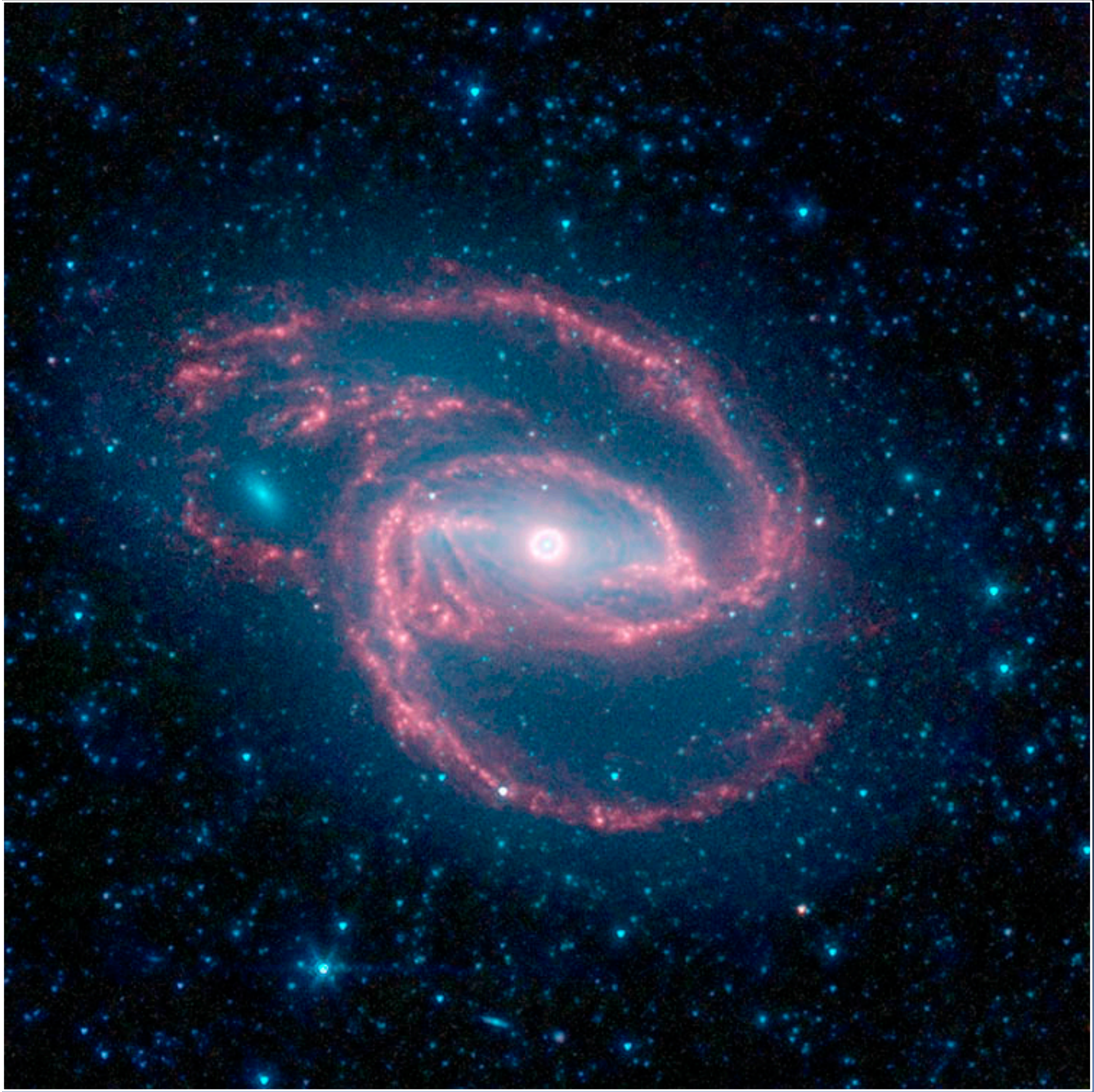
A. Alonso-Herrero

The Spitzer view of starburst galaxies

In this talk I will review some of the new findings for nearby starburst galaxies obtained with the imaging (IRAC and MIPS) and spectroscopy (IRS) instruments on board of the Spitzer SpaceTelescope. In particular I will summarize new results about the most prominent features in the mid-infrared spectra detected in nearby starbursts, such as PAH features, fine structure lines, the 9.7micron silicate feature, and molecular hydrogen lines. Finally I will discuss our progress on using mid-infrared features (e.g., monochromatic luminosities, PAH features, neon lines) as tracers of the star formation rate of galaxies in the local Universe and at high redshift.

NGC1097, credit Spitzer



The Spitzer view of nearby starburst galaxies

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Outline of the talk

- The Spitzer Space Telescope
- IR properties of starburst galaxies
  - MIR spectra and features
  - Metallicity and Ionization Effects
  - Morphologies and emission mechanisms
- MIR AGN Indicators
- IR Star Formation Rate (SFR) Tracers
- Luminous and Ultraluminous Infrared Galaxies
- Conclusions

The Spitzer Space Telescope

- Background Limited Performance 3-180μm
- 85 cm f/12 Beryllium Telescope, T < 5.5K
- 6.5μm Diffraction Limit
- Spectrophotometry, 50-100μm
- >75% of observing time for the
- General Scientific Community
- Launched in August 2003 (Delta 7920H)
- Solar Orbit
- Cornerstone of NASA's Origins Program

- Cryogen mission finished in May 2009
- Warm Mission already started!

- Only IRAC 3.6 and 4.5μm observations allowed

- See Spitzer webpage for more details: http://www.spitzer.caltech.edu

Spitzer Instrumentation Overview

Infrared Array Camera (IRAC), G.G.Fazio, SAO

- Wide-field (5'x5') imaging. Simultaneous viewing at 3.6, 4.5, 5.8, 8 μm
- *InSb and Si:As IBC arrays, 256x256 pixel format*

Infrared Spectrograph (IRS), J.R.Houck, Cornell

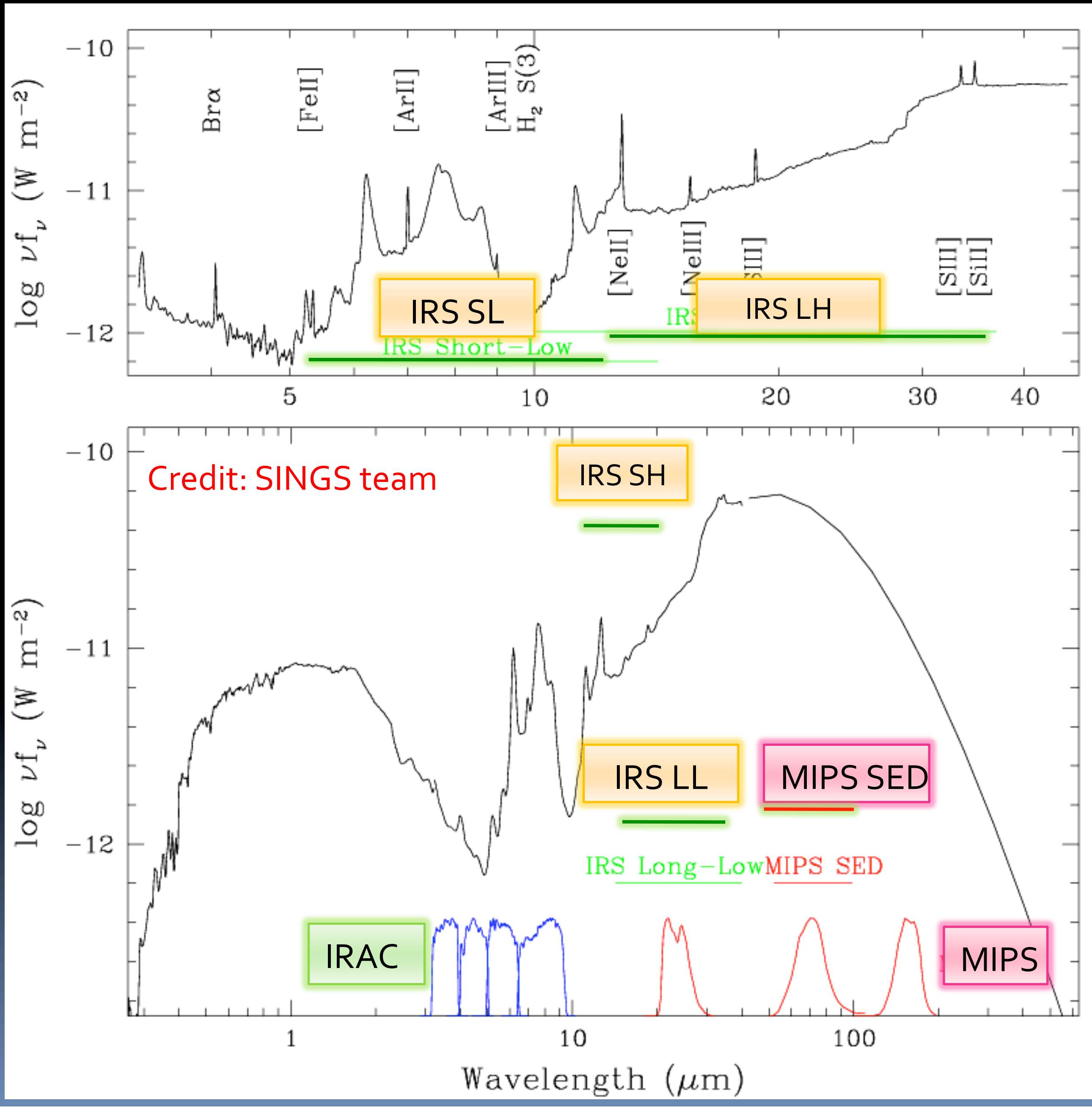
- R=600 echelle spectrographs, 10-20 and 20-40 μm
- R=50 long-slit spectrographs, 5-15 μm and 15-40 μm
- Imaging/Photometry, 15 μm
- *Si:As and Si:Sb IBC arrays, 128x128 pixel format*

Multi-band Imaging Photometer for Spitzer (MIPS), G.Rieke, AZ

- *Imaging and photometry: 24, 70, 160* μm; optimized for efficient large area surveys and superresolution; R~15 spectrophotometry, 50-100 μm
- *Si*:As IBC and Ge:Ga arrays, 128x128 (24μm) and 32x32 (70μm) format
- *Stressed Ge:Ga array, 2x20 format (160*μm)

