Astrofisica nell'infrarosso: The Dusty Universe

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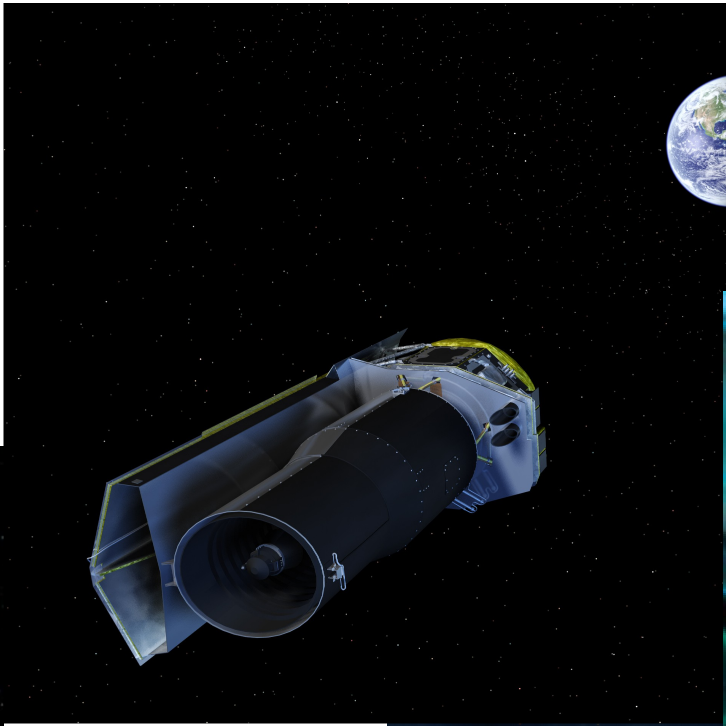
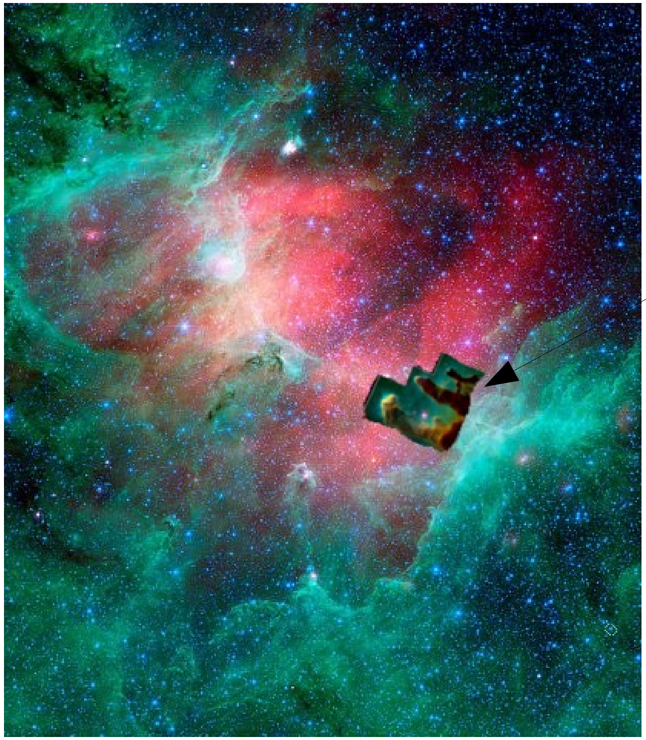


Dust is everywhere stars form



Spitzer Mountains of Creation

IRAC+MIPS image of Eagle Nebula (Carina)

HST Pillars of Creation

Spitzer merger

IRAC composite image
of interacting galaxies
N2207+IC2163

Overriding themes

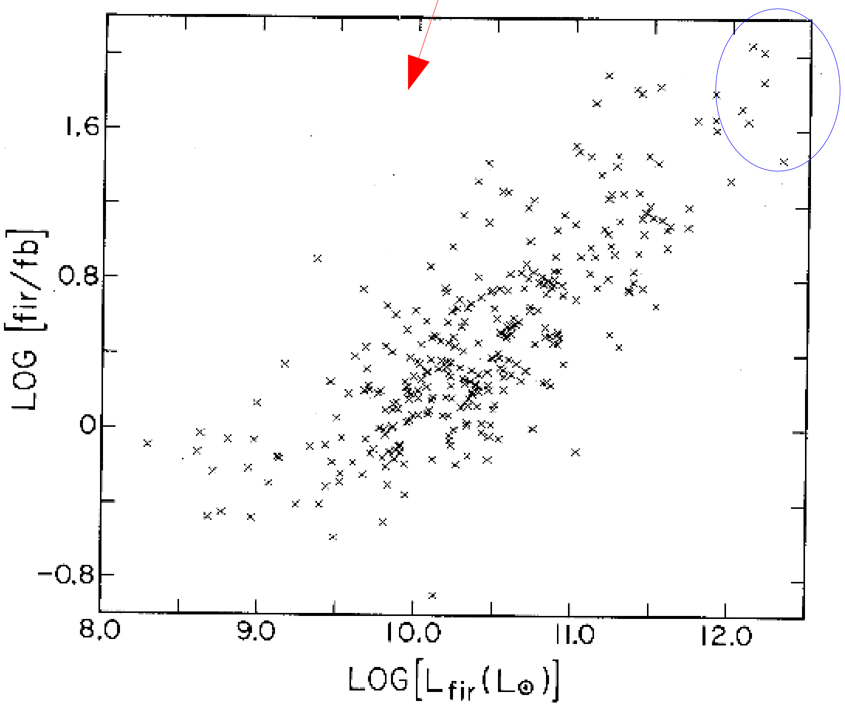
- Where we were before **Spitzer**: **IRAS** discoveries and what we already learned with **ISO**
- **Star-forming galaxies**, with a view to AGN/starburst diagnostics
- Compare **star formation at different metallicities**, since primordial galaxies start out chemically unevolved
- Looking to the future with **Herschel** and **JWST**

IRAS identified a new IR-luminous galaxy population

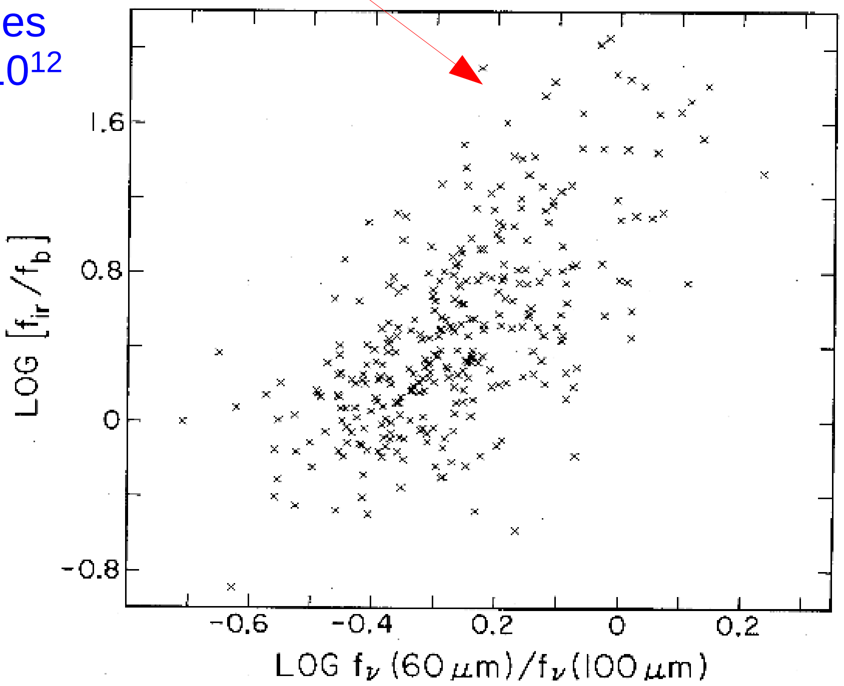
60-µm flux-limited sample (IRAS Bright Galaxy Sample, Soifer et al. 1987) finds 324 galaxies in the local universe, with luminosities ranging from 10^8 to >= 10^{12} Lsun.

Obscuration (LFIR/LB) depends on luminosity (LFIR)

Obcuration depends on large-grain temperature (F60µm/F100µm)

