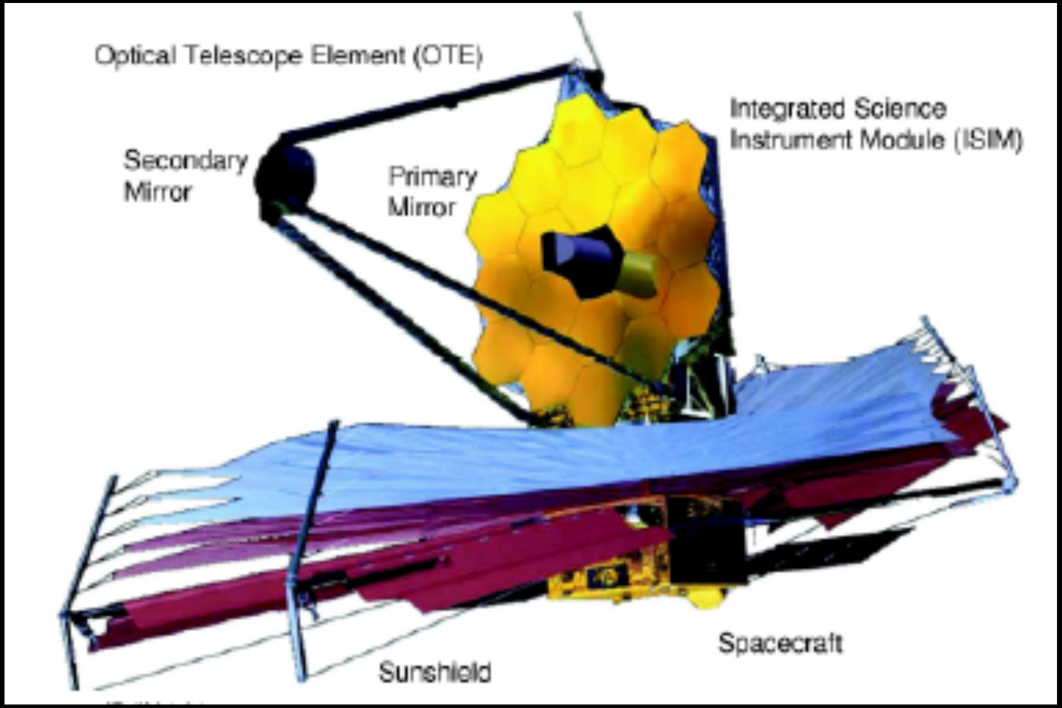
- SMG's have lower silicate optical depths than local ULIRGs.

- Majority of bright 24µm (S>0.5 mJy) $1 < z < 3$ sources are AGN dominated, but by pushing fainter, selecting on IR color, or FIR excess, extremely powerful SB are found.

- SMGs look a lot more like low-luminosity SB galaxies than low-z ULIRGs. Strong PAH, low tau – consistent with large sizes estimated from radio, CO

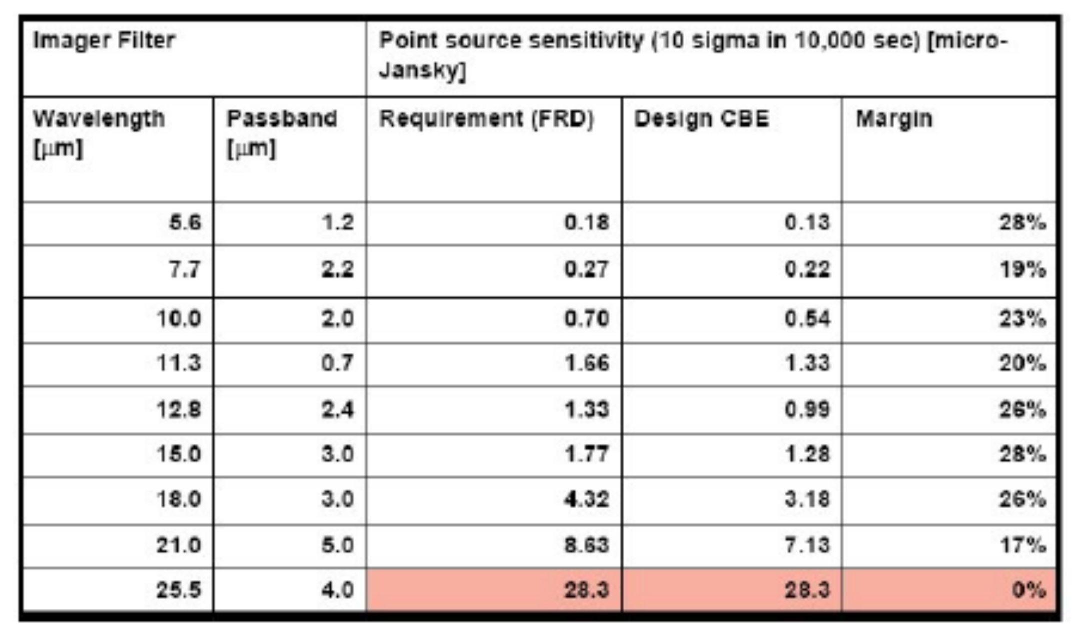
- High-luminosity, high-z SB are not mostly late-stage mergers (like they are at low-z).