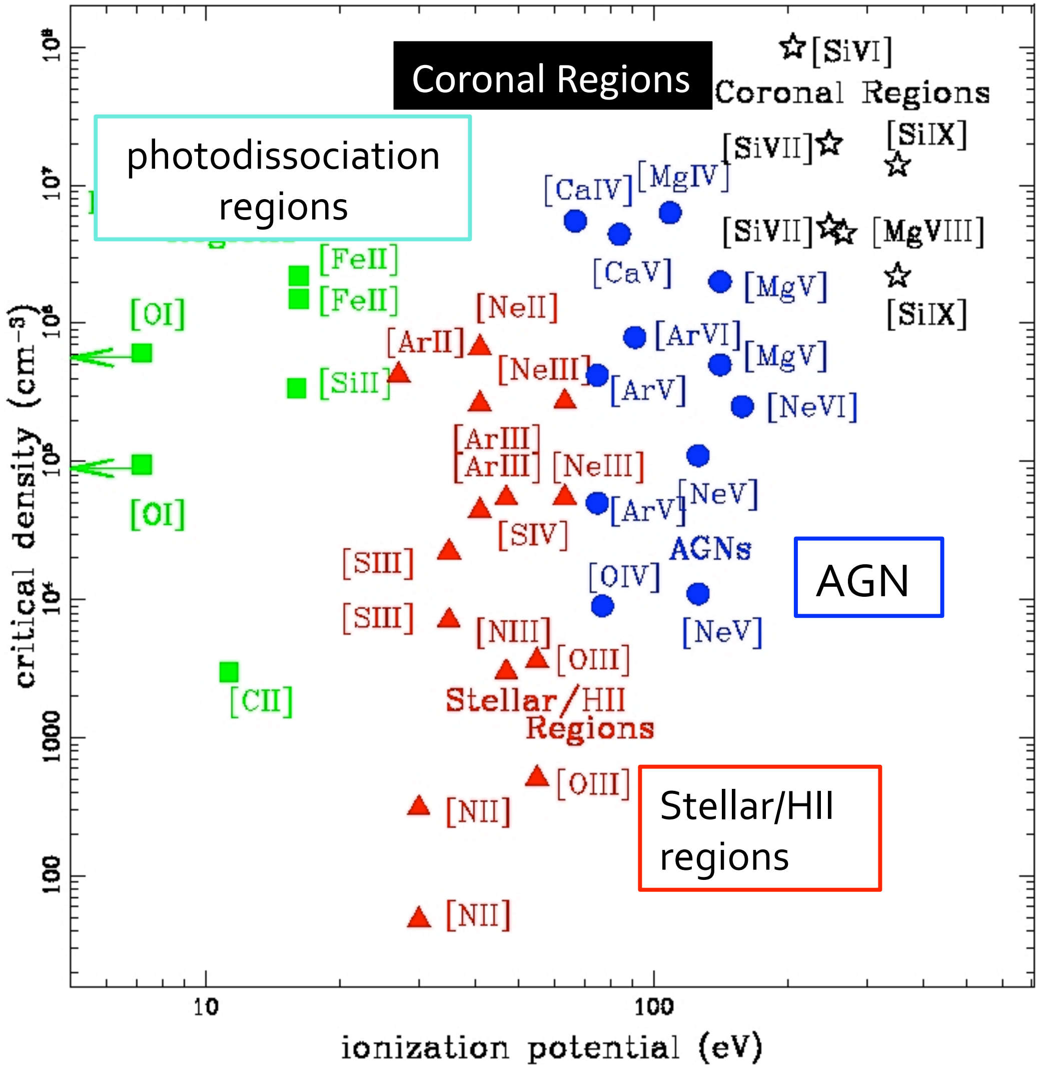
http://www.spitzer.caltech.edu

Wavelength coverage of Spitzer Instruments



Brightest mid-IR fine structure lines in galaxies

Spinoglio et al. 2007



[NeII]12.8µm+[NeIII]15.6µm tracers of star formation rate

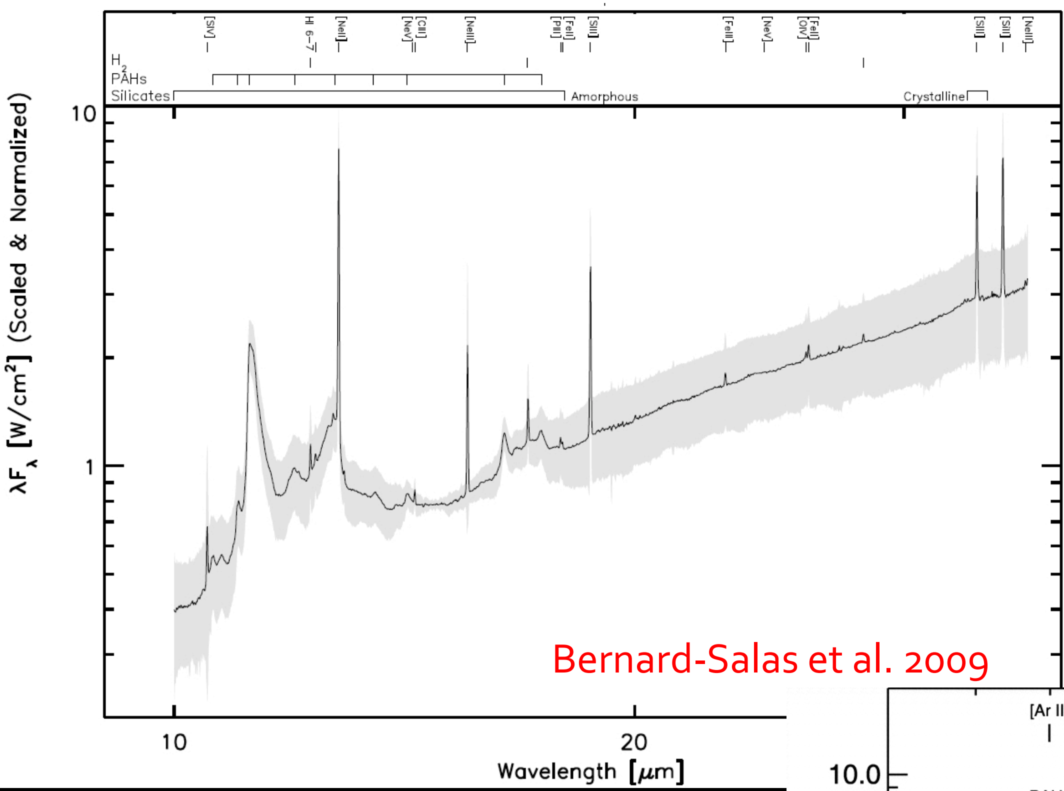
[SIII]18.7µm/[SIII]33.5µm: tracers of density

[NeV]14.3µm or [NeV]24.3µm: presence of an AGN

[NeIII]15.6µm/[NeII]12.8µm and [SIV]10.5µm/[SIII]18.7µm: tracers of the hardness of the radiation field

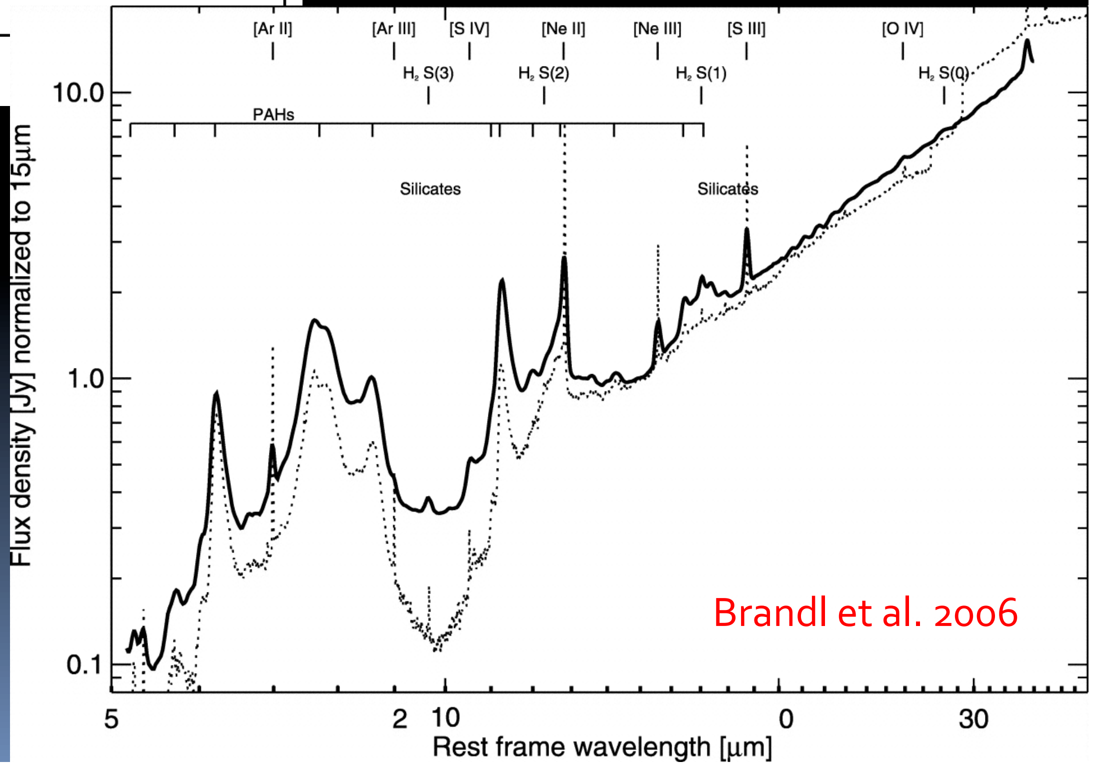
[OIV]25.89µm: mostly AGN but also Star Formation

List of IR lines and features: Http://www.mpe-garching.mpg.de/iso/linelists/

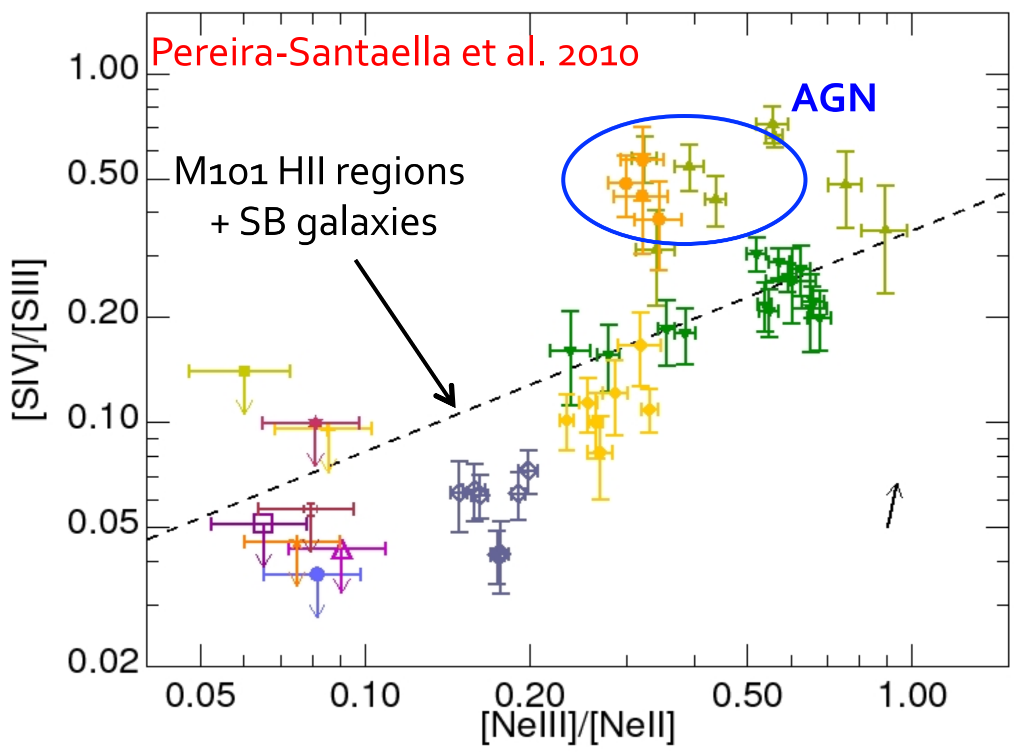


Average high-res IRS spectrum of local starbursts

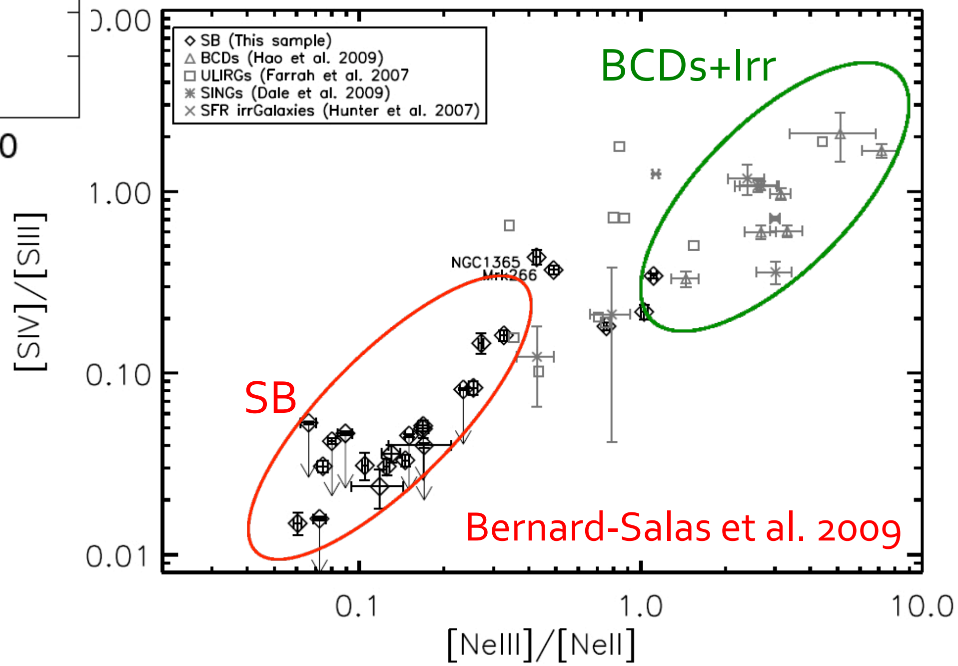
Average low-res IRS spectrum of local starbursts