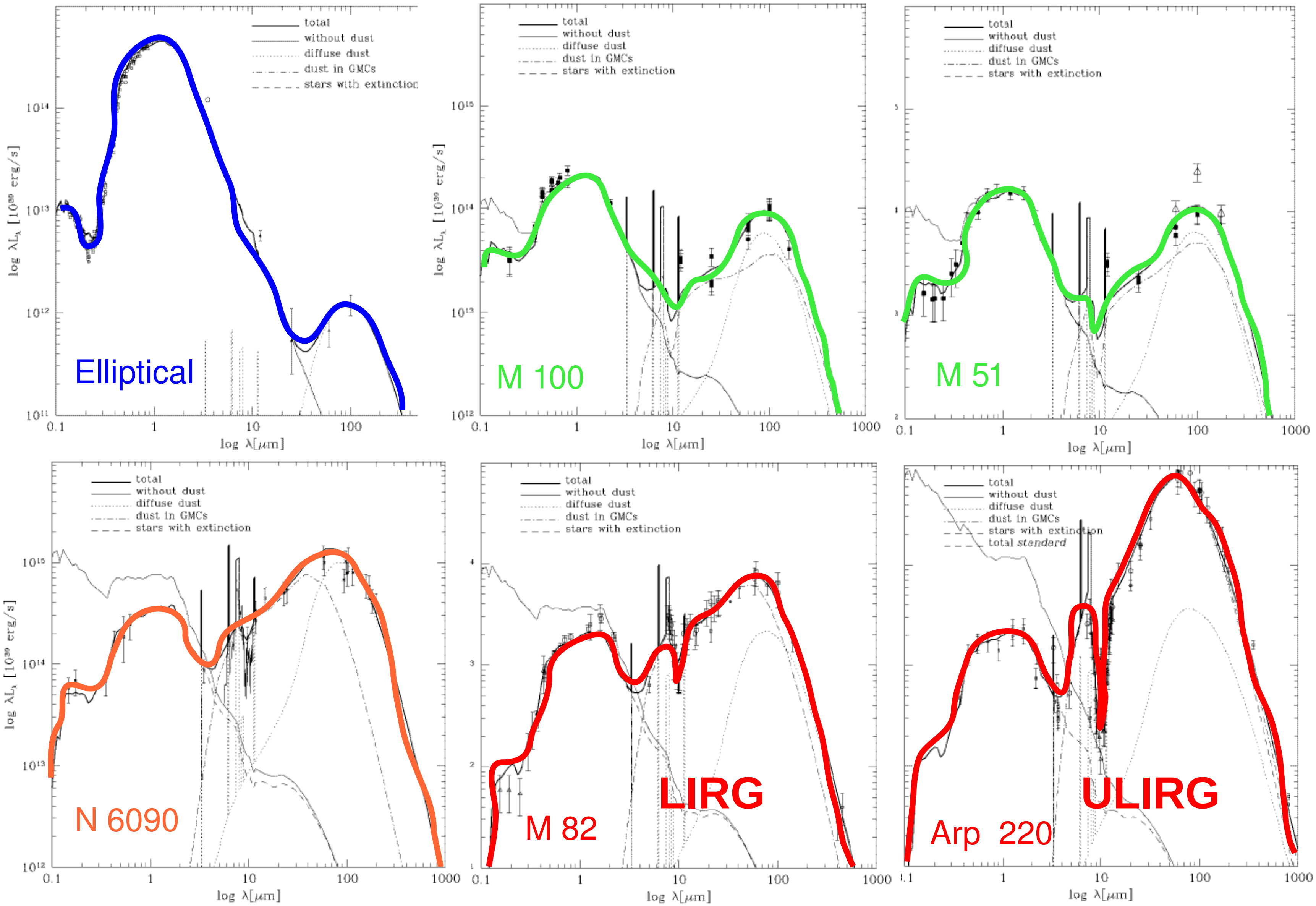


10 galaxies > LFIR 10^{12}



Luminous IR galaxies and Ultraluminous IRGs

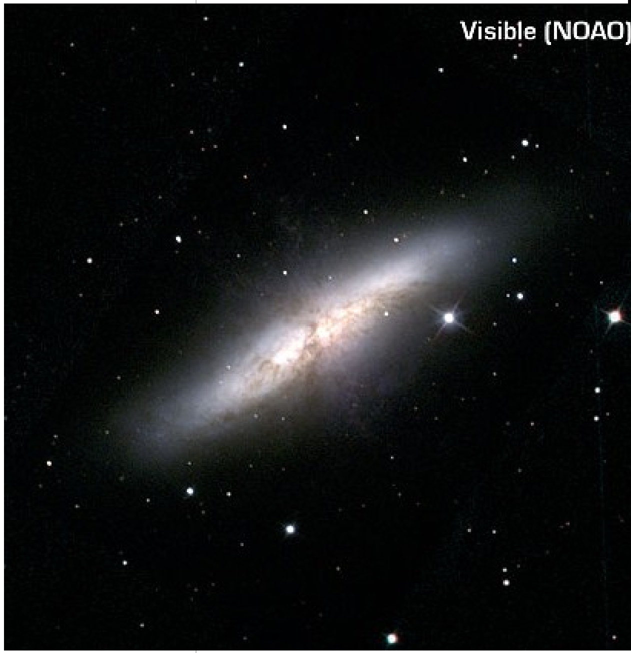
SEDs (GRASIL, Silva et al. 1998) shown as a function of increasing dust opacities



Anatomy of a LIRG: prototypical starburst M82

3.6-8μm Spitzer/IRAC image: “smoky” dust being entrained in outflow

Optical image shows dust patches



Composite Chandra, HST, Spitzer image shows dust mixed in with multimillion degree gas

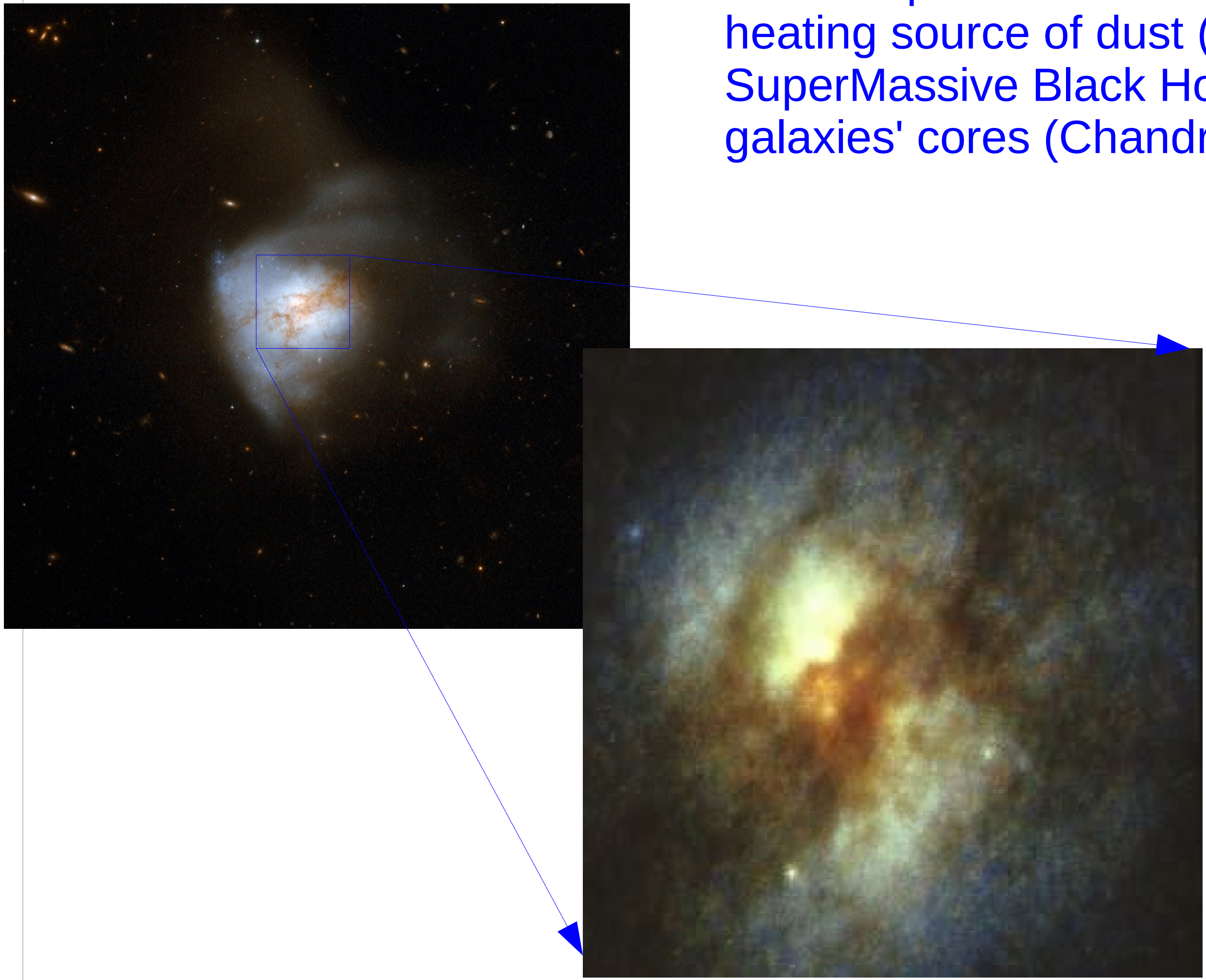
Σgas ~ 3×10^3 Msun/pc^2

ΣSFR ~ 30 Msun/kpc^2

A prototypical ULIRG? Arp220

- Two merged spiral galaxies, 95% of light in IR powered by the interaction
- Giant SuperStar Clusters in core are the primary heating source of dust (HST), together with two SuperMassive Black Holes in the parent galaxies' cores (Chandra)

As in M82, optical image shows dust patches

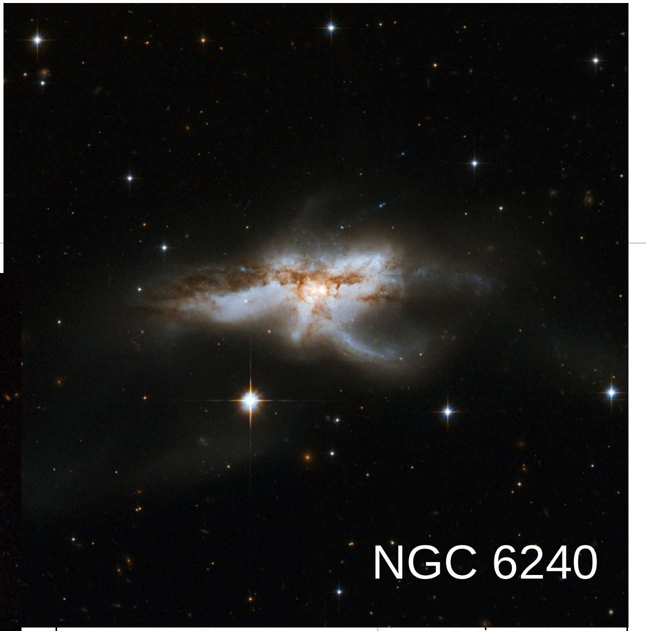


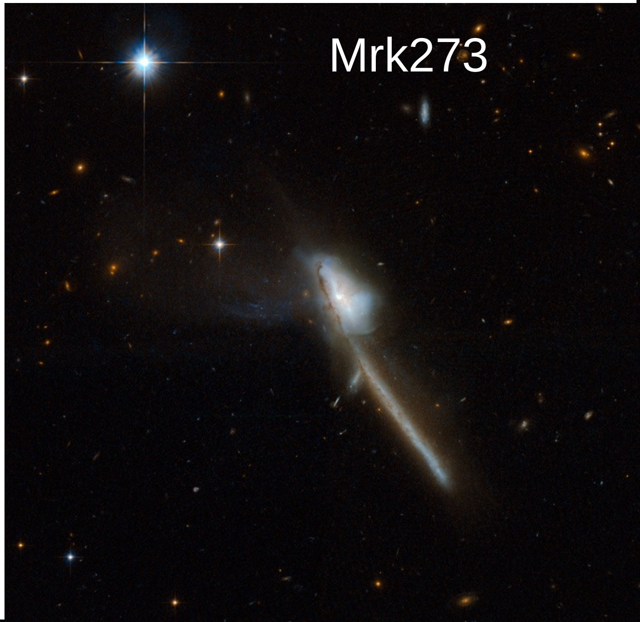
Core ~1kpc in diameter contains 200 star clusters and M(H2) = 2 x 10^8 Msun, as much molecular gas as the entire MW

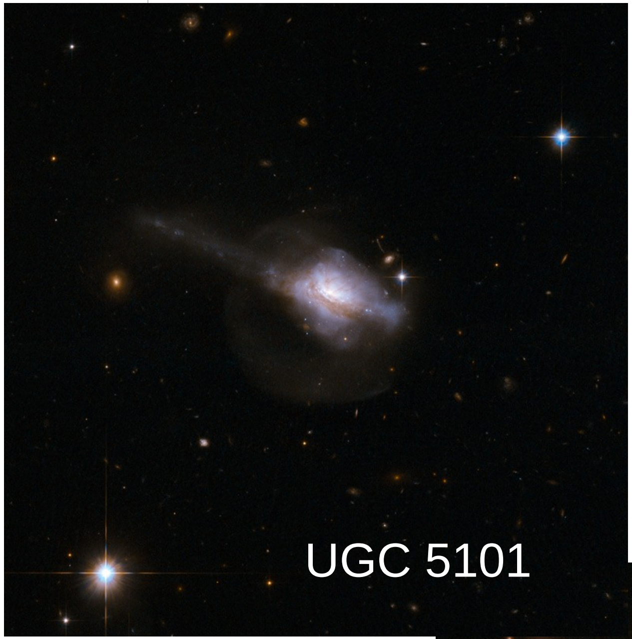
Σgas ~ 6x10^4 Msun/pc^2 (20 x M82)