JWST MIRI : a new MIR window into the Universe

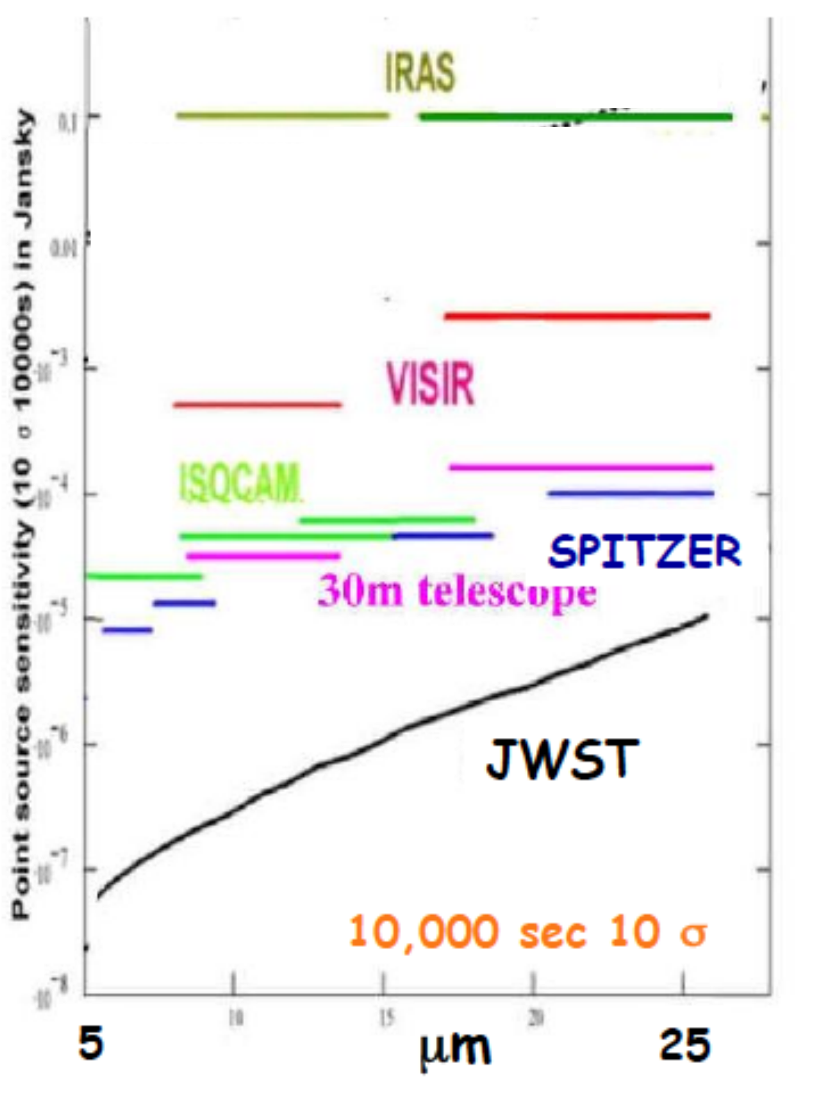


http://www.roe.ac.uk/ukatc/consortium/miri/index.html

MIRI imaging sensitivity

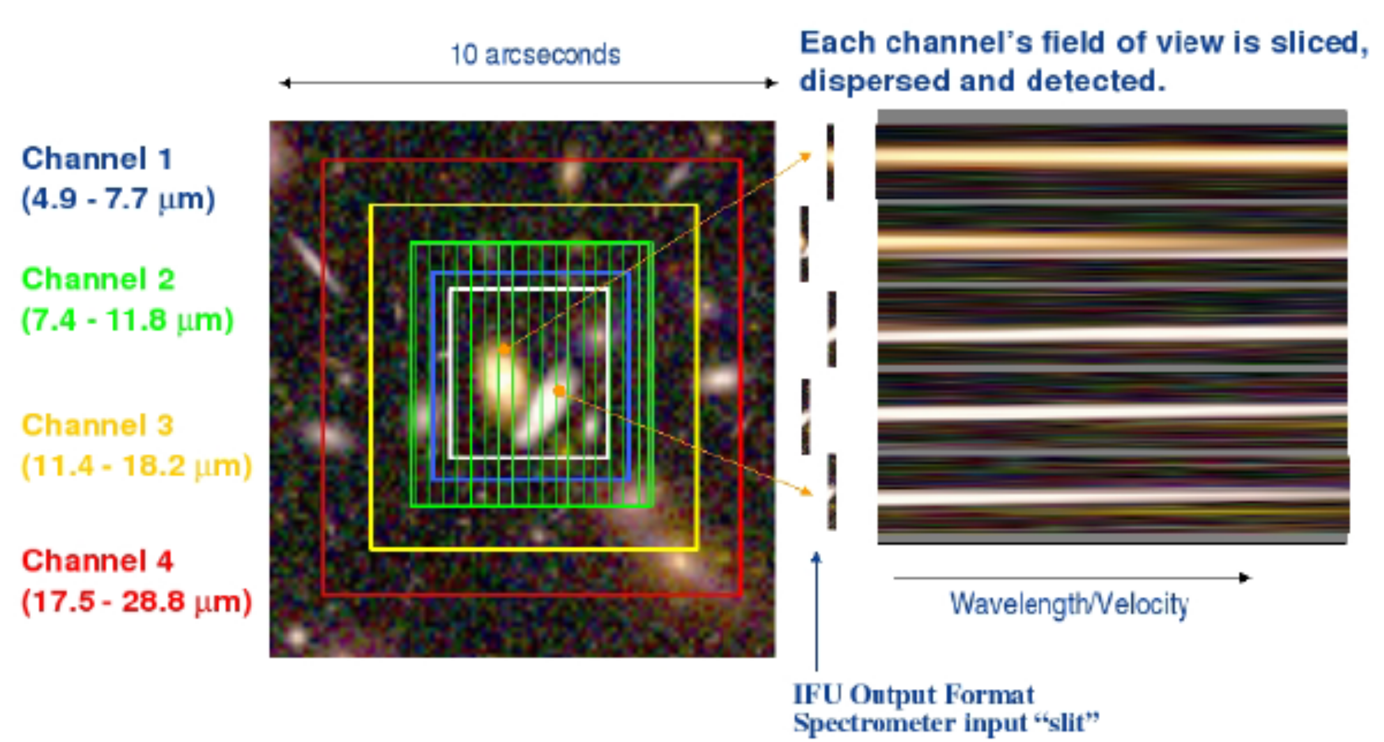


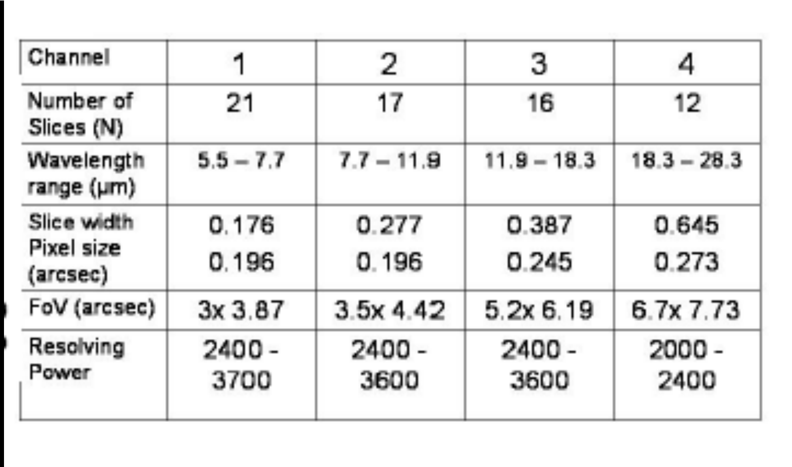
Imager Filter		Point source sensitivity (10 sigma in 10,000 sec) [micro-Jansky]		
Wavelength [µm]	Passband [µm]	Requirement (FRD)	Design CBE	Margin
5.6	1.2	0.18	0.13	28%
7.7	2.2	0.27	0.22	19%
10.0	2.0	0.70	0.54	23%
11.3	0.7	1.66	1.33	20%
12.8	2.4	1.33	0.99	26%
15.0	3.0	1.77	1.28	28%
18.0	3.0	4.32	3.18	26%
21.0	5.0	8.63	7.13	17%
25.5	4.0	28.3	28.3	0%