Hardness of the radiation field



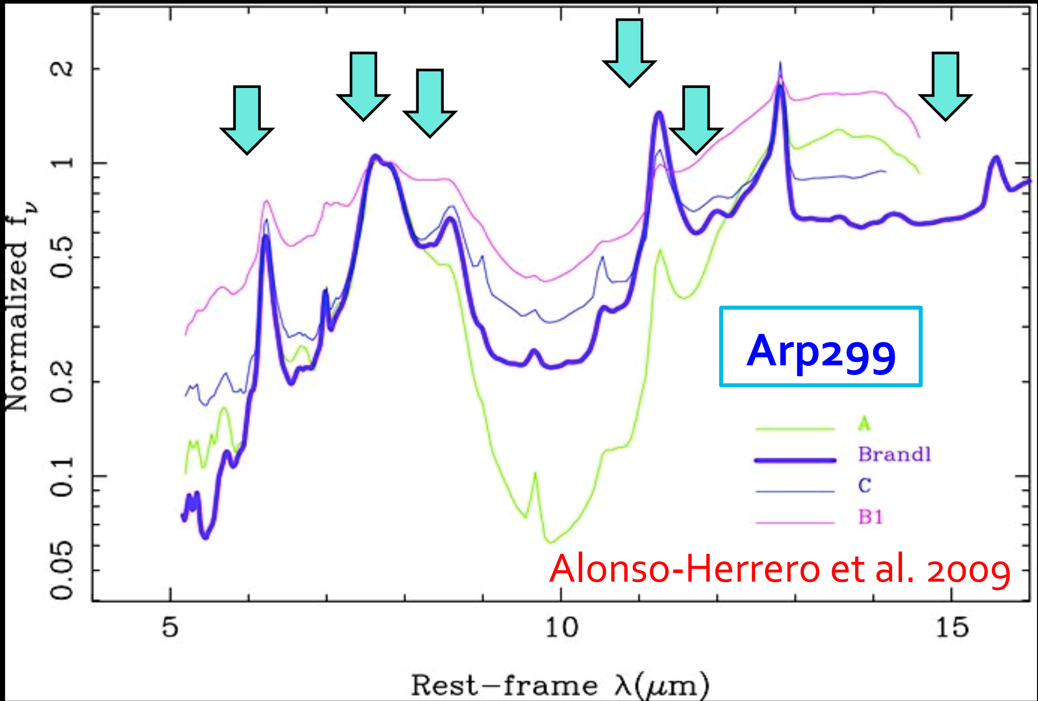
Starburst galaxies have lower ionization than BCDs and star forming irregulars indicating that starbursts have fewer massive stars and/or older stars



The hardness of radiation field of spatially resolved regions in LIRGs is similar to that of starbursts

Gives an indication for age of the ionizing stellar population

Mid-IR Polycyclic Aromatic Hydrocarbon (PAH) Features



PAHs appear to be excited by B stars, and thus they probe the ¨recent¨ SF of galaxies

Different PAH feature ratios probe the ionization conditions of ISM (Galliano 2006)

They are also the best redshift indicators for distant, obscured galaxies.

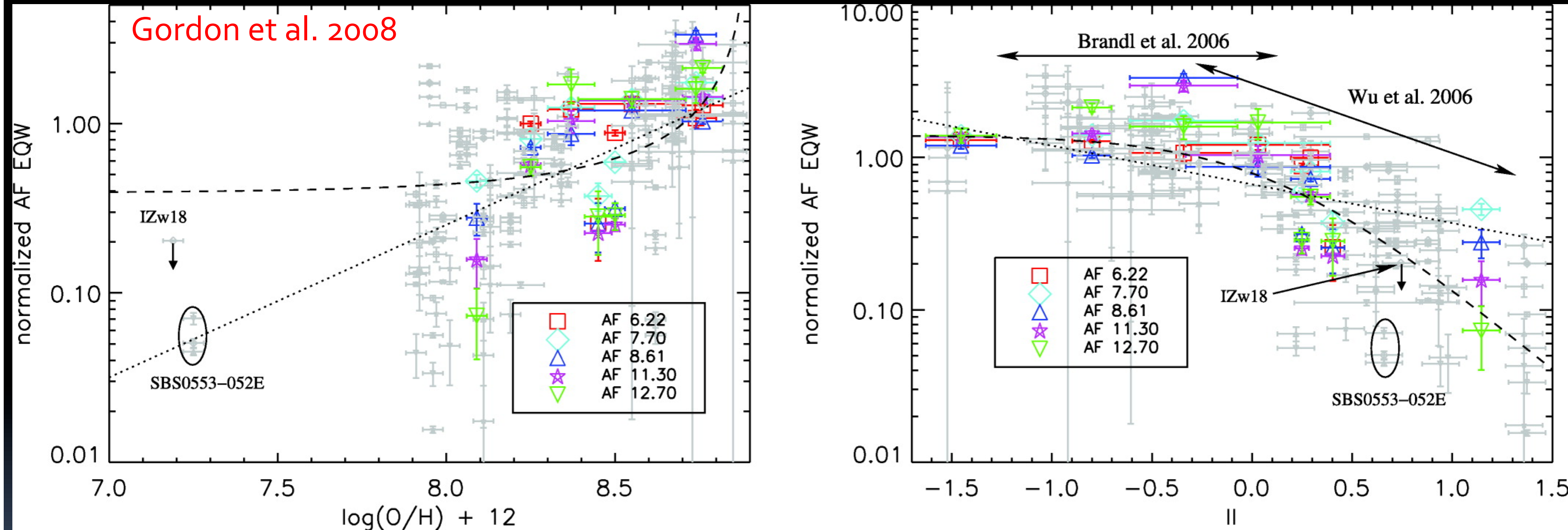
Smith et al. (2007)

λ_r (μm) (1)	γ_r (2)	FWHM (μm) (3)
5.27	0.034	0.179
5.70	0.035	0.200
6.22	0.030	0.187
6.69	0.070	0.468
7.42[a]	0.126	0.935
7.60[a]	0.044	0.334
7.85[a]	0.053	0.416
8.33	0.050	0.417
8.61	0.039	0.336
10.68	0.020	0.214
11.23[b]	0.012	0.135
11.33[b]	0.032	0.363
11.99	0.045	0.540
12.62[c]	0.042	0.530
12.69[c]	0.013	0.165
13.48	0.040	0.539
14.04	0.016	0.225
14.19	0.025	0.355
15.90	0.020	0.318
16.45[d]	0.014	0.230
17.04[d]	0.065	1.108
17.375[d]	0.012	0.209
17.87[d]	0.016	0.286
18.92	0.019	0.359
33.10	0.050	1.655

PAHs in Starbursts, low metallicity galaxies and HII regions

PAHs features weaken with decreasing Z and increasing ionization level

EW of PAH features is better correlated with the ionization index than with metallicity
Gordon et al. 2008 interpreted this result as due to processing (destruction) rather than formation processes



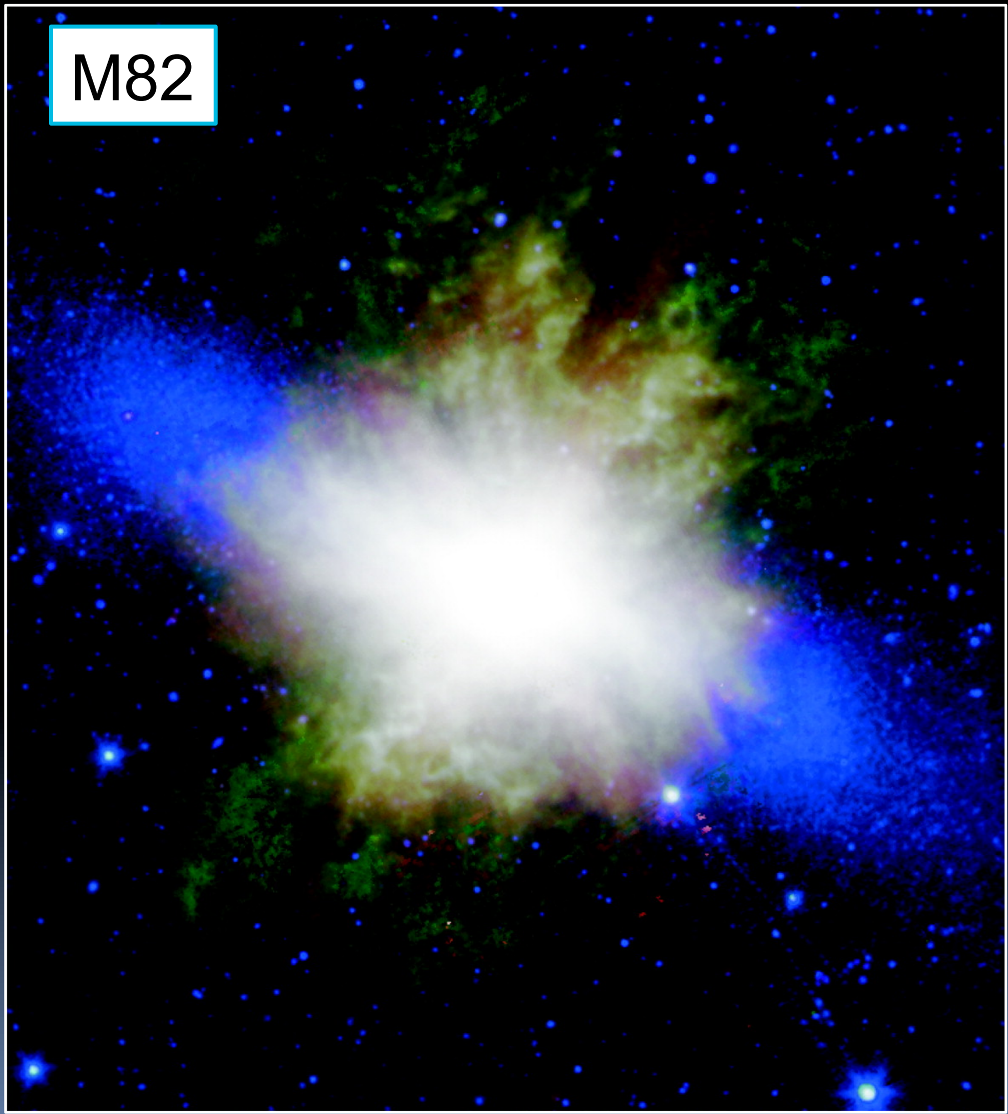
Metallicity

Ionization index

See also Madden et al. 2006; Wu et al. 2006; Engelbracht et al. 2005, 2008

The Spitzer view of the prototypical starburst galaxy M82

Engelbracht et al. 2006



Composite image
Blue: IRAC 3.6μm (stars in disk and possibly 3.3μm PAH in extraplanar region)
Green: IRAC 8μm (PAHs)
Red: MIPS 24μm (hot dust)

MIR emission extends at least 6kpc outside the plane of the galaxy

Strong component of PAH emission and hot dust in superwind area but also outside in the disk of the galaxy

IRS Spatially Resolved Observations of Starbursts: The Antennae

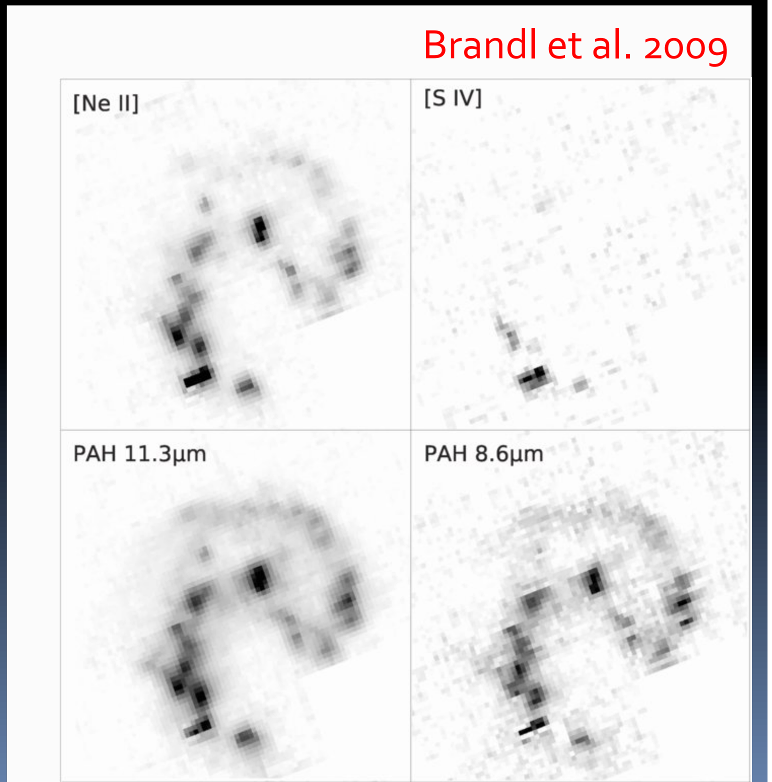
Regions with **SFR~0.2 and 2 $M_{\odot}$ yr^{-1}**, with a total of 6.6 $M_{\odot}$ yr^{-1}