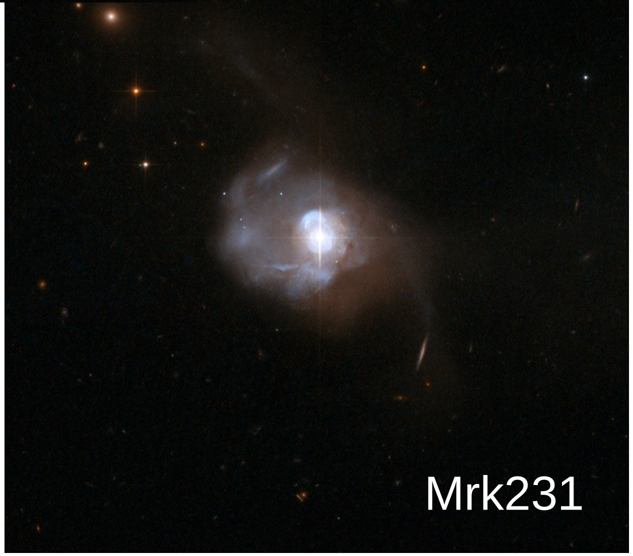
ΣSFR ~ 10^3 Msun/kpc^2 (30 x)

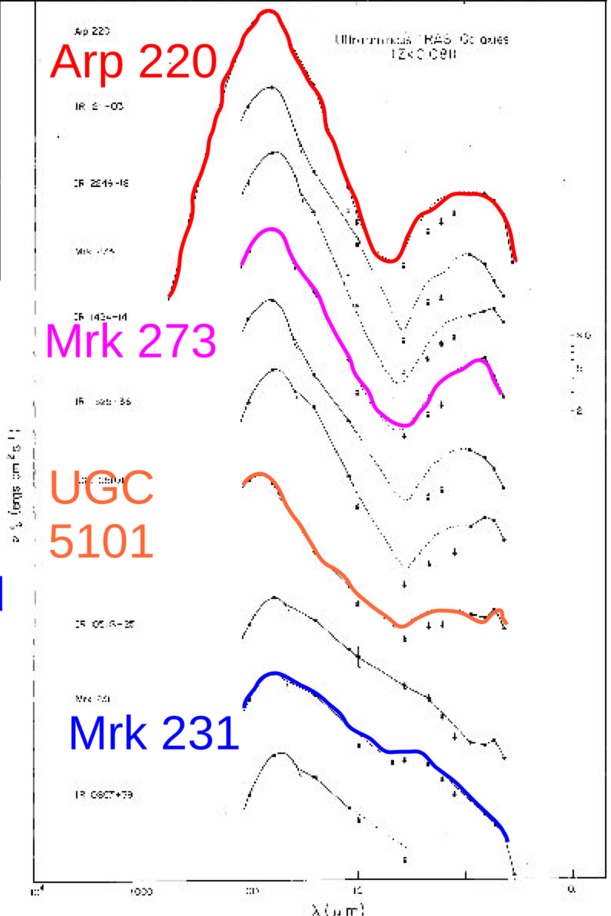
ULIRGs: the power of interaction











Mrk231 is a special case of a ULIRG with a very luminous **unobscured AGN**

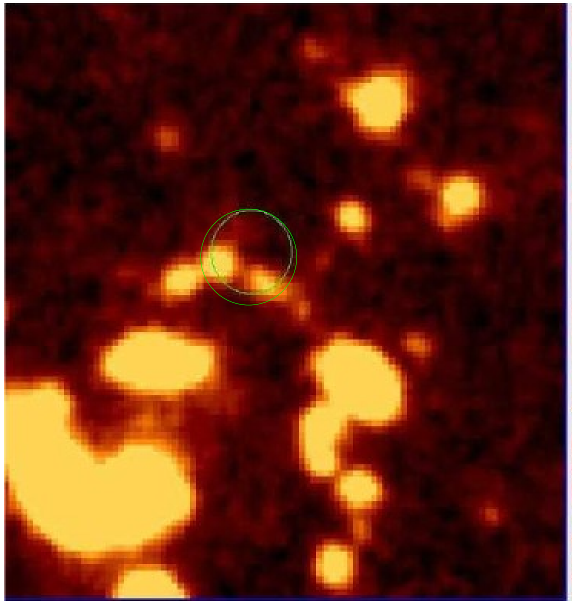
Mostly obscured AGN identified with Chandra (e.g., Gerrsen et al. 2004) or with VLA. **But with or without AGN, IR powered by the starburst!**

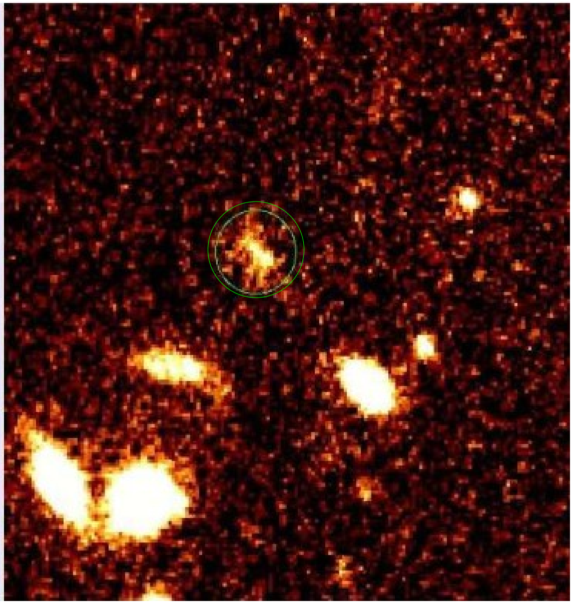
High-redshift ULIRG counterparts: SMGs

Submillimeter Galaxies (SMGs) discovered ~10 years ago through a strong 850 µm continuum detected with array cameras on sub-mm/mm telescopes (Smail et al. 1997) [c.f., LeonardoTesti's talk].

Very dusty very luminous galaxies at z~2-3, with cooler dust than ULIRGs (Pope et al. 2006), but similarly high (or higher) SFRs, ~> 500-1000 Msun/yr.

More gas rich than local ULIRGs (~40% by mass vs. ~10%, Tacconi et al. 2006)

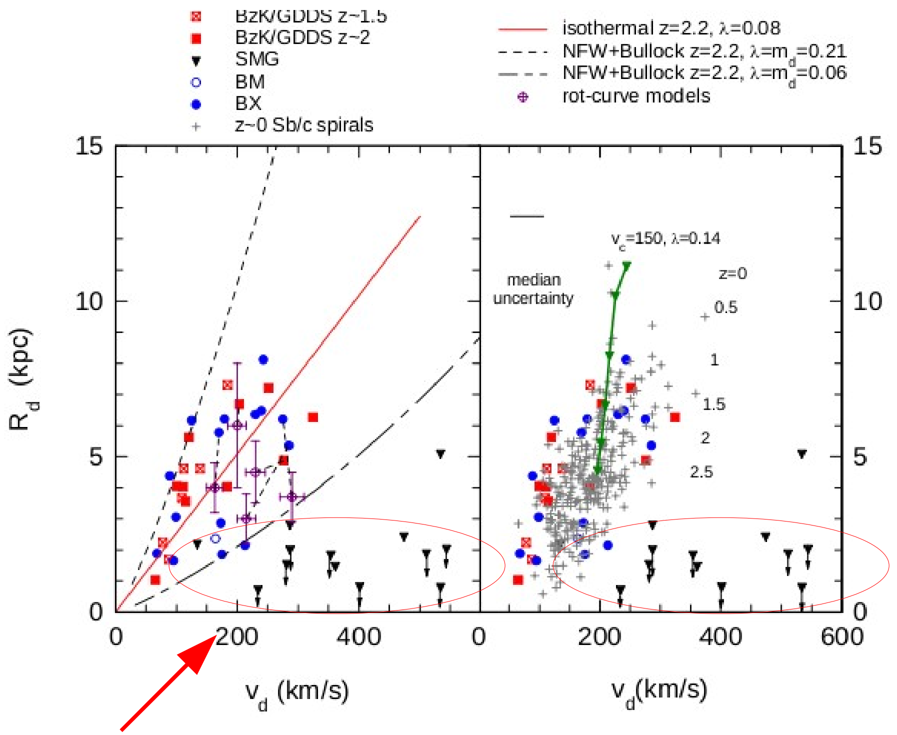

R band


K band

Positions need to be confirmed with VLA interferometry or submm interferometry (e.g., SMA).

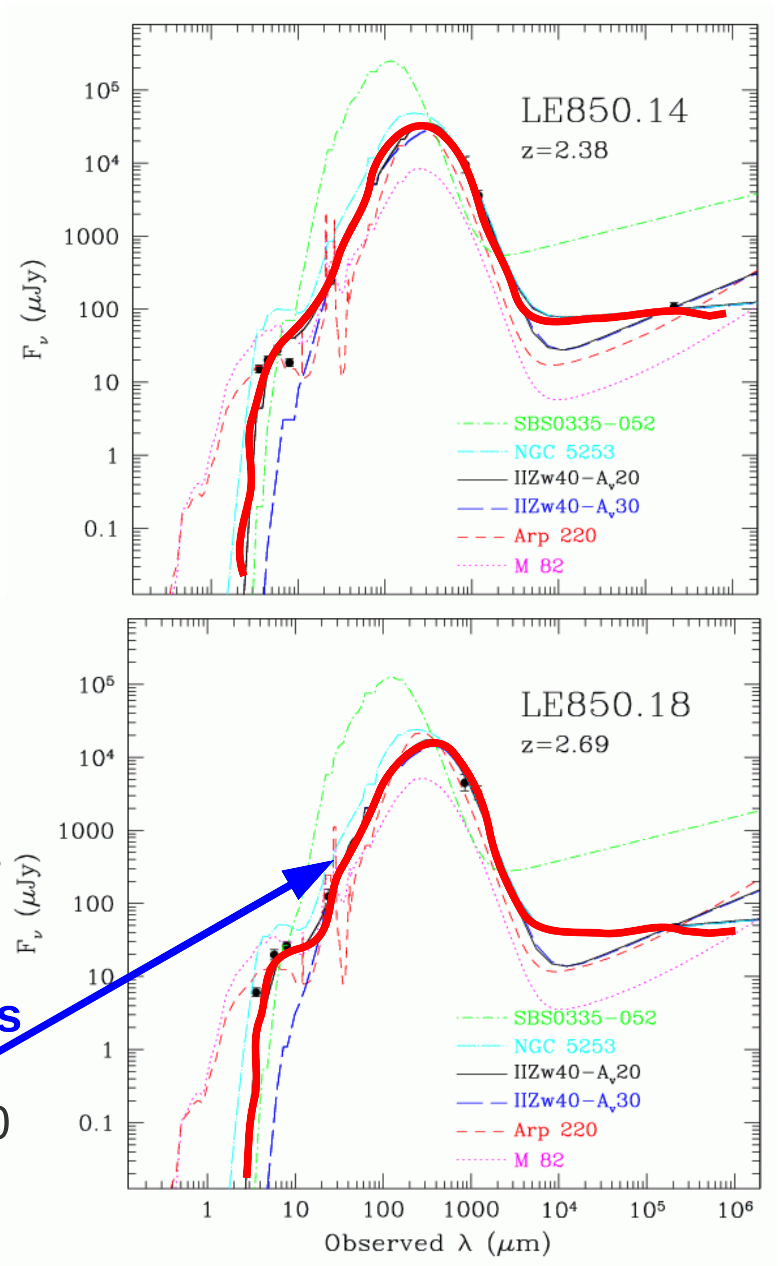
SMGs tend to be optical (BVR) band dropouts, but visible at 2µm (K band) (Iono et al. 2007, Younger et al. 2008)

SMGs very compact, dense, and dusty



SMGs are smaller and wider in velocity width than optically bright (K<20) z~2 galaxies (Bouché et al. 2007)

Their **(broader) SEDs are better fit by models of compact dust-enshrouded (AV ~ 20) star clusters** (e.g., DUSTY) than by M82 or Arp220 (Hunt & Maiolino 2005)



ULIRGs and SMGs:
Elliptical galaxies in formation

Number densities of IR galaxies and interactions increase with z at least until z ~ 1 (Elbaz et al. 2002, Le Floc'h et al. 2005).