http://www.roe.ac.uk/ukatc/consortium/miri/index.html

MIRI spectroscopic capabilities

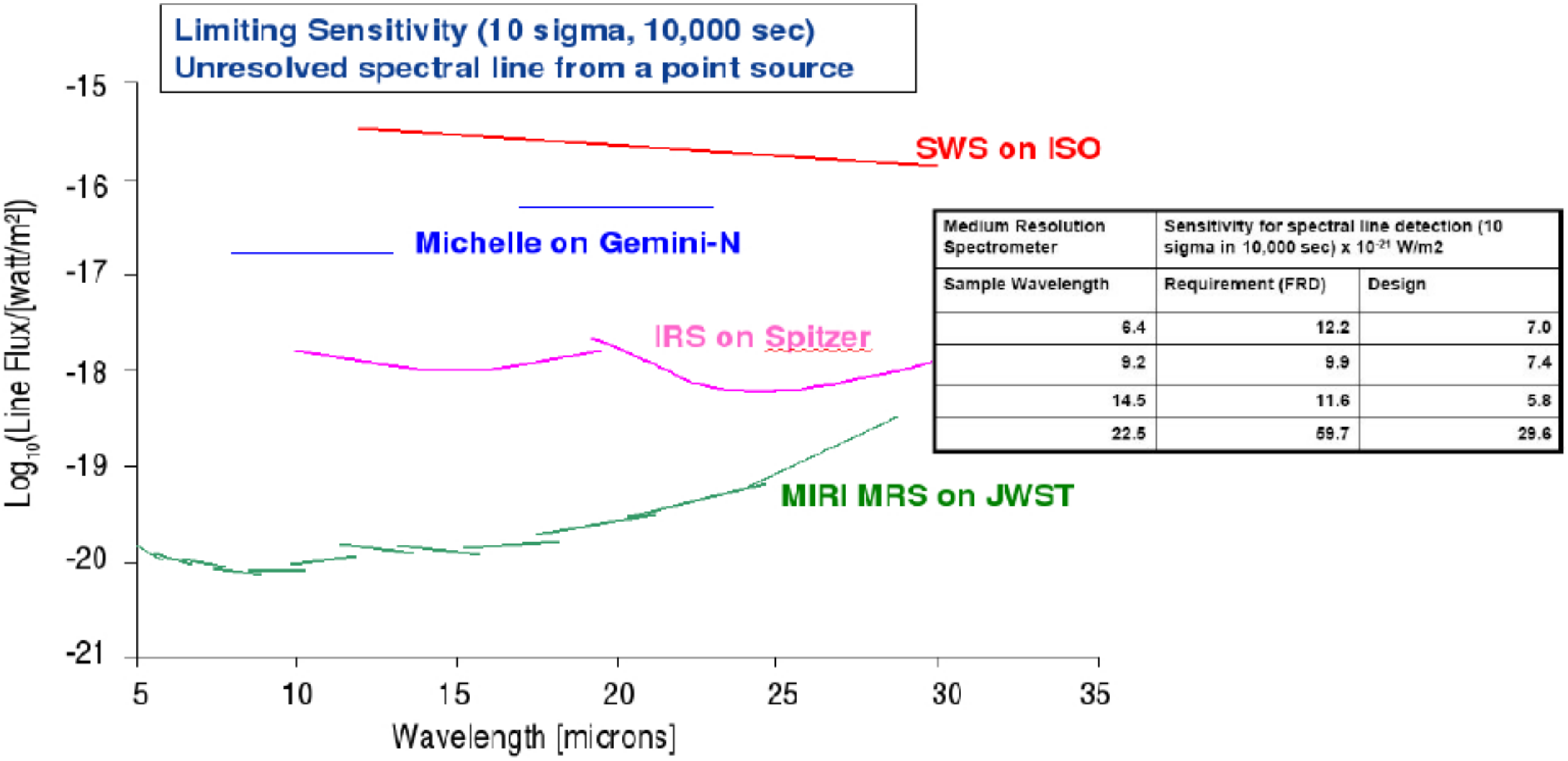




Channel	1	2	3	4
Number of Slices (N)	21	17	16	12
Wavelength range (µm)	5.5 – 7.7	7.7 – 11.9	11.9 – 18.3	18.3 – 28.3
Slice width Pixel size (arcsec)	0.176 0.196	0.277 0.196	0.387 0.245	0.645 0.273
FoV (arcsec)	3x 3.87	3.5x 4.42	5.2x 6.19	6.7x 7.73
Resolving Power	2400 - 3700	2400 - 3600	2400 - 3600	2000 - 2400