No evidence for an AGN with mid-IR tracers

The hardest and most luminous radiation originates from two compact clusters in the southern part of the overlap region, which also have the highest dust temperatures

PAH emission is spatially extended throughout and beyond the overlap region, but regions with a harder and more intense radiation field show a reduced PAH strength

Other studies: Beirao et al. 2006, 2008; Alonso-Herrero et al. 2009; Pereira-Santaella et al. 2010



MIR AGN Indicators: high excitation lines

MIR high excitation emission lines:

[NeV] at 14.3μm and 24μm (91.7eV)
[OIV] at 25.9μm (54.9eV)

Good correlation with other AGN indicators (Melendez et al. 2008, Diamond-Stanic et al. 2009, Rigby et al. 2009)

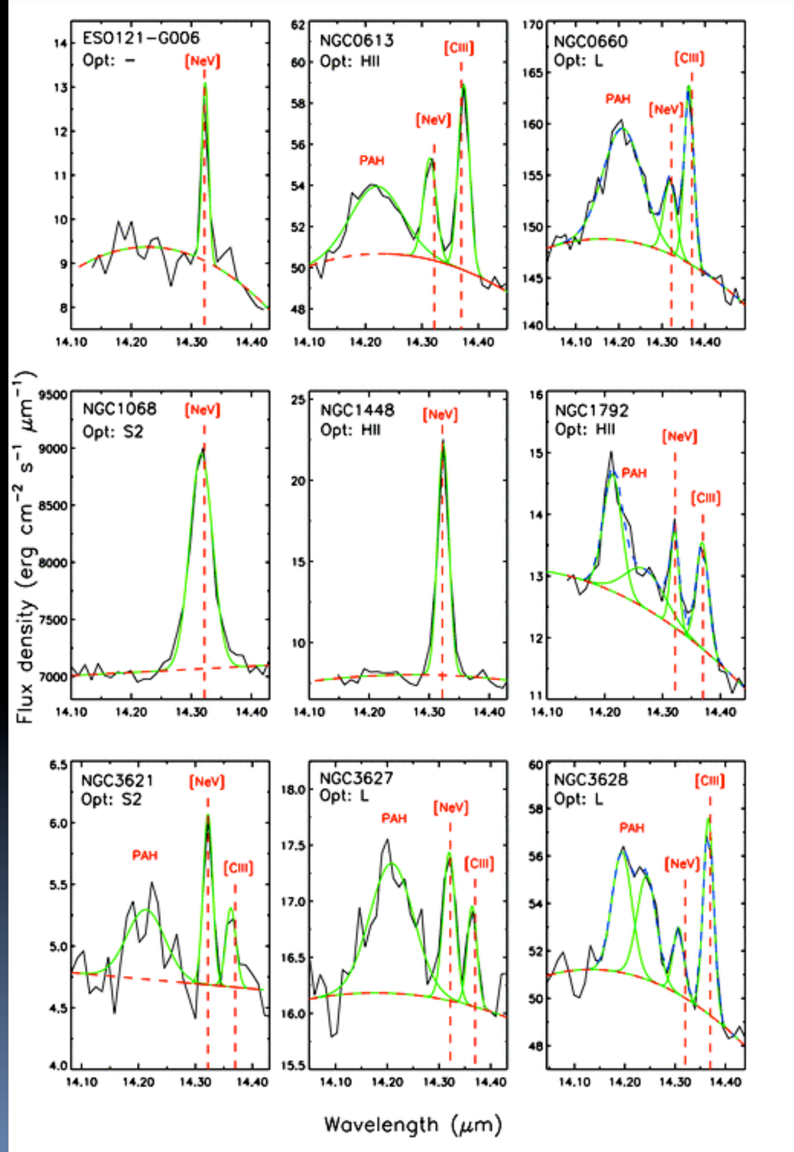
They have been used to:

identify low-luminosity AGN in local galaxies

quantify the accretion power in the local Universe

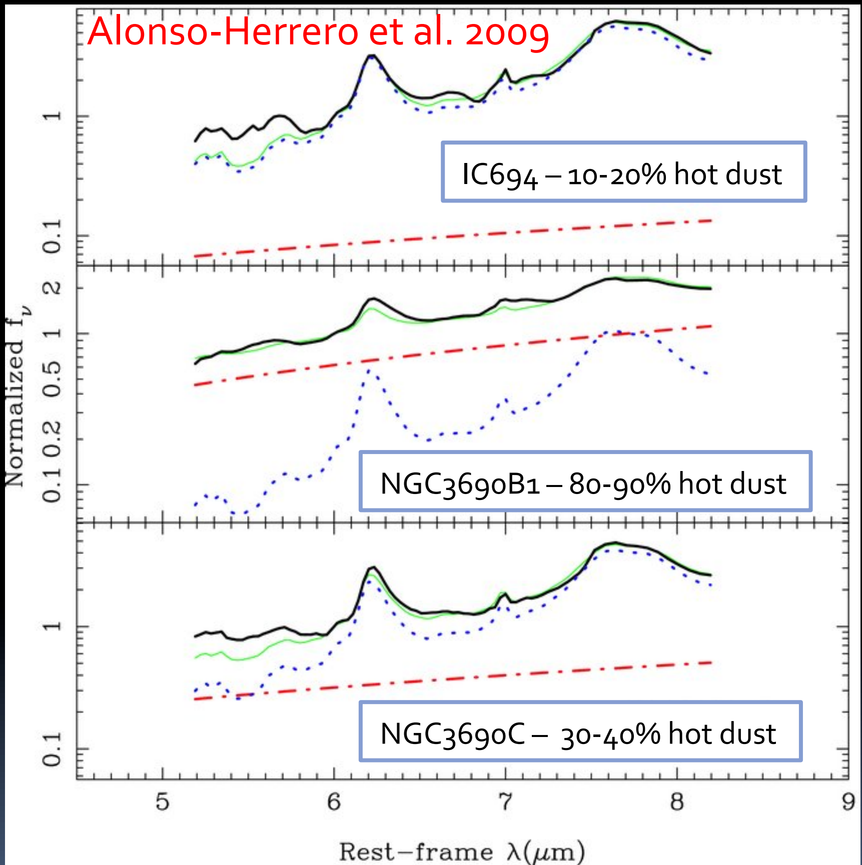
Satyapal et al. 2008, 2009; Goulding et al. 2009, 2010; Tommasin et al. 2010

Goulding & Alexander 2009

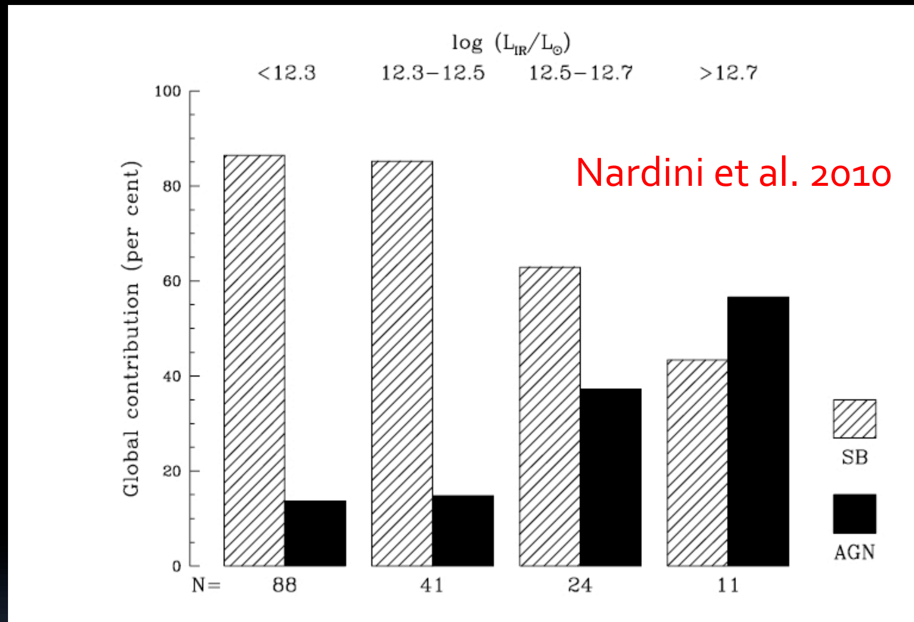


MIR AGN Indicators: hot dust emission at 6μm

Nardini et al. 2008 method is based on similarity of 5-8μm spectra of starburst galaxies



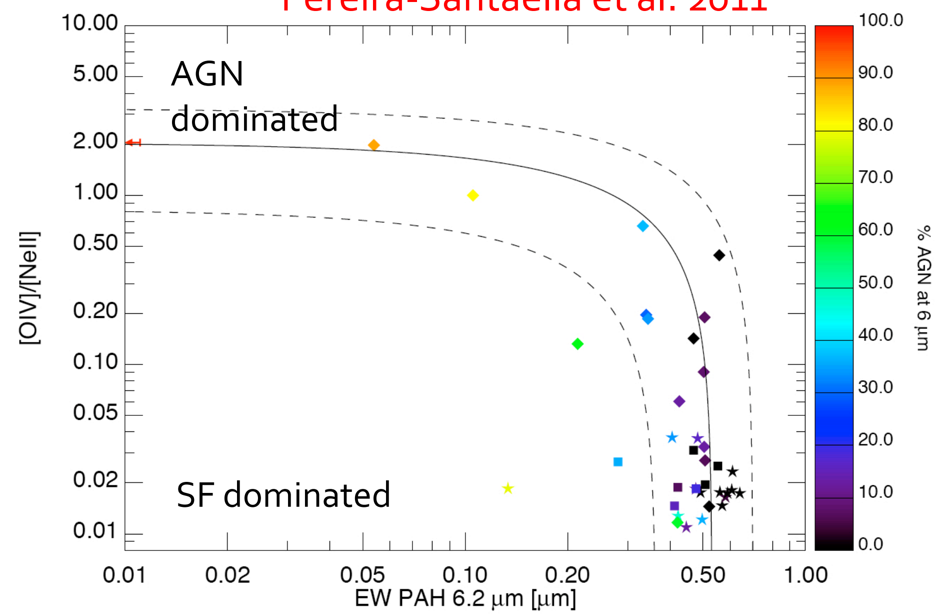
Method applied to nuclei of LIRG Arp299



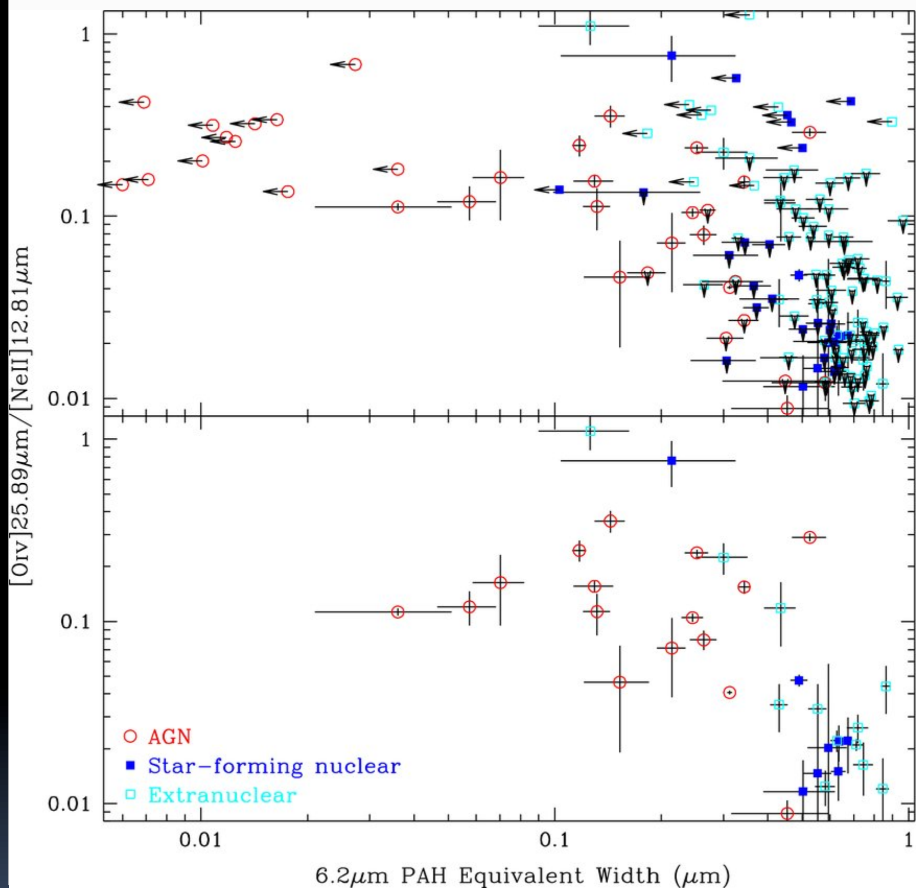
Method applied to sample of ULIRGs to estimate AGN contribution to L_{bol}, see also works and talk by Masa Imanishi