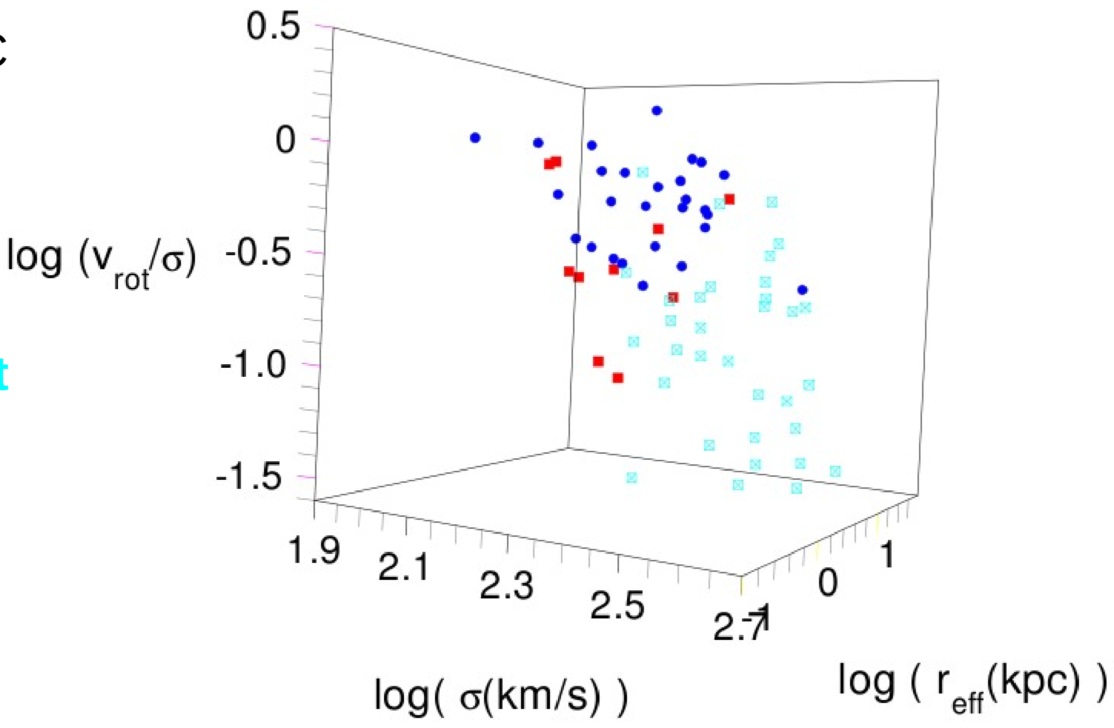
ULIRGs as a dust-enshrouded phase of quasar formation was proposed by Sanders et al. (1988), but ULIRGs and SMGs are the likely progenitors of intermediate-luminosity elliptical galaxies (Genzel et al. 2001).

VLT/ISAAC+Keck/NIRSPEC
σ-reff-vrot/σ distribution of:

ULIRG mergers (filled red squares),

Boxy giant ellipticals (light blue, open squares with crosses, M(B)<-20.5, B-K=3.9)

Disky ellipticals/lenticulars (dark blue, filled circles, M(B)<-18.5, B-K=3.9)

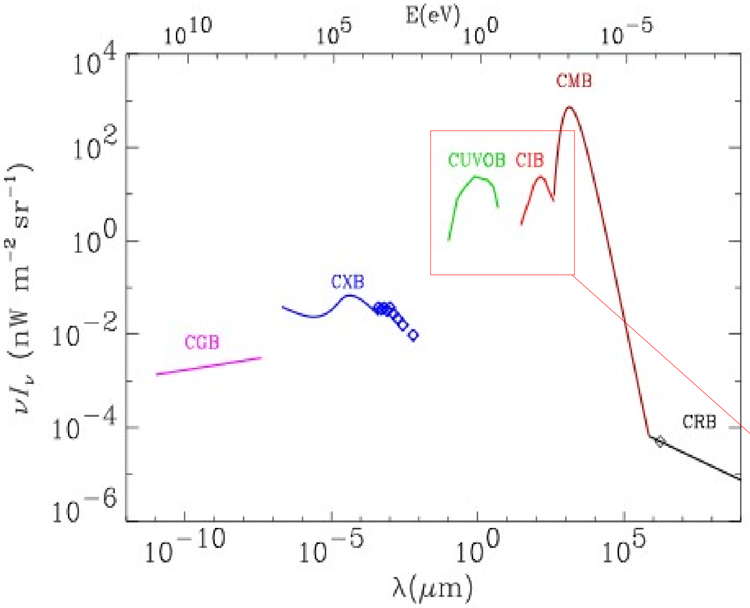


Cosmic IR Background:
Dust heated at high redshift by star formation

50:50 present-day optical/IR contributions: maybe as high as 20:80 in past. *70% of SF up to z~2 (4?) occurs in galaxies with Lbol>10^{11} Lsun (Chary & Elbaz 2001)*

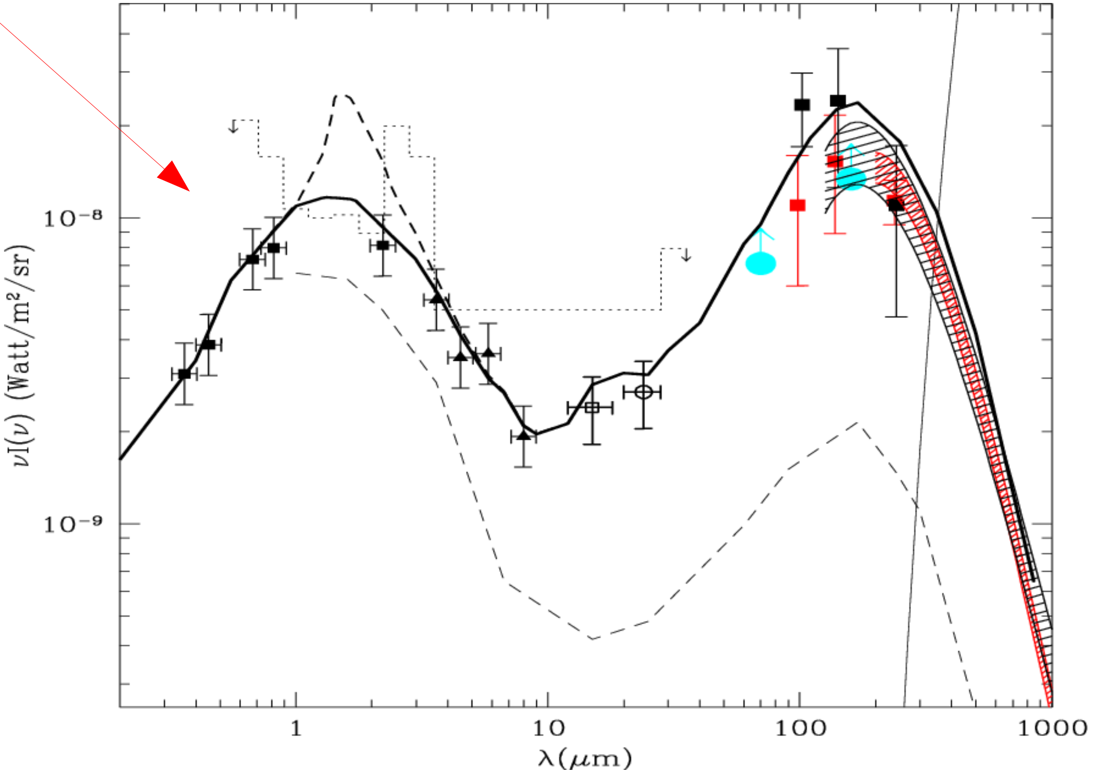
80% of CIRB at 140µm produced by z~1.5, but only 30% of 850µm in same range (ISO, Chary & Elbaz 2001)

AGN <~ 7% at 850µm (Servergnini et al. 2000), 10-20% overall (Hauser & Dwek 2001)



Schematic of Cosmic Background spectrum (Hauser & Dwek 2001)

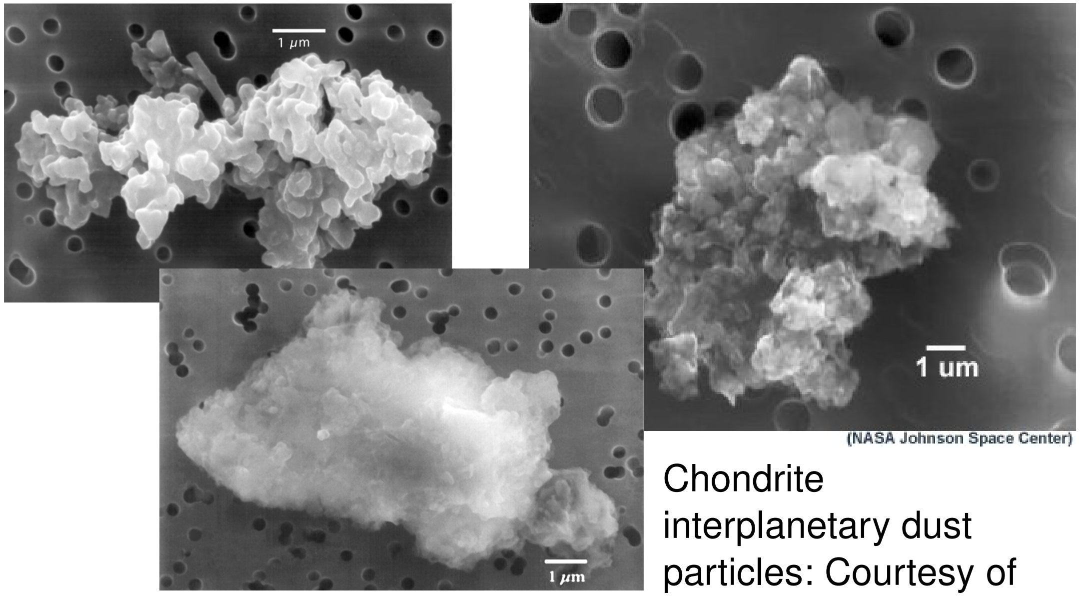
Compilation of optical+UV+IR background (Franceschini et al. 2008)



How is all this dust produced?