http://www.roe.ac.uk/ukatc/consortium/miri/index.html

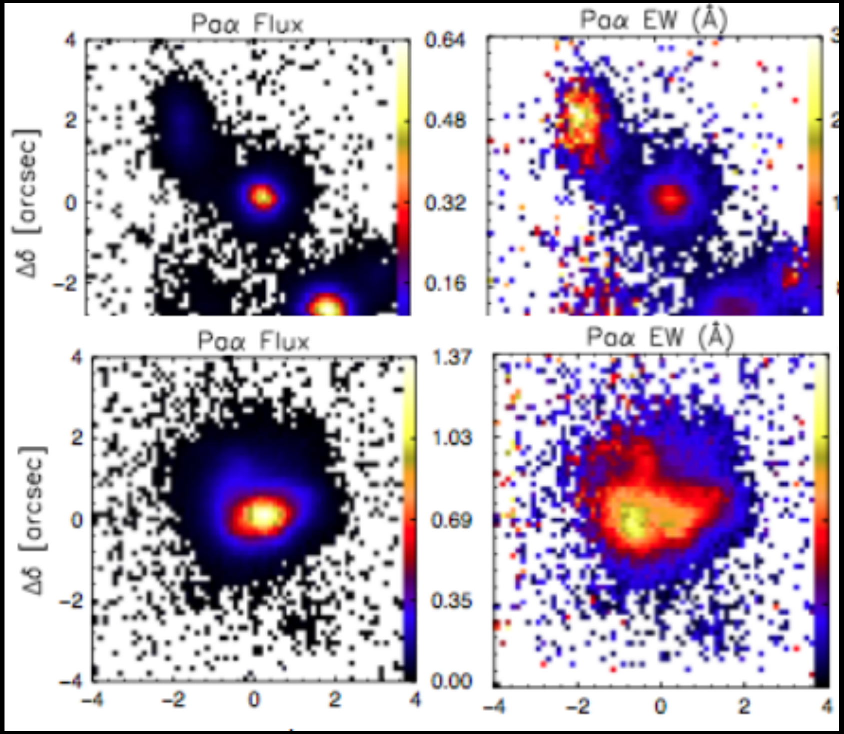
MIRI spectroscopy sensitivity



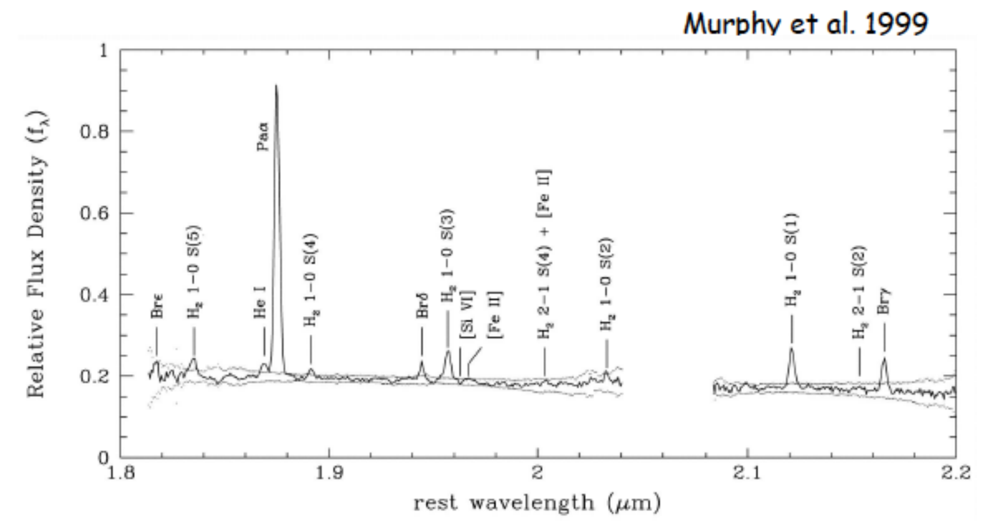
Medium Resolution Spectrometer	Sensitivity for spectral line detection (10 sigma in 10,000 sec) x 10^{-21} W/m2	
Sample Wavelength	Requirement (FRD)	Design
6.4	12.2	7.0
9.2	9.9	7.4
14.5	11.6	5.8
22.5	59.7	29.6