MIR AGN Diagnostics: Line Ratios + EW (PAH)

Pereira-Santaella et al. 2011



Dale et al. 2009



Method applied to sample of local LIRGs

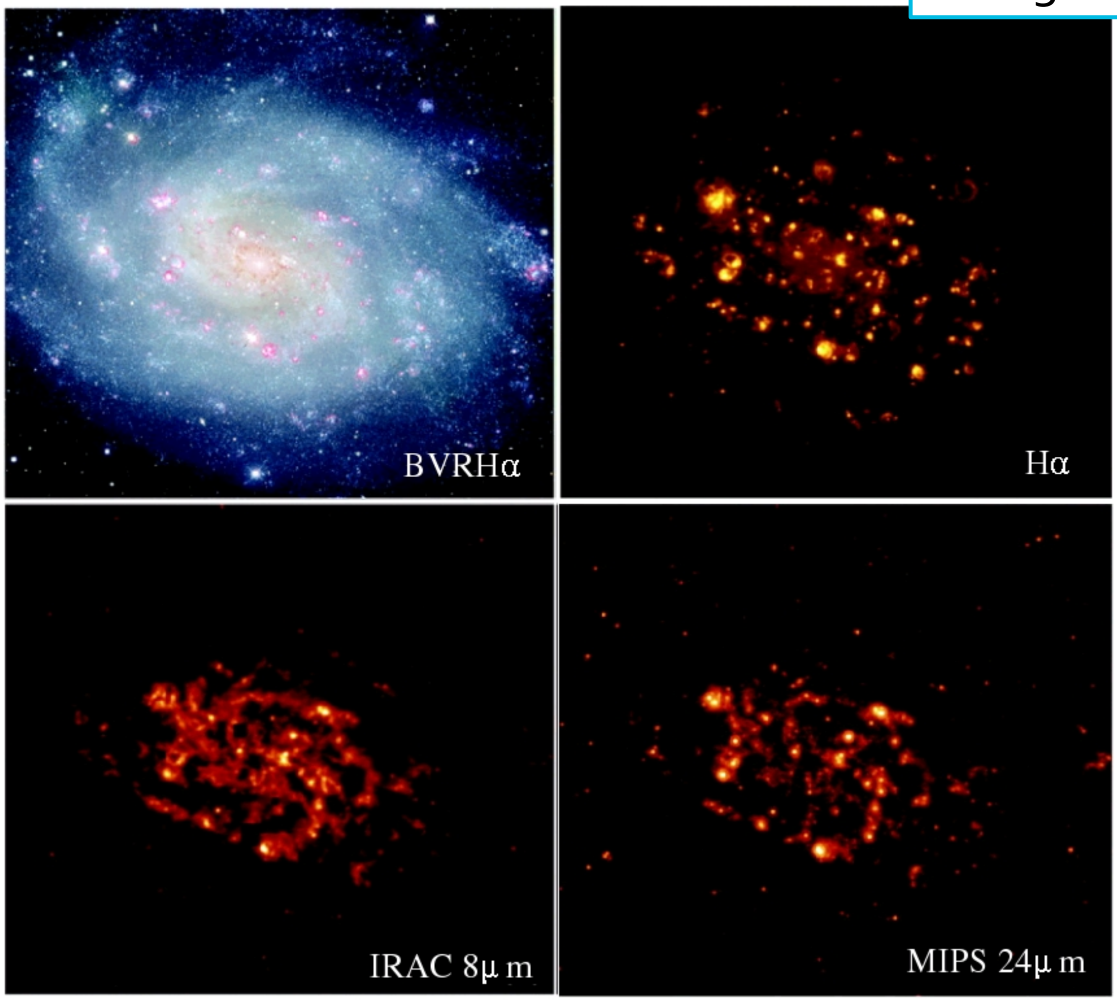
Method applied to SINGS galaxies

Mid-IR emission as a Star Formation Rate (SFR) indicator

Good morphological correspondence between Hα (or Paα) and mid-IR emission, in particular 24μm (e.g., Helou et al. 2004, Hinz et al. 2004, Gordon et al. 2004,2008, Calzetti et al. 2005, Engelbracht et al. 2006)

Helou et al. 2004

NGC300



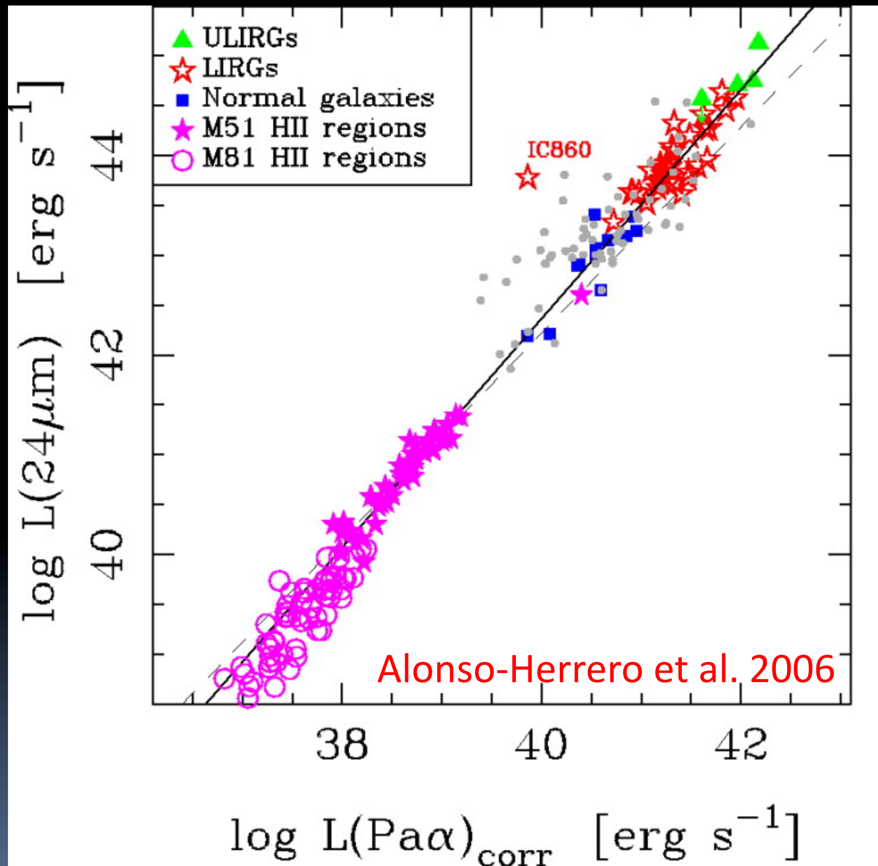
24μm emission as a SFR tracer

A tight correlation is seen between extinction-corrected Pa-α and 25μm (from IRAS) or 24μm (from Spitzer) flux density for SINGS HII regions, and integrated luminosities of LIRGs, ULIRGs, and normal galaxies.

- 8-70μm emission is powered by young stars
- >70μm emission is diffuse interstellar radiation field powered by modest-age stars

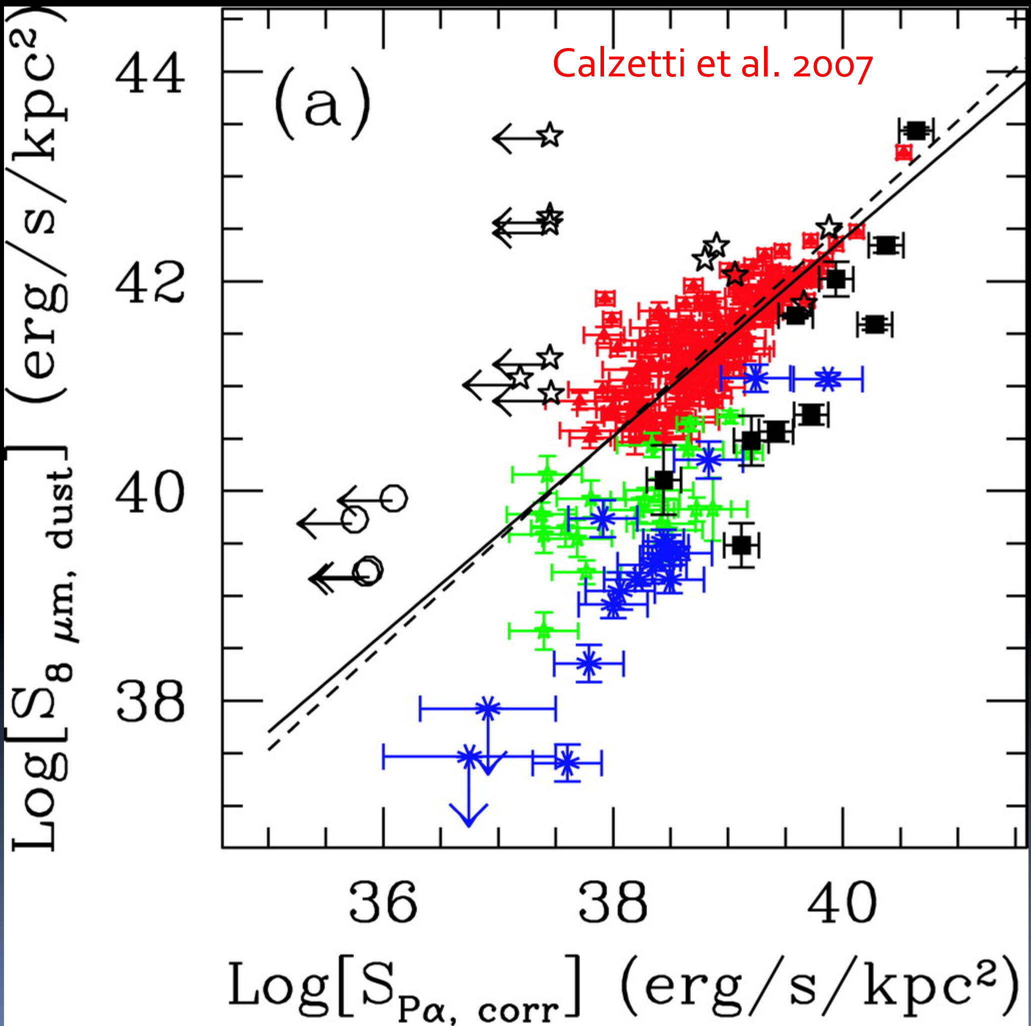
The SFR in terms of the 24μm monochromatic luminosity for **luminous dusty galaxies:**

$$SFR(M_{\odot}/yr) = 8.5\times10^{-38}\,(L(24\mu m)/erg/s))^{0.87}$$



See also Calzetti et al. 2005, 2007, Wu et al. 2005, Relaño et al. 2007, Rieke et al. 2009

8μm vs. Paα emission of SINGS HII regions on scales of 500pc



The 8μm vs Paα/Hα relation shows a much larger scatter than at 24μm

Strong dependence with metallicity, the size of the emitting region and SF history of galaxy

Range of Metallicities of SINGS galaxies:

High:
12+log(O/H)>8.25

Intermediate:
7.90<12+log(O/H)<8.25

Low:
log(O/H)<7.90

See also Alonso-Herrero et al. (2006), Díaz-Santos et al. (2008)