Silicate-type and carbonaceous grains form in the molecular outflows of **Asymptotic Giant Branch stars** (Gehrz 1989, Whittet 1992, Habing et al. 1994, Busso et al. 1999)

Dust grains are also thought to form in **Type II supernovae** (Dwek & Scalo 1980,Todini & Ferrara 2001)



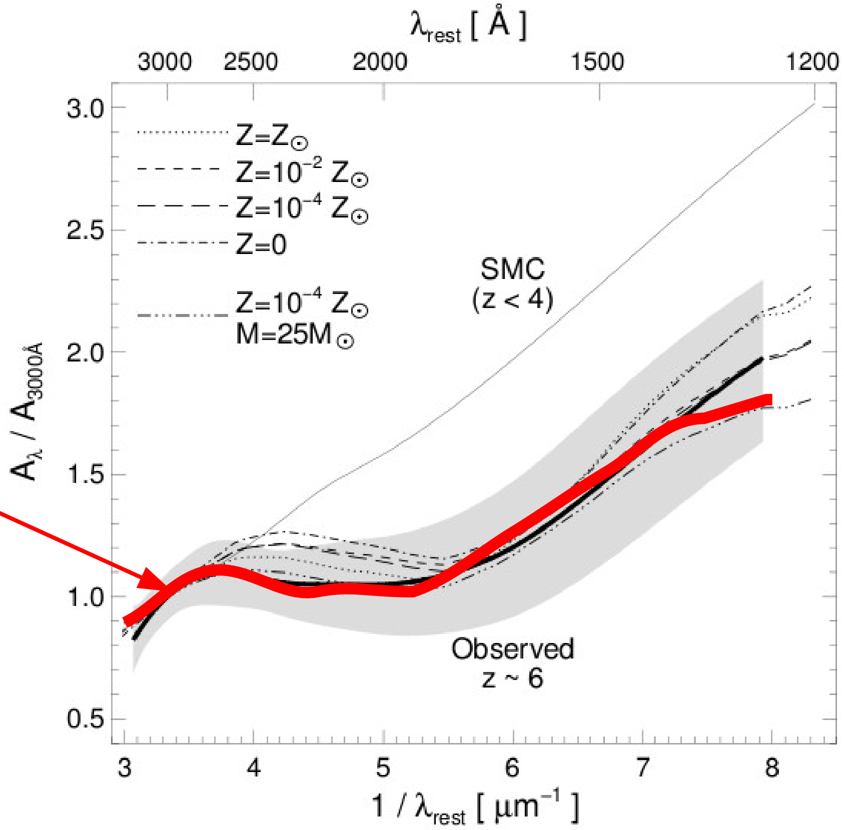
(NASA Johnson Space Center)

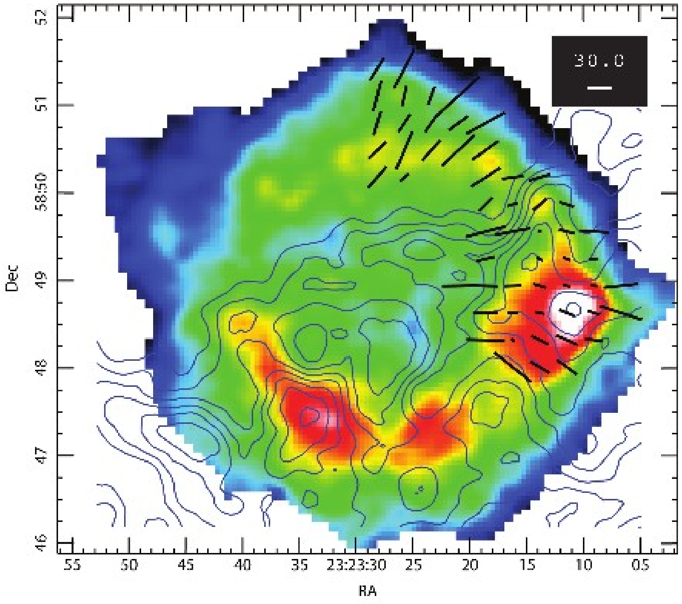
Chondrite interplanetary dust particles: Courtesy of E.K. Jessberger, Institut für Planetologie, Münster, Germany, and Don Brownlee, University of Washington, Seattle

But if dust is observed at redshifts >~ 6, there has been insufficient time (~1 Gyr) for onset of the AGB phase!

Supernova origin for high-redshift dust

Absorption-line quasar at z=6.2 shows extinction curve consistent with **10^{-4} Zsun Type II SN from a 25Msun progenitor** (Maiolino et al. 2004)





Observations of 850μm polarized emission in solar metallicity SNR Cas A support Type II SNe as dust factories (Dunne et al. 2003, 2009)

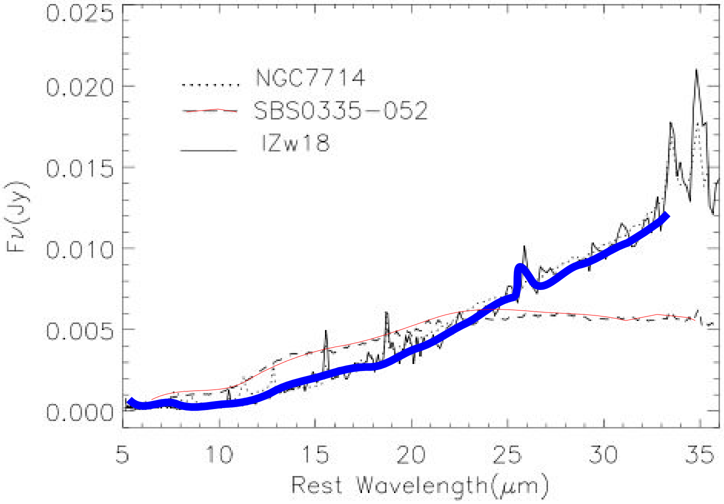
But still **CONTROVERSIAL!**

Metal-poor dust in the local universe

Most metal-deficient star-forming dwarfs in the local universe: >10^2-10^3 Msun in dust grains, 10^8-10^9 Lsun (Hunt et al. 2005, Wu et al. 2007).

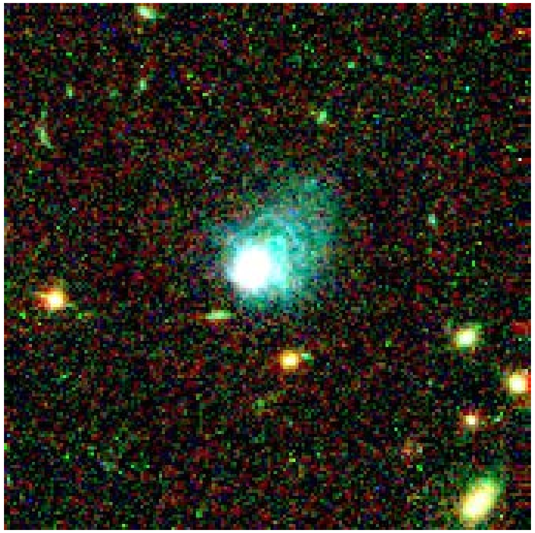
Consistent with Type II SN production!

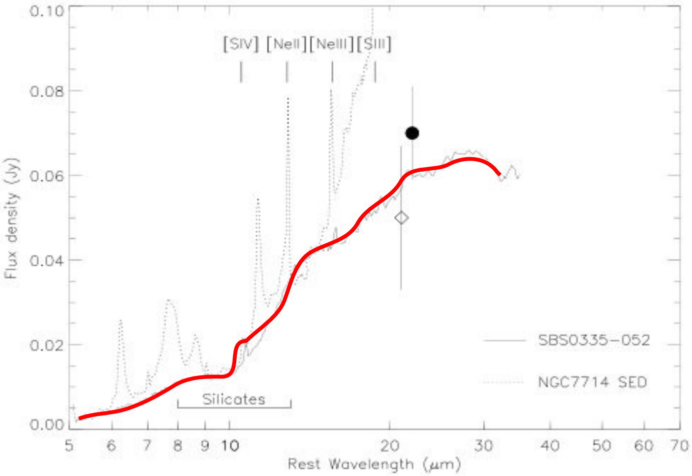
IZw18
12+logO/H=7.18 (1/30-1/50 Zsun)



Wu et al. 2007

SBS0335-052
12+logO/H=7.23 (1/24-1/40 Zsun)





Houck et al. 2004

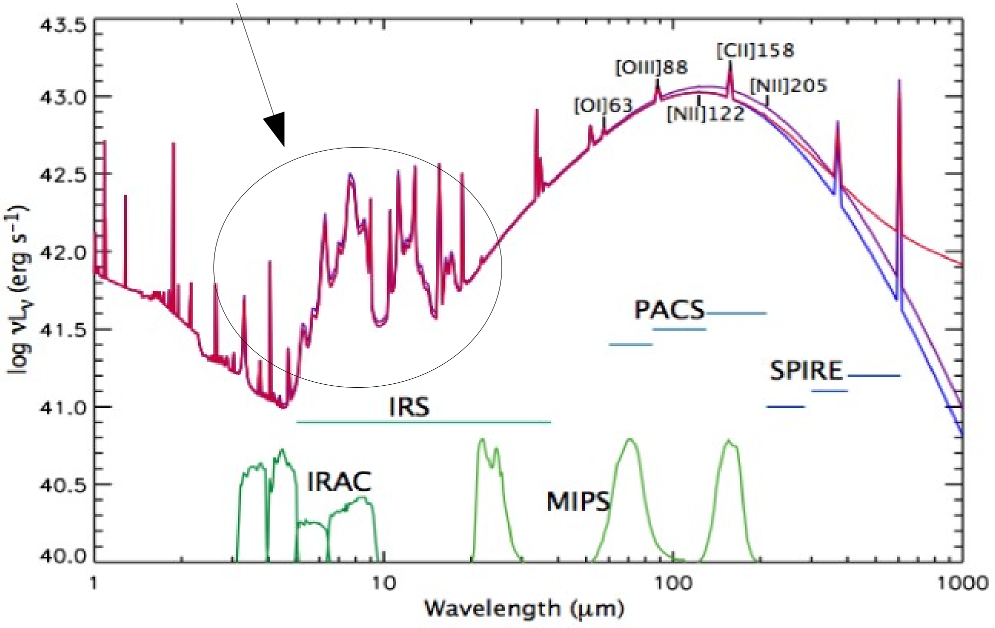
Not just continuum: IR spectral lines and features

Mid- and far-infrared fine structure lines

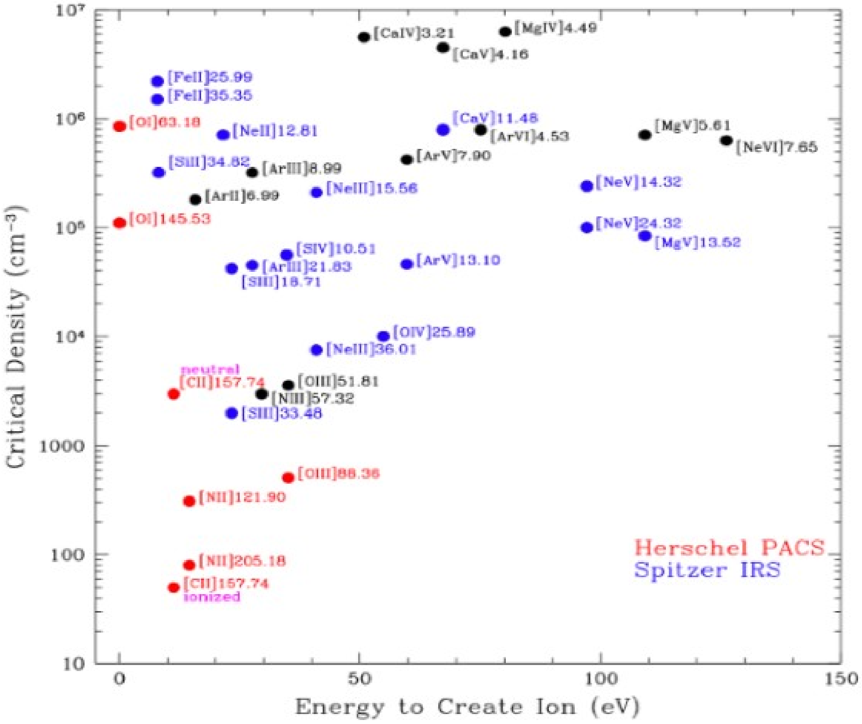
([SiII] 35 μm, [OI] 63μm, [CII] 158 μm, [NeIII] 15.6μm, [SIII] 18, 33 μm, [OIII] 52, 88 μm, [NII] 122, 205 μm) dominant cooling lines for neutral ISM gas in Photon Dominated Regions, and strong coolants for HII regions, respectively.