Science highlights with MIRI

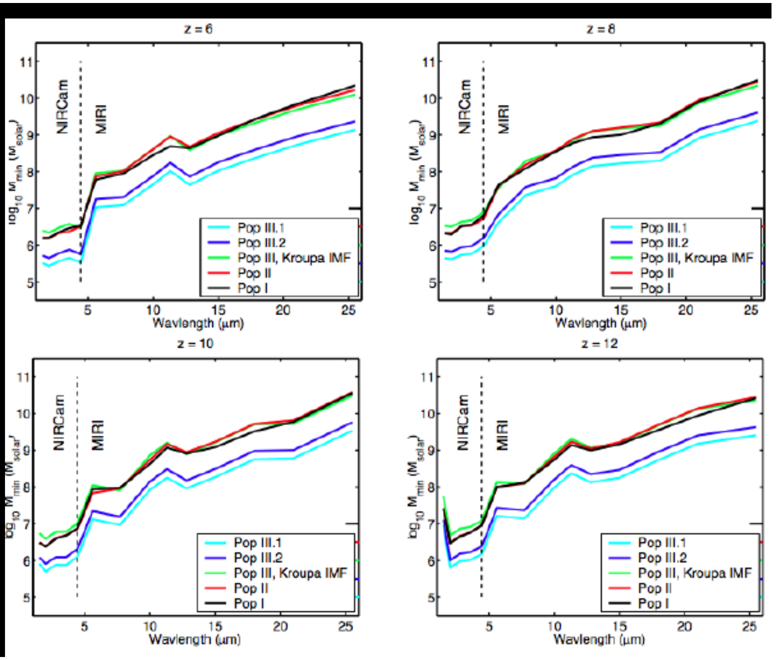
IFS studies of high-z starbursts down to Kpc scales



Probing the ISM: Red-shifted near-IR spectra


Murphy et al. 1999

JWST- MIRI UDFs



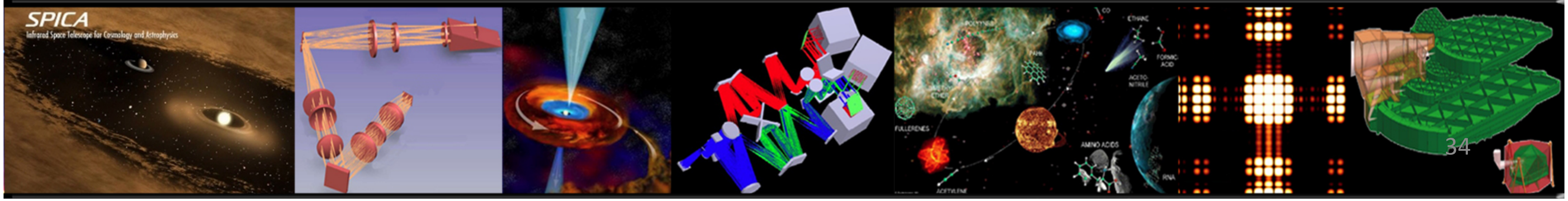
Taken from a presentation by L. Colina (2011)