Combination of Hα and infrared SFR tracers

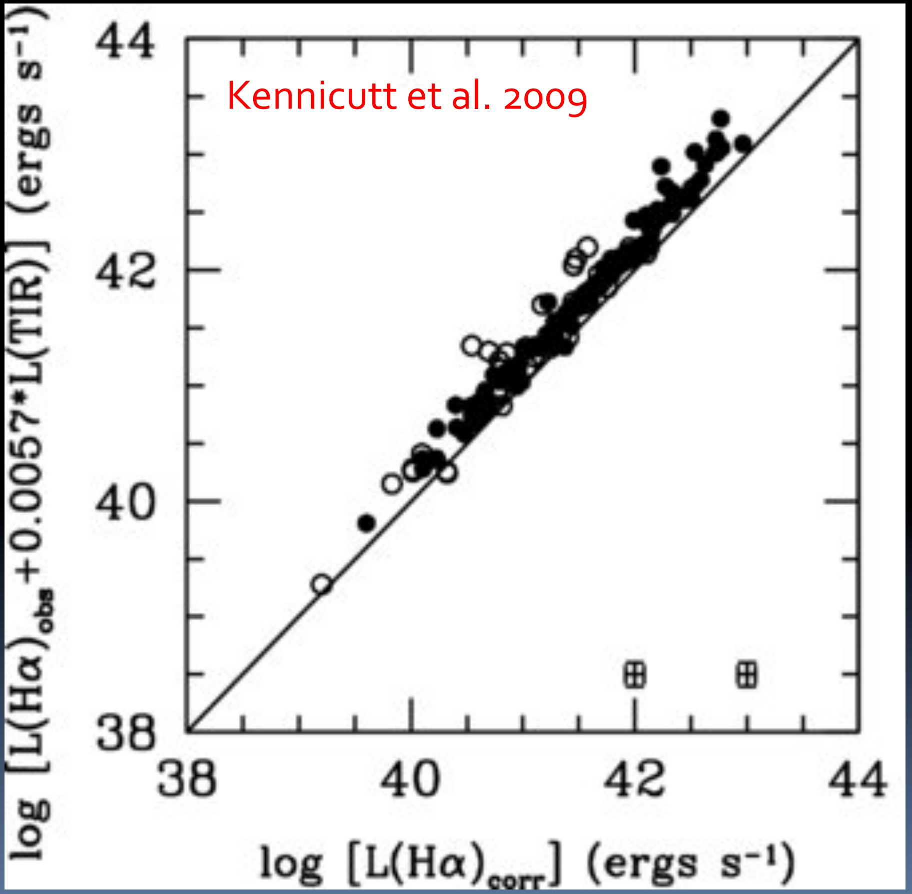
SFRs of galaxies can be obtained as: linear combinations of Hα (or [O ii]λ3727) emission lines with TIR, 24 μm, or 8 μm IR measurements, or 1.4 GHz radio continuum.

Reliable for normal star-forming galaxies with SFRs ~ 0-80 $M_{\odot}$ yr^{-1} and *A*(Hα) = 0-2.5 mag.

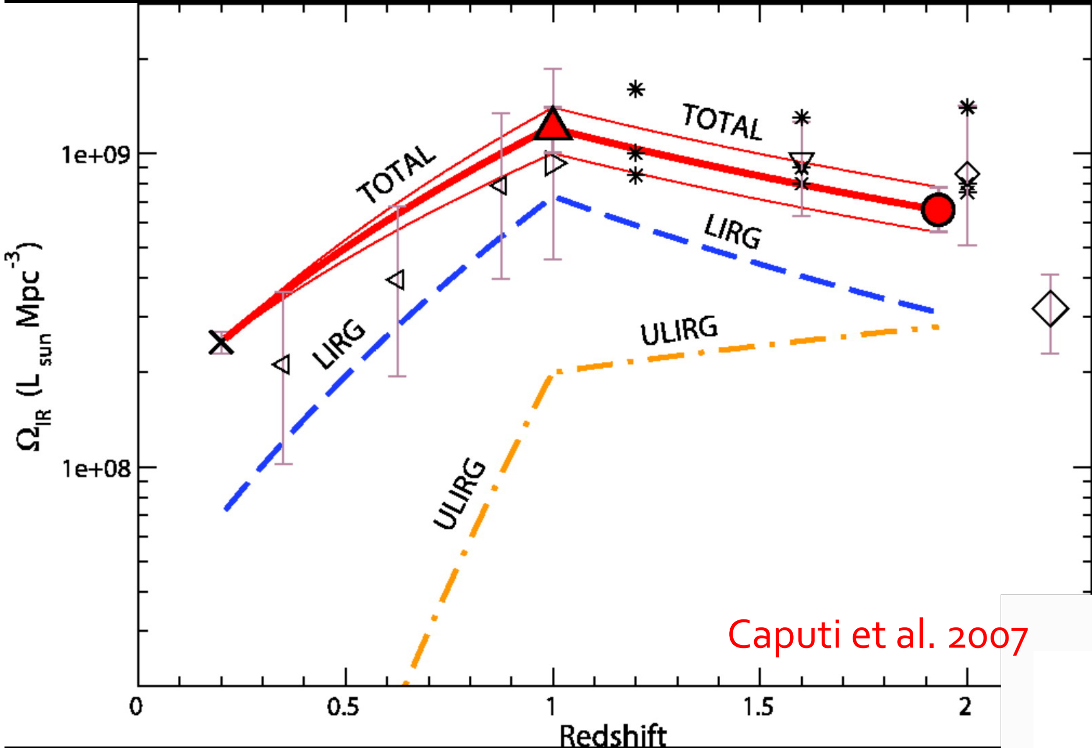
The calibrations may be less reliable for:

- **early-type galaxies** with UV-optical radiation fields dominated by evolved stars
- **very highly obscured starbursts** , where very young stars dominate dust heating

See also Pérez-González et al. 2006, Relaño et al. 2007

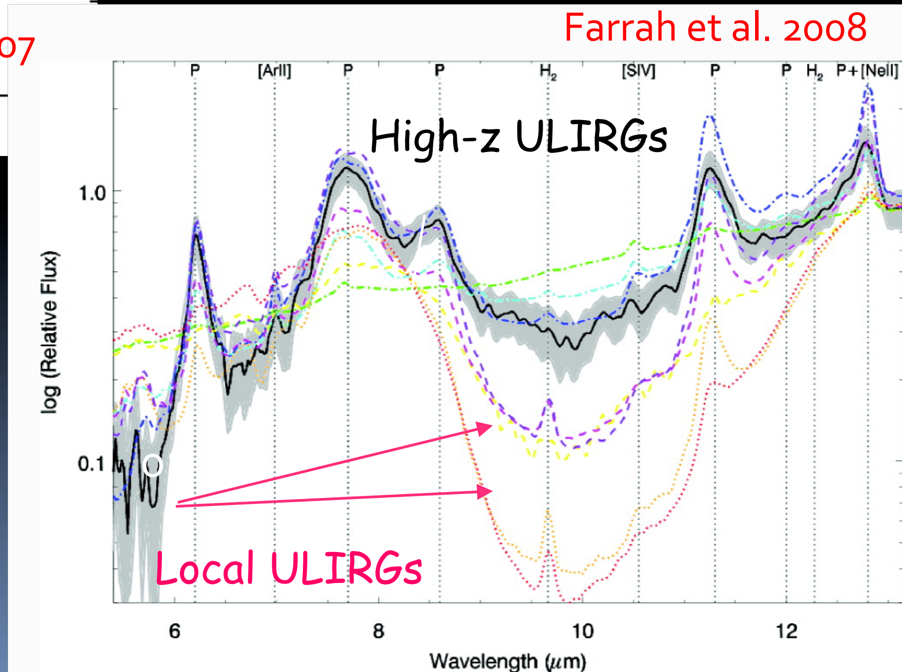


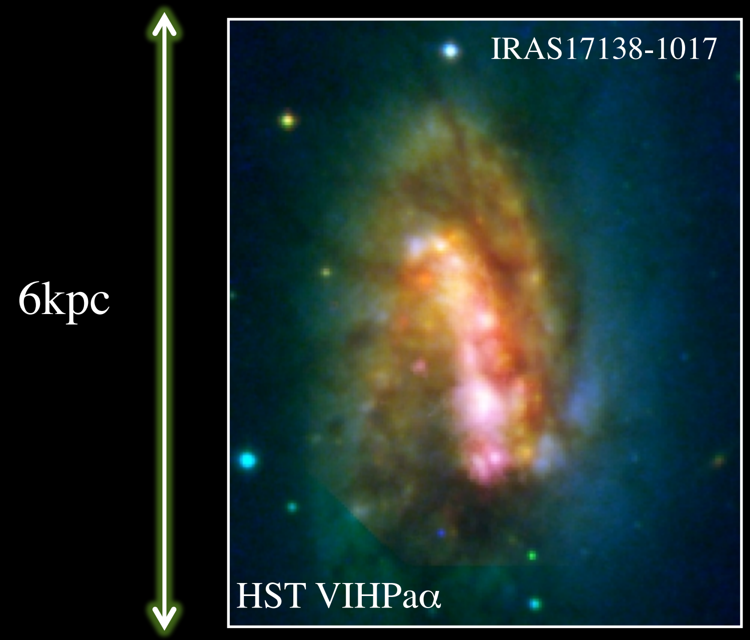
(U)LIRGs at high redshift (z~0.5-2.5)



LIRGs are major contributors to the comoving IR luminosity density (~ SFR) at z=1 and have a similar contribution to ULIRGs at z=2 (Le Floc'h et al. 2005; Pérez-González et al. 2005; Caputi et al. 2007).

The mid-IR spectra of distant (z~1.7-2) ULIRGs and SMG are more similar to those of local starbursts and LIRGs: shallow 9.7μm silicate feature (Farrah et al. 2008, Rigby et al. 2008, Menendez-Delmestre et al. 2009)





The Mid-IR Emission of Nuclear Regions of LIRGs and ULIRGs

SF nuclei: 8μm emitting regions 1 to a few kpc (FWHM)

Nuclear IR emission accounts for 10-50% L_{IR} of the system for LIRGs and almost 100% for ULIRGs – **Tanio Díaz-Santos talk**

IR surface brightness: $1\times10^{11}-2\times10^{13} L_{\odot} kpc^{-2}$ and ULIRGs ×10

ORION: $2\times10^{12} L_{\odot} kpc^{-2}$

AGN: Unresolved, but sometimes with nuclear (<40-80pc) star formation

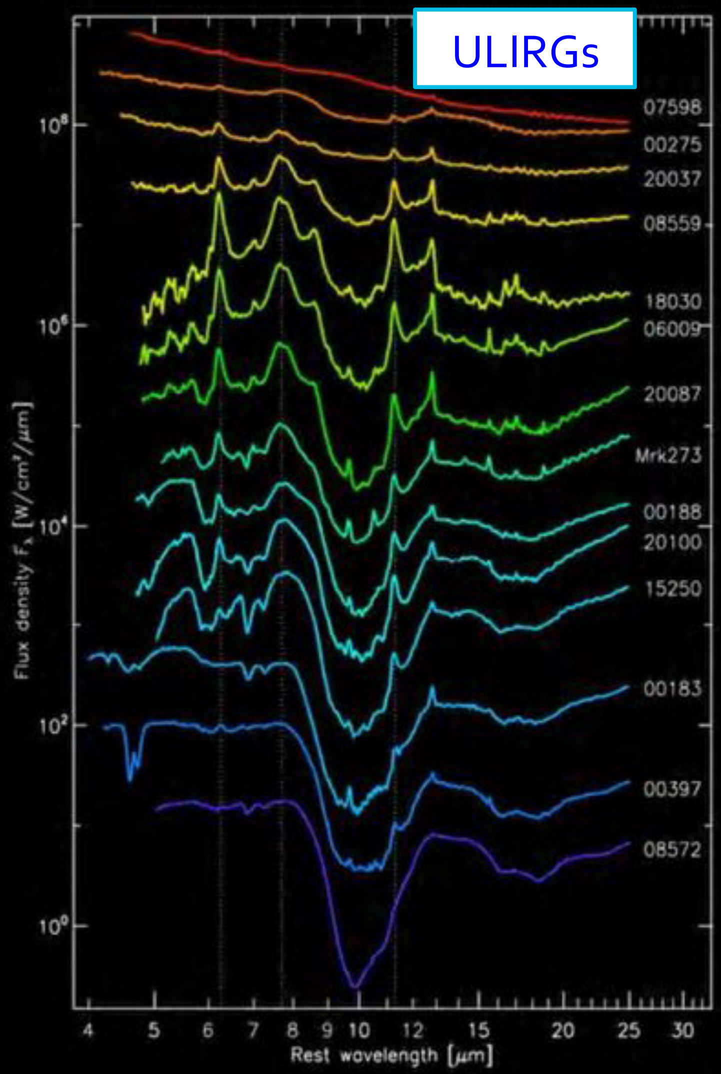
AGN, if present, 10-50% of L_{IR} of LIRGs and can dominate in ULIRGs