Rotational transitions of H_2 [S(0) 28μm, S(1) 17μm, S(2) 12μm, S(3) 9.7μm, S(4) 8μm, S(5) 6.9μm, S(6) 6.1μm, S(7) 5.5μm]

Aromatic Features in Emission = PAHs Essentially PDR tracers



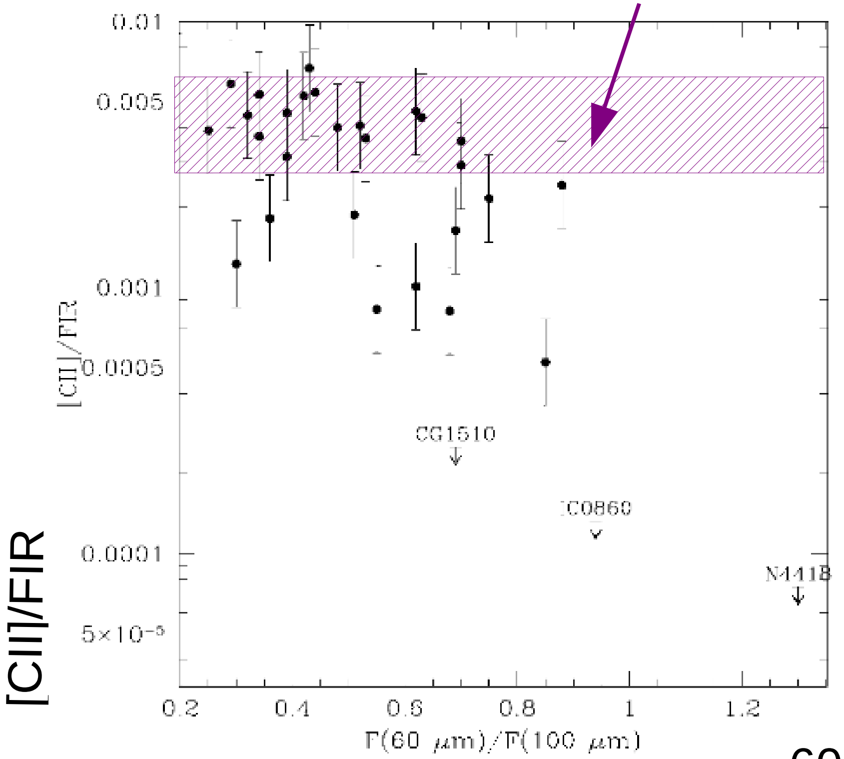
(Kennicutt et al. -KINGFISH- 2007)



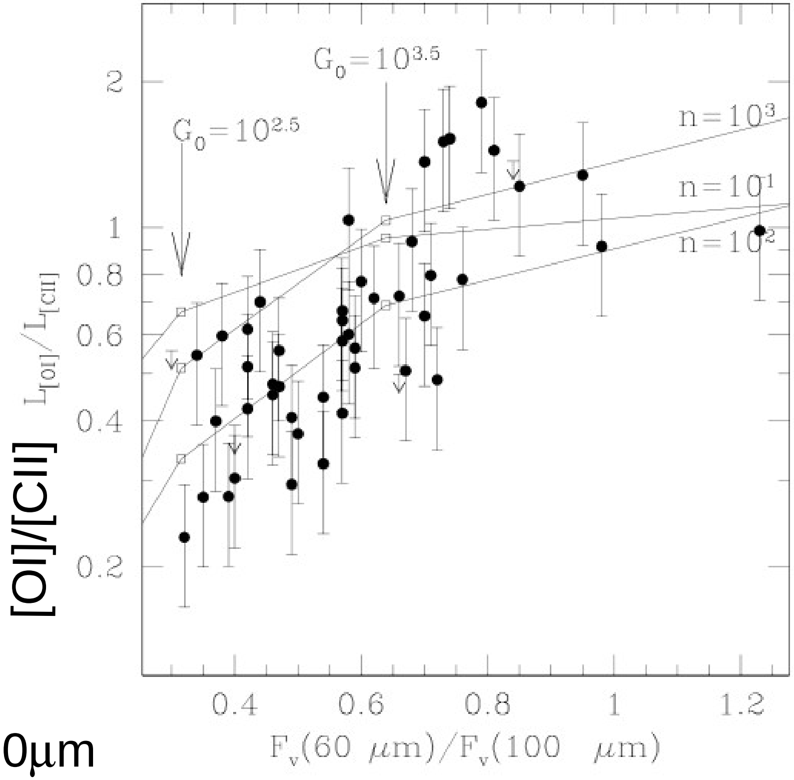
IR spectral lines: [CII] with ISO/LWS

[CII] 158µm line is > 1500 x more intense than ^{12}CO(1-0) in normal spirals, and > 6000 x more intense in starburst nuclei and Galactic starburst regions (Crawford etal. 1985, Stacey et al. 1991): ISO Normal Galaxy Key Project (Helou et al. 1996)

[CII]/FIR ~ 5x10^{-3}



PDR diagnostic (density, G$_0$)

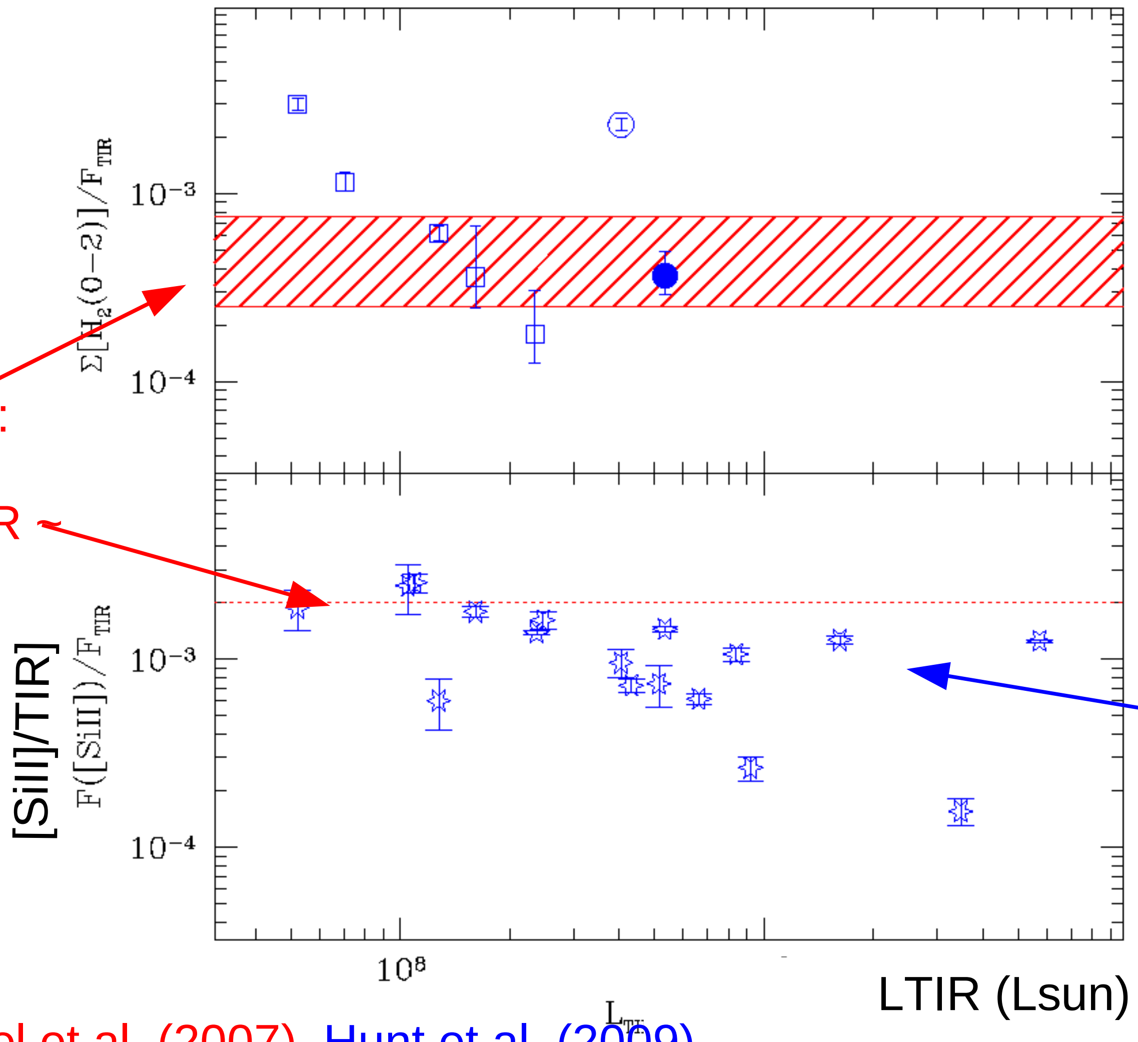


60/100µm

Malhotra et al. (1997, 2001)

IR spectral lines: [SiII] and H_2 with Spitzer/IRS

[SiII] 35µm line roughly half as intense (relative to FIR) as [CII], but still an important neutral ISM coolant, even at low metallicity.



SINGS galaxies:

[SiII]/TIR ~ $2x10^{-3}$

Rotational H_2 lines/TIR:
Important indicator of molecular gas in metal-poor dwarfs where CO not usually detected.
[see also next slide]

In metal-poor compact dwarf galaxies:

[SiII]/TIR ~ $7x10^{-4}$ - $2x10^{-3}$

Roussel et al. (2007), Hunt et al. (2009)

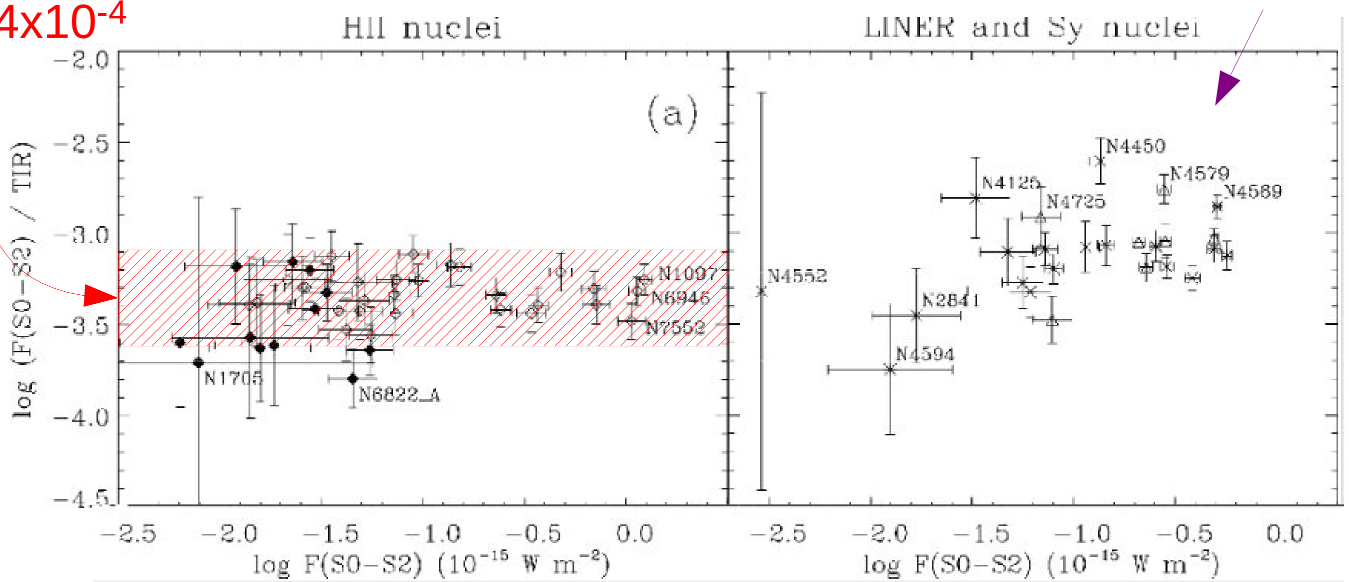
IR spectral lines: H_2 with Spitzer/IRS

Rotational transitions of H_2 (5-28 μm) trace warm gas with T ranging from 100 to ~1000K; one of the important coolants of warm molecular gas.