What is next: SPICA JAXA + ESA Cosmic Vision

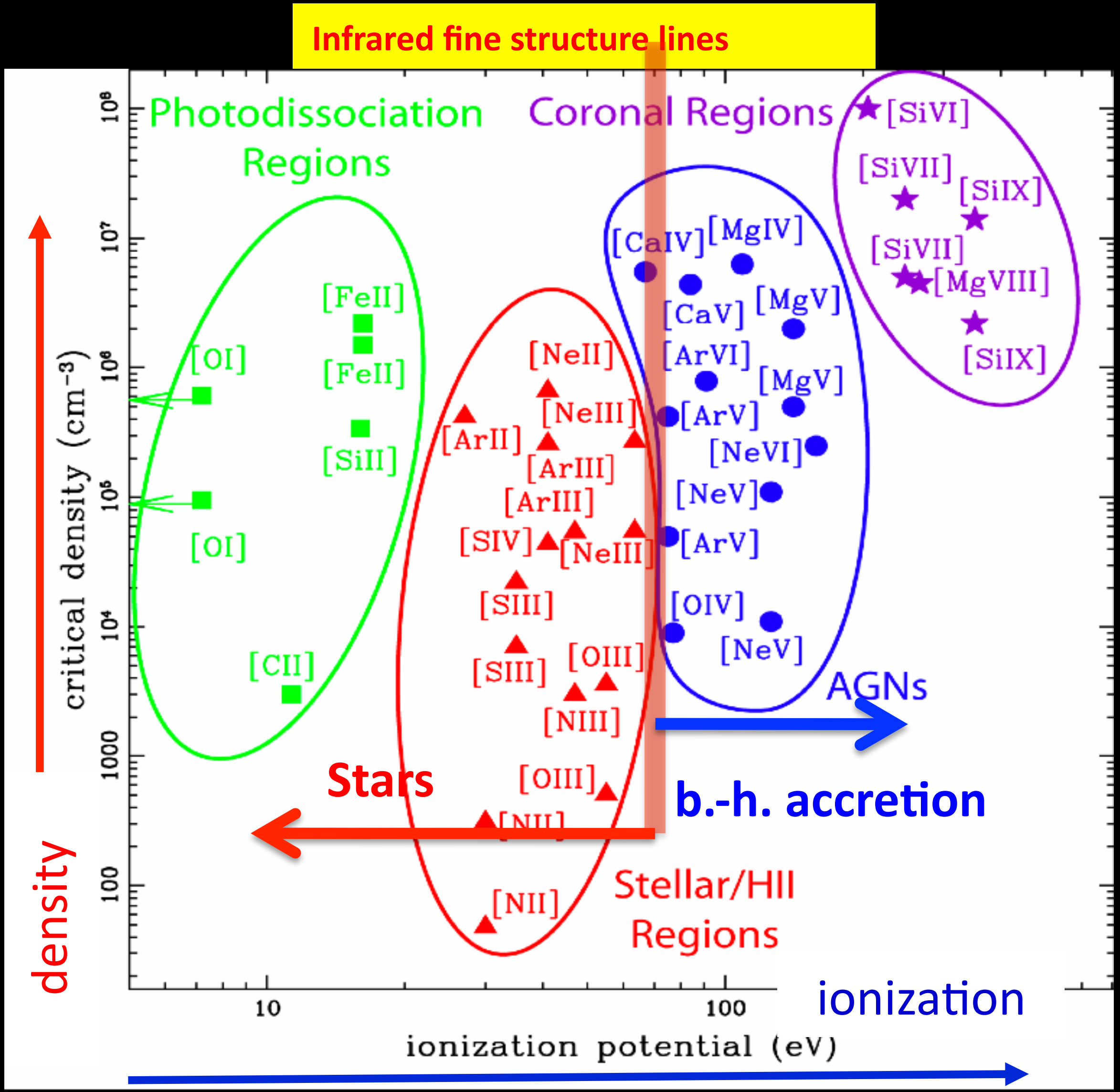
2.5m class telescope

Cooled to < 8K

Core SPICA Instruments (λλ:12 - 210 µm)
Europe:
- FIR grating spectrometer R~300 (+ FP R~3000)
➔ galaxy evolution, star formation
Japan:
- MIR 5’ x 5’ imaging (R~50) spectro-photometer
- MIR Medium Resolution long slit Spectrometer (R~1000) 20<λ<37µm
- MIR High Resolution Spectrometer (R>25000) 12<λ<18µm



The power of IR spectroscopy to disentagle star formation and accretion



IR fine structure lines:

- separate different physical mechanisms,
- cover the ionization-density parameter space
- do not suffer heavily from extinction
- (Spinoglio & Malkan 1992)