Surface Brightnesses of Infrared Starburst Galaxies

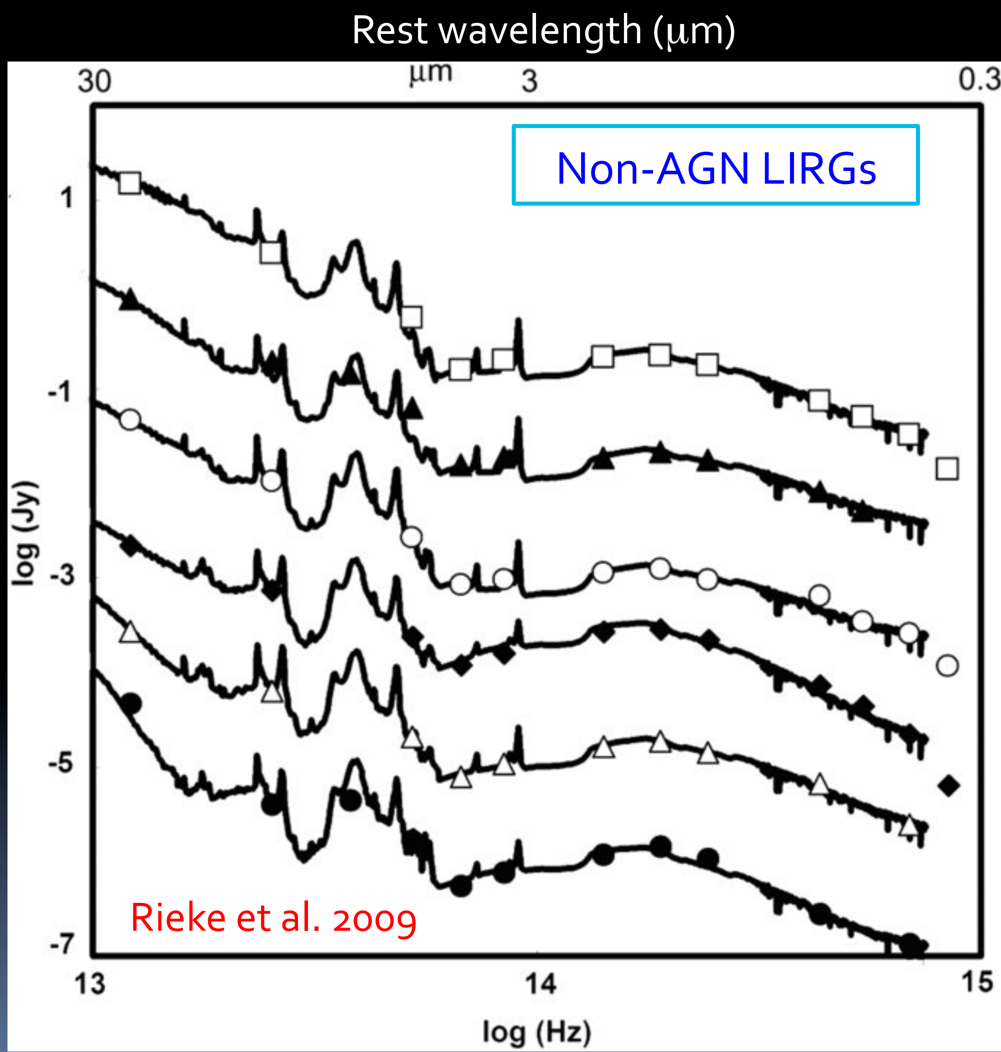
Soifer et al. 2000

Object	Type	Infrared Luminosity (L_{bol} ($L_{\odot}$))	Surface Brightness ($L_{\odot} kpc^{-2}$)
Orion	H II region	1×10^{6}	2×10^{12}
M 82	Local starburst	3×10^{10}	2×10^{11}
NGC 6090	Starburst	3×10^{11}	2×10^{11}
NGC 1614	Starburst	4×10^{11}	1.5×10^{12}
Mrk 331	Starburst	2.5×10^{11}	$\sim2\times10^{12}$
IC 883	Starburst	3×10^{11}	2×10^{12}
VV 114	Starburst	4×10^{11}	$\sim5\times10^{12}$
NGC 2623	Starburst	3×10^{11}	$\sim10^{13}$
NGC 3690	Starburst	8×10^{11}	$\sim10^{13}$
IRAS 17208...	ULIRG	3×10^{12}	1.2×10^{12}
Mrk 273	ULIRG	1.3×10^{12}	$>2.2\times10^{13}$
IRAS 08572...	ULIRG	1.3×10^{12}	$>2.8\times10^{13}$
Arp 220	ULIRG	1.5×10^{12}	6.0×10^{13}

Mid-IR integrated spectra of LIRGs and ULIRGs



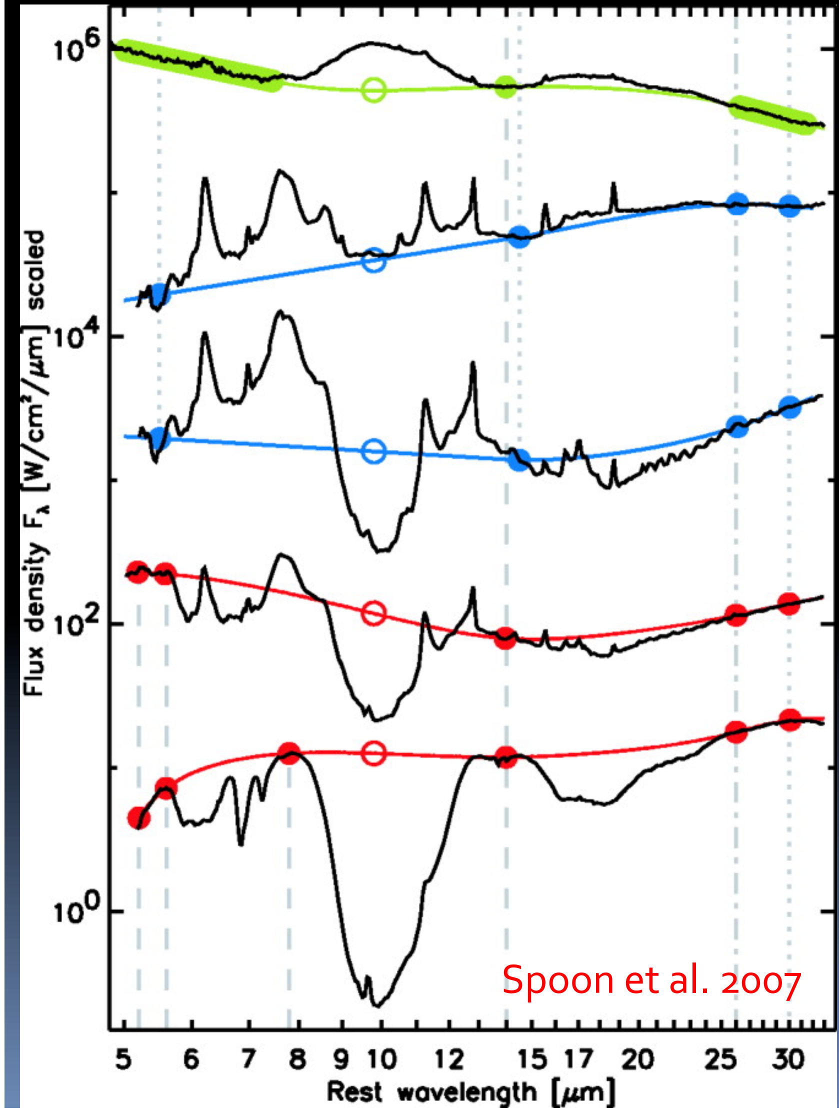
Armus et al. 2007



The 9.7μm feature in galaxies

The apparent strength of the 9.7 μm feature:

$$S_{sil} = \ln \frac{f_{obs}(9.7\ \mu m)}{f_{cont}(9.7\ \mu m)}.$$



Quasars:
silicate feature in emission

Star-forming galaxies:
nearly zero strength, moderate extinctions

ULIRGs:
variety of strengths, with some galaxies showing extremely deep silicate feature, highly embedded sources

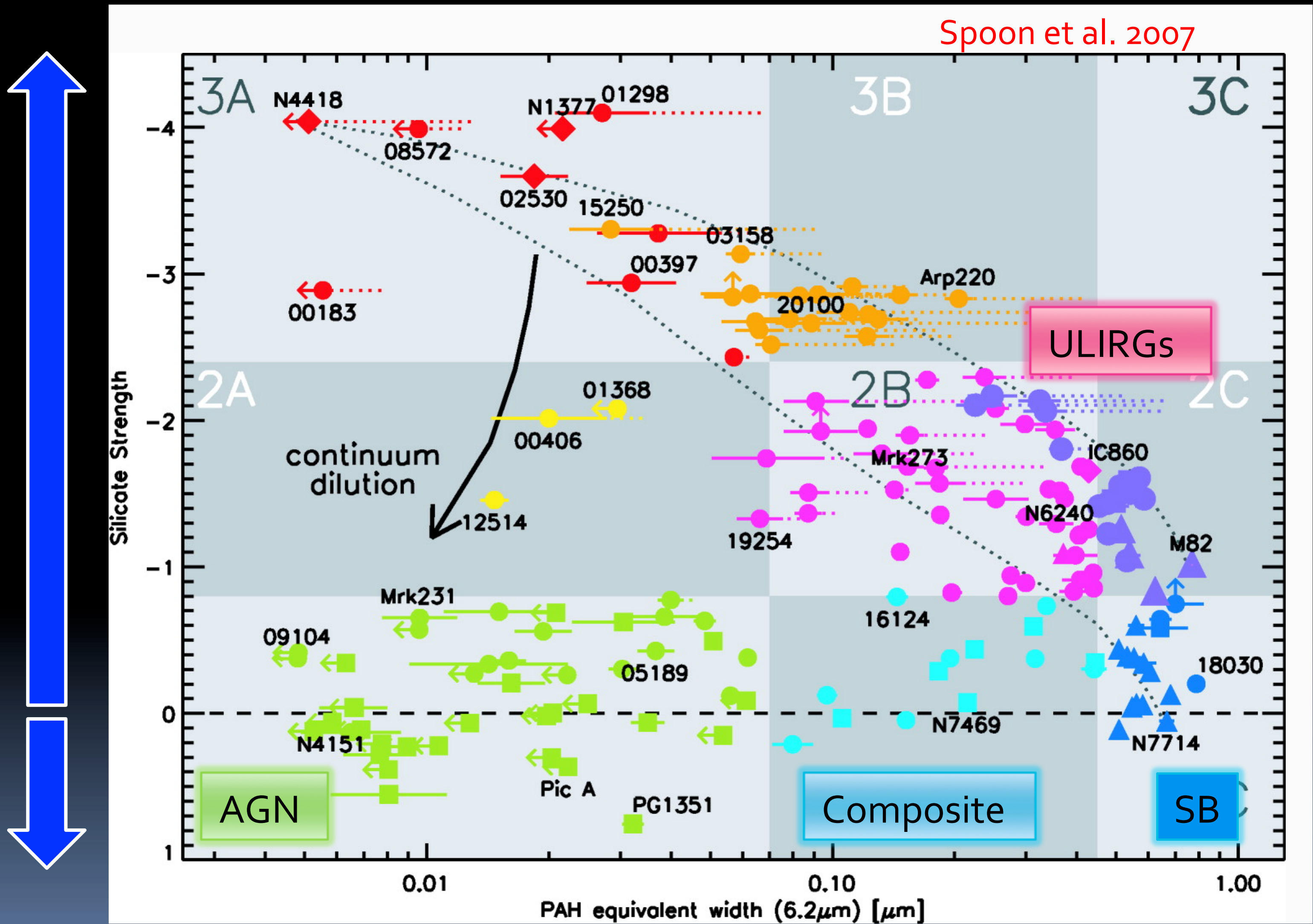
Dust screen geometry:

$$A_V \approx 16.6 \times S_{Sil}$$

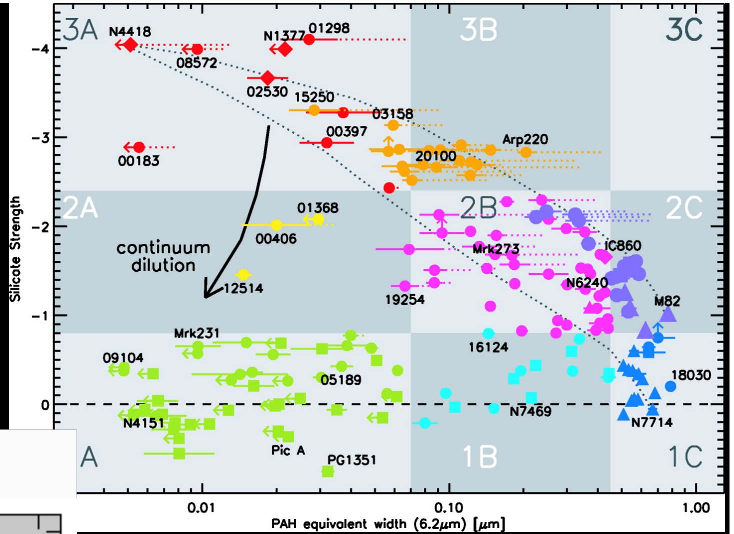
Activity class using silicate feature and EW of PAHs