Better tracers of (warm) molecular mass than the NIR roto-vibrational lines: the latter need higher excitation (T>1000K) and because of higher critical densities, may not be thermalized, but rather excited by fluorescence.

AGN diagnostic

H2/TIR ~ 4x10^{-4}

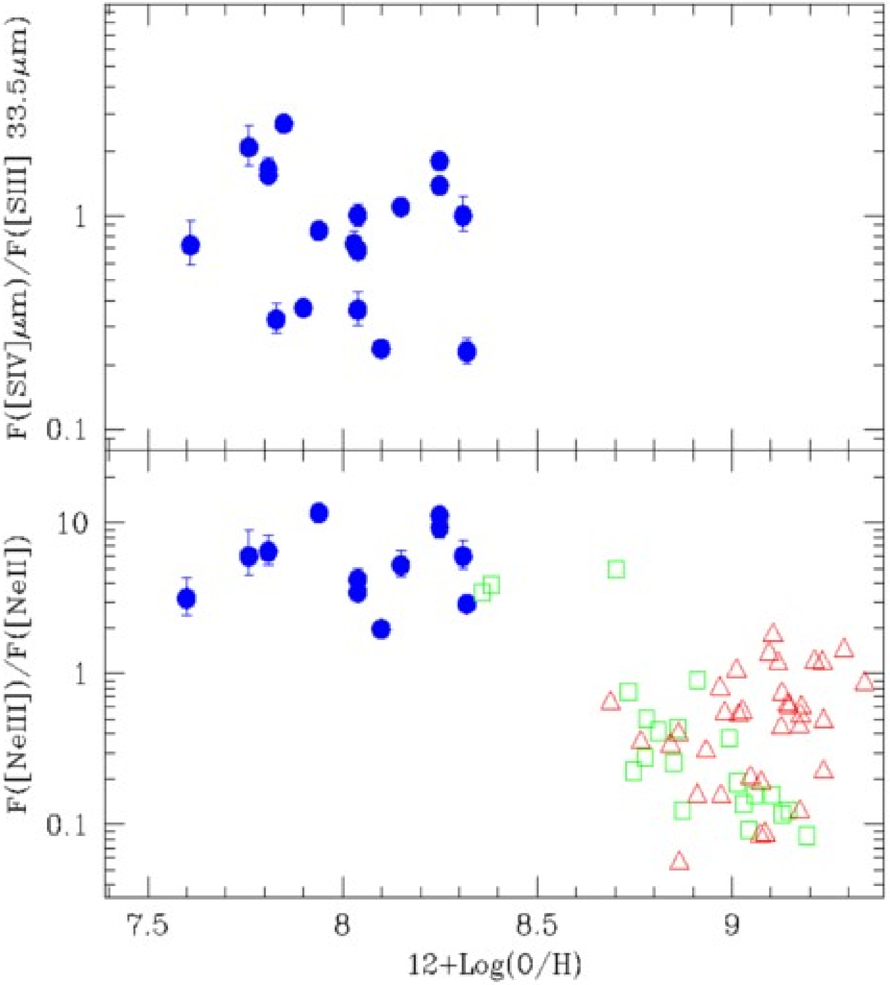


SINGS: Roussel et al. (2007)

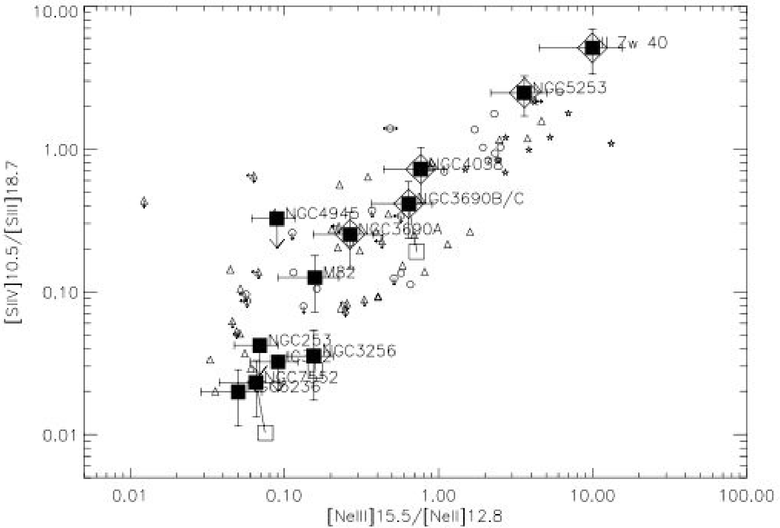
IR spectral lines: [NeII], [NeIII] , [SIII], [SIV]

Because of different ionization potentials (41 eV vs. 23.3 eV, 34.8 eV vs. 23.3 eV), [NeIII] 15.55µm/[NeII] 12.8µm and [SIV] 10.5µm /[SIII] 18.7, 33 µm trace excitation and hardness of the InterStellar Radiation Field (ISRF), but ratios “saturate” at low metallicity!

SINGS **galaxies**+**AGN**, **metal-poor compact dwarfs** (Dale et al. 2009, Hunt et al. 2009)



ISO starbursts (Verma et al. 2003)



[SIVI]/[SIII]

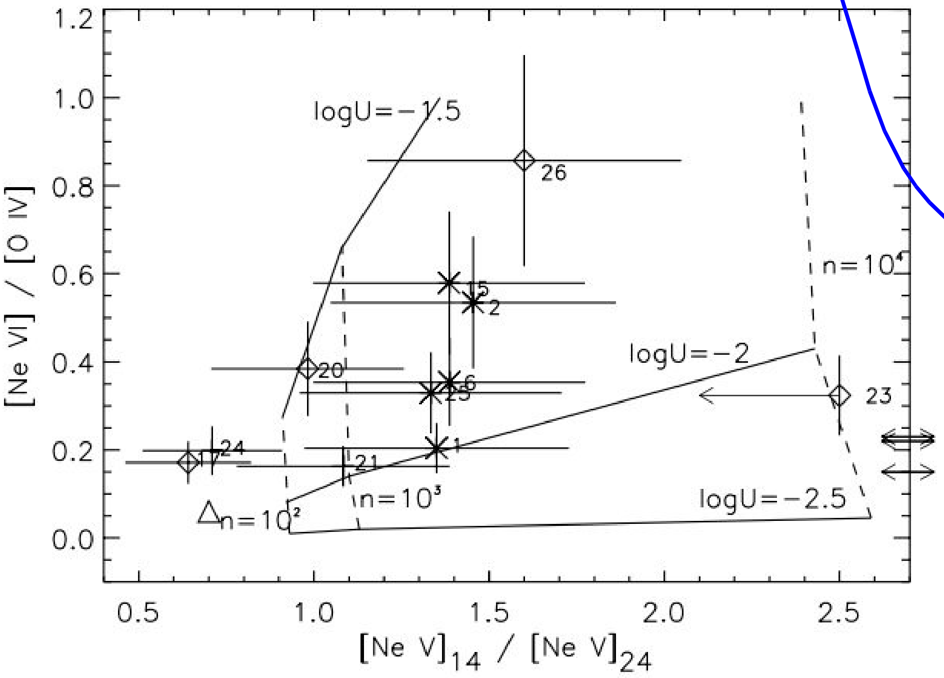
[NeIII]/[NeII]

IR spectral lines: [OIV], [NeV]

With ionization potentials of **54.9 eV ([OIV])** and **97 eV ([NeV])**, these lines trace ***hard ionizing radiation.***

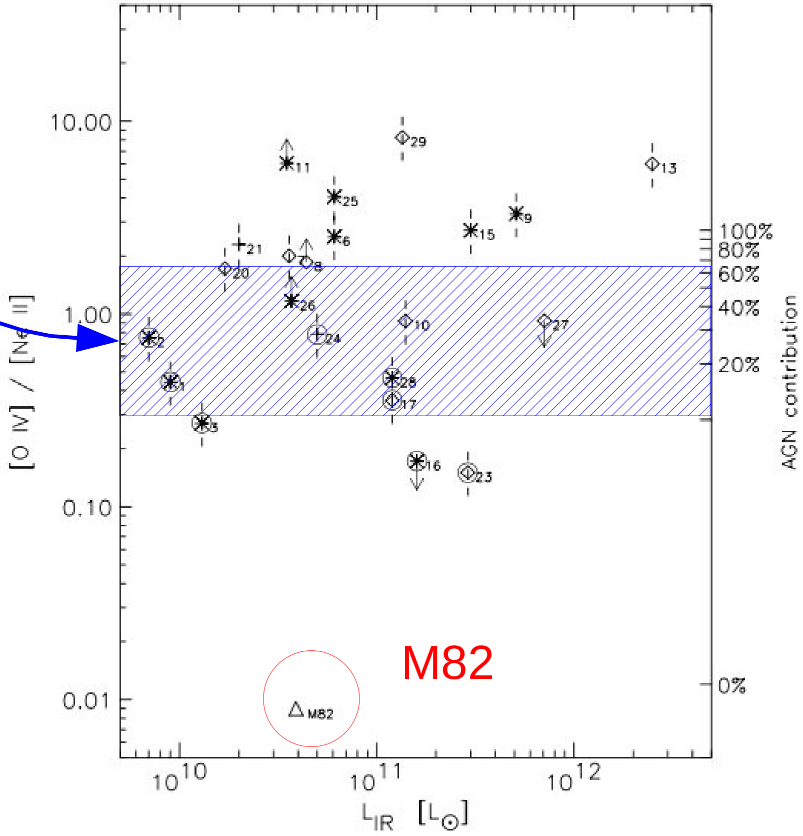
But *low metallicity star formation* mimics an AGN (for [OIV]).