Current baseline

- Orbit: S-E L2 Halo orbit
- Launcher: H-X Vehicle of JAXA

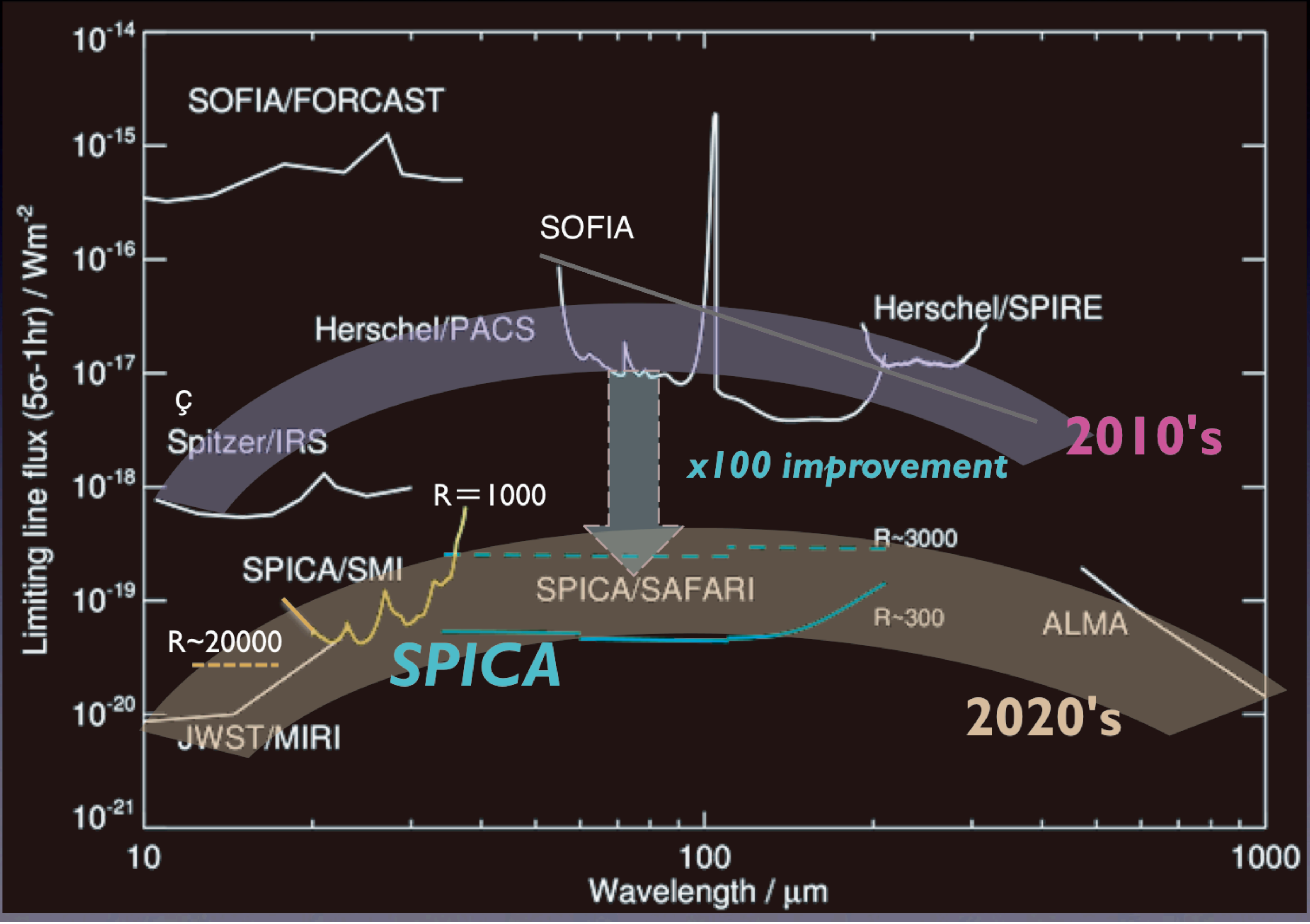
- Focal plane instruments
  - SAFARI (34 - 230μm)
  - SMI (17 - 37μm) + HRS (12 - 18μm)
  - SPEChO (5 -20μm) (under consideration)

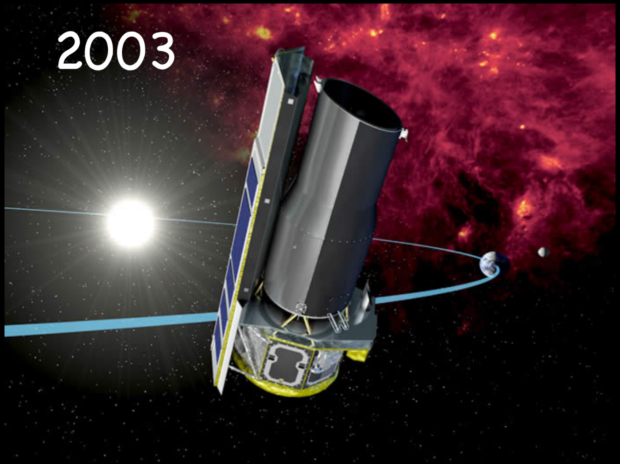
- Schedule

  In JAXA SPICA is now in the redefinition phase and will go to the M-class competition in ESA

2015 June	International preview by JAXA
2015 Sept	Mission Definition Review by JAXA
2016	ESA M5 proposal submission
2027-2028	Launch (>3 year operation: goal >5 years)

SPICA sensitivity and other facilities





Thank you!