absorption

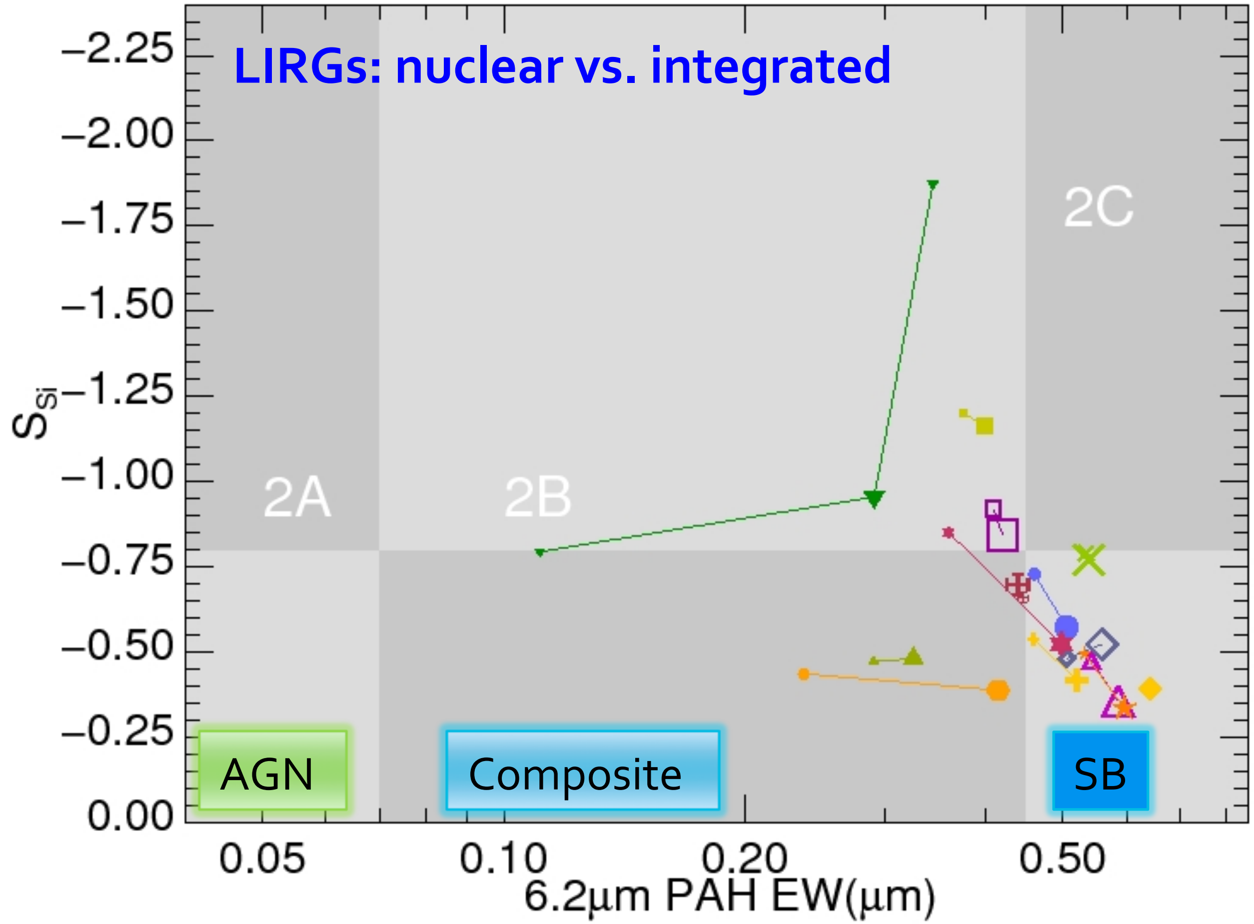
emission



Mid-IR Activity Classification of LIRGs



Pereira-Santaella et al. 2010



LIRG nuclei do not show extremely deep silicate features

Nuclei known to host an AGN located in Composite region

Integrated spectra of LIRGs tend to be classified as starburst-like

Spatially resolved line ratios in LIRGs

[SIII]18.7μm/[NeII]12.8μm

Sensitive to density

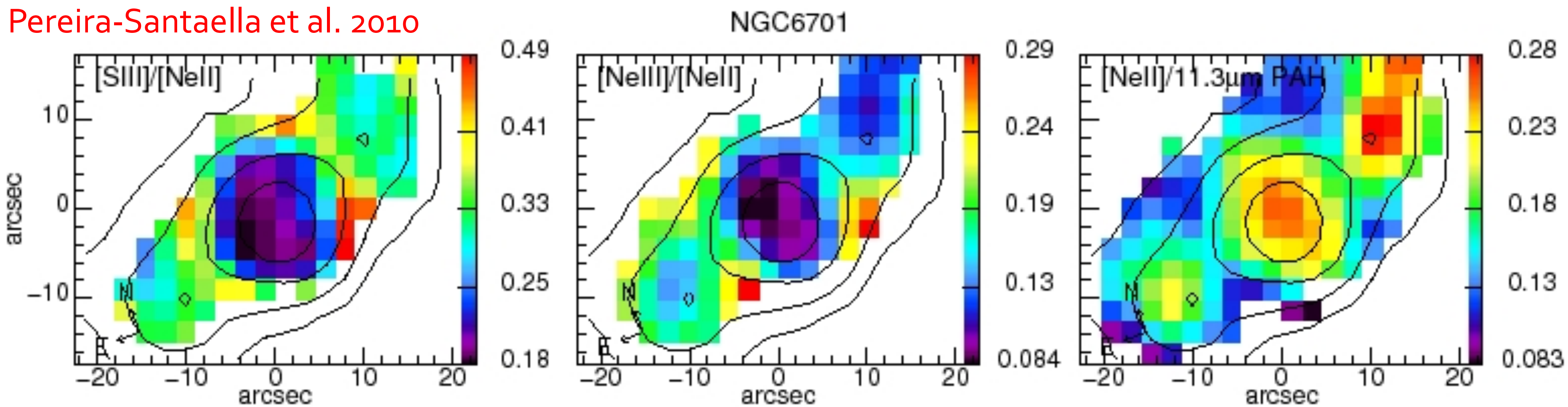
[NeIII]15.6μm/[NeII]12.8μm

Sensitive to hardness of radiation field , metallicity, density, age

[NeII]12.8μm/PAH11.3μm

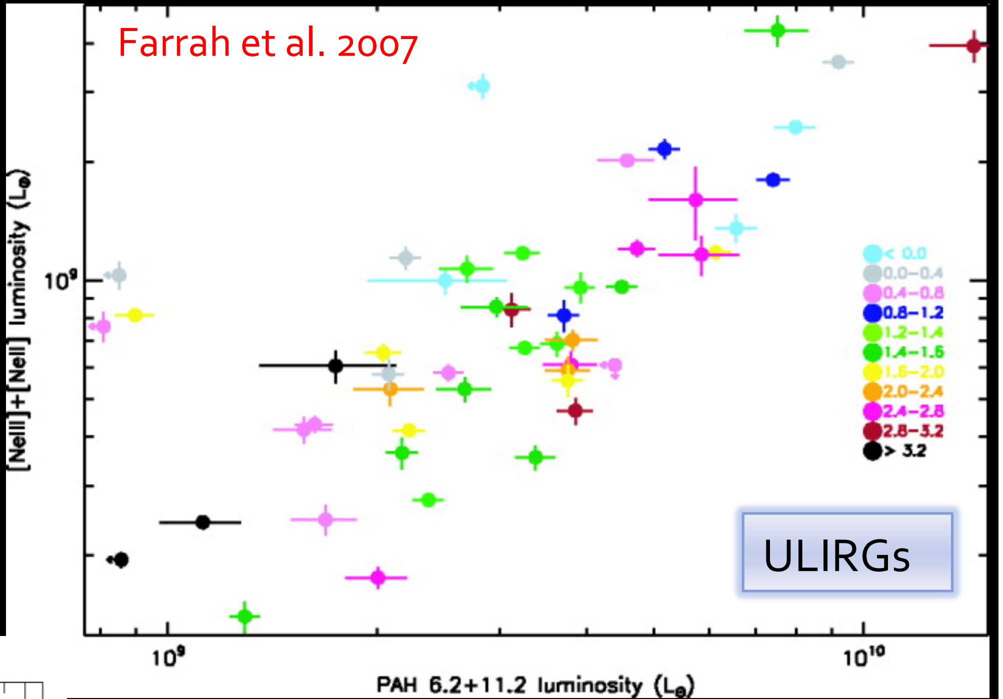
Sensitive to current vs. recent star formation activity

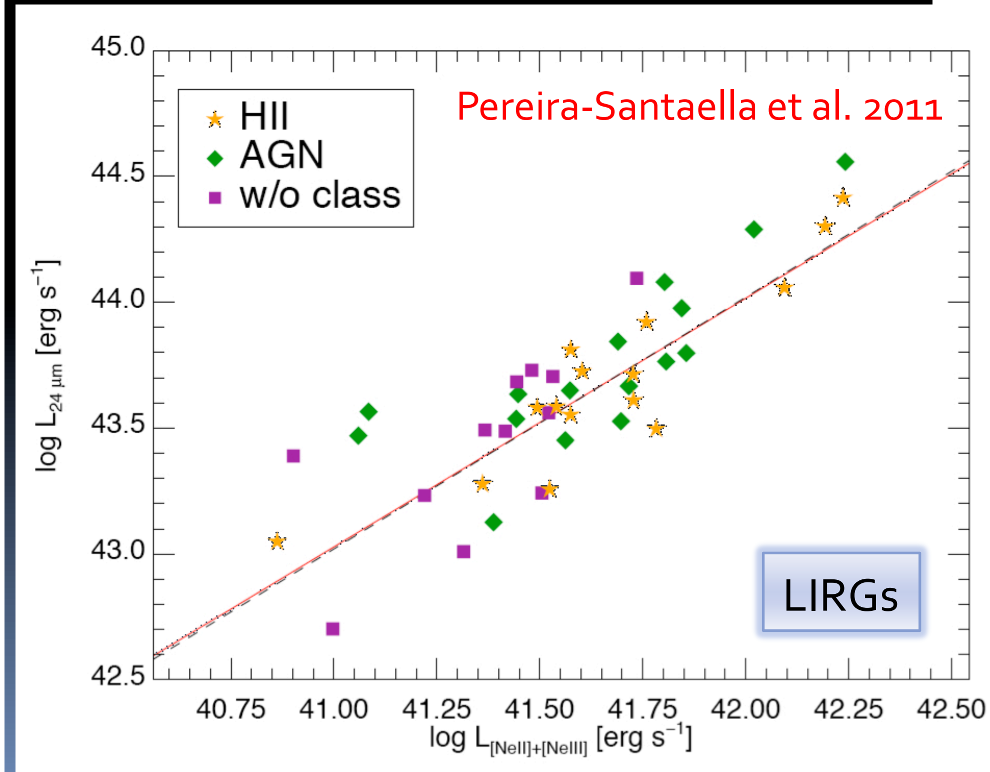
Pereira-Santaella et al. 2010



SFR tracers for LIRGs and ULIRGs

[NeII]12.8μm + [NeIII]15.6μm luminosities in SF galaxies good tracer of SFR (Ho & Keto 2007)





Sum of PAH 6.2μm and 11.3μu luminosities and 24μm monochromatic luminosities are good estimators of SFR of ULIRGs and LIRGs

See also Bernard-Salas et al. 2009 for starburst galaxies

Conclusions

Mid-IR observations of nearby starbursts can be used to get properties such as:

- ❖Extinction: 9.7μm silicate feature
- ❖ Age of the stellar population: ratios of fine structure lines
- ❖ Excitation conditions of the ionized and molecular gas: ratios of fine structure lines, PAHs and H2
- ❖(Obscured) SFR: monochromatic 24μm, FIR, PAH, [NeII]+[NeIII]
- ❖ Find obscured and low-luminosity AGN: [NeV], hot dust continuum, ratios of fine structure lines and PAHs
- ❖Dynamics and kinematics

All this in relatively obscured environments (A_V~5-30mag) and with spatially resolved observations

All this is important for understanding high-z IR bright galaxies which share a lot of properties with local starbursts and LIRGs