ISO AGN (Sturm et al. 2002)



NLR diagnostic diagram, with model grids from Spinoglio et al. (2000)

AGN diagnostic

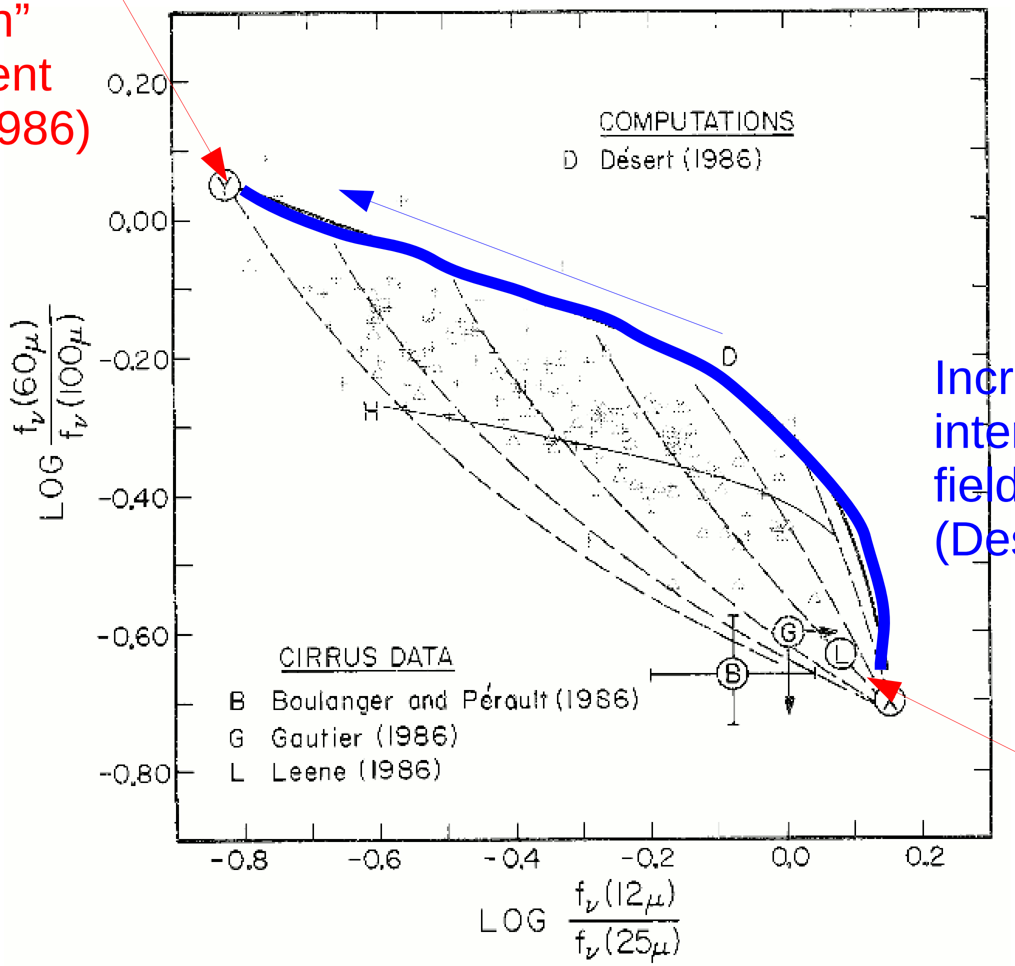


M82

IRAS revealed a new dust component: Aromatics

As 12/25 μm ratio in star-forming galaxies increases (quiescent “cirrus”, stochastically heated Aromatic Features in Emission), they get cooler at 60/100 μm, with a...

...predominant “active star formation” component (Helou 1986)



AFEs, or PAHs, are carbon-chain macromolecules/very small dust grains stochastically heated in a moderate UV field, such as in a PDR

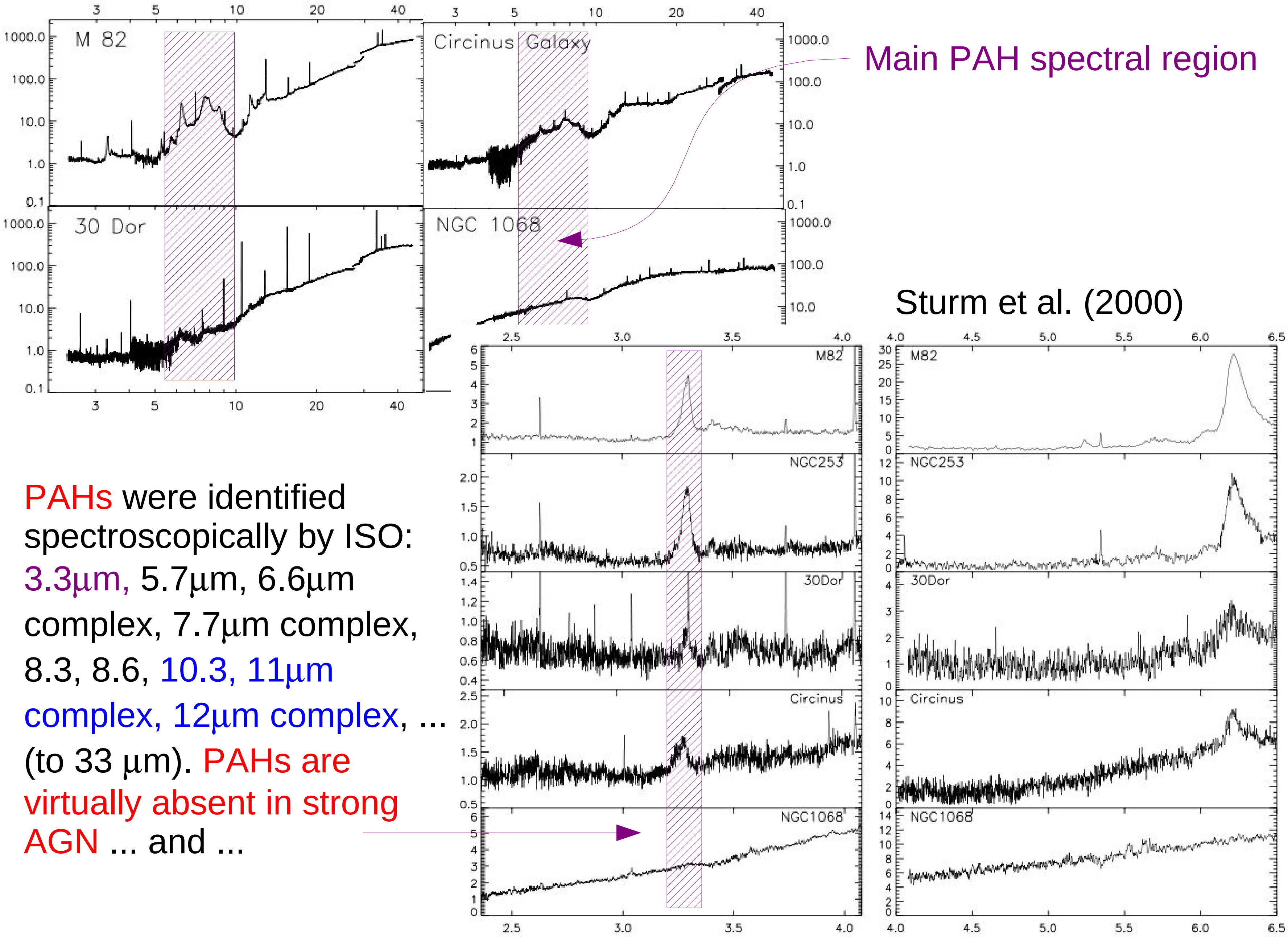
Increasing interstellar radiation field intensity (Desert 1986)

“Cirrus” component (IRAS 12 μm band)

ISO SWS spectra of star-forming regions and AGN

Flux (Jy)

IRAS 12 µm band



Main PAH spectral region

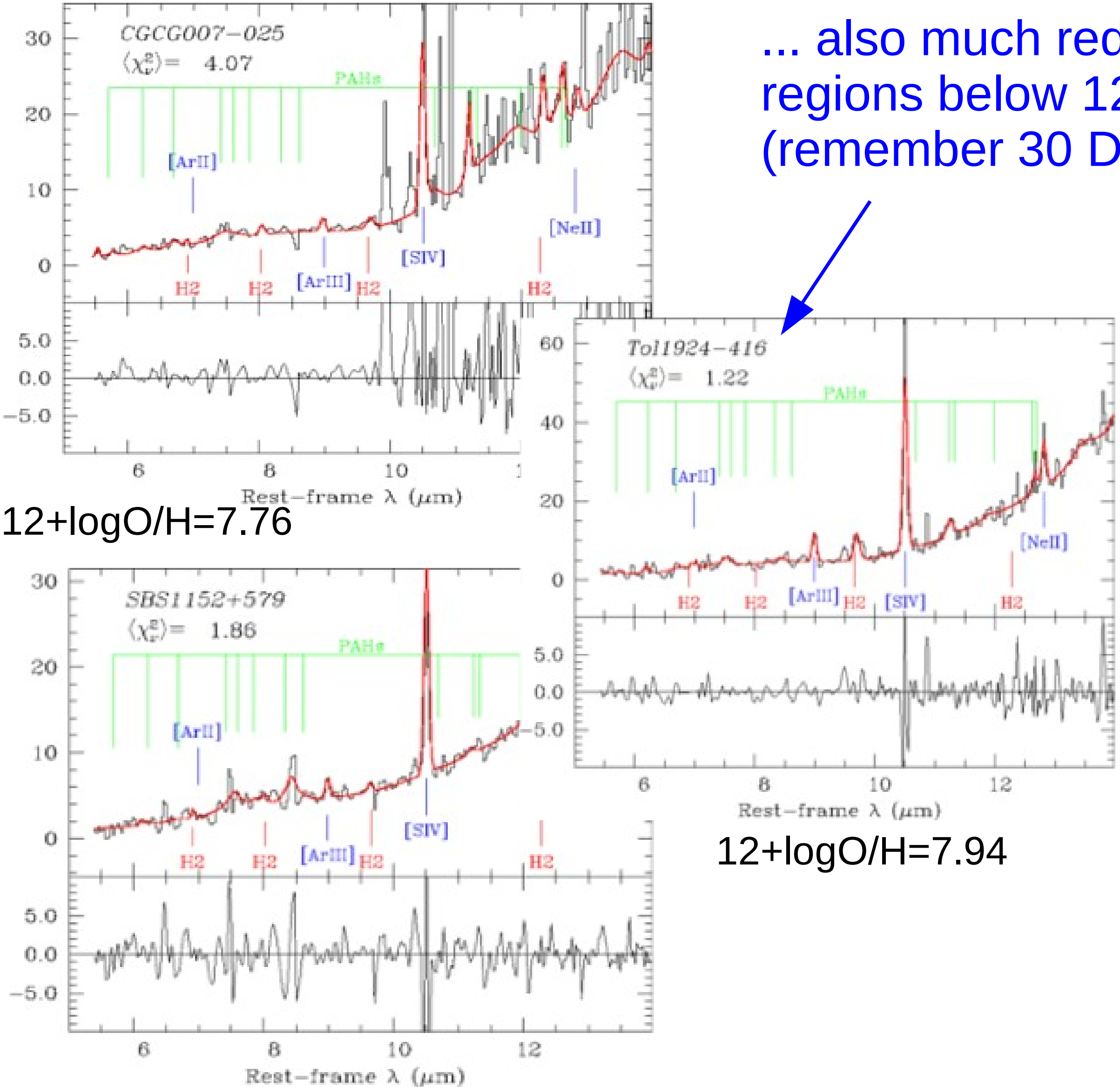
Sturm et al. (2000)

PAHs were identified spectroscopically by ISO: 3.3µm, 5.7µm, 6.6µm complex, 7.7µm complex, 8.3, 8.6, 10.3, 11µm complex, 12µm complex, ... (to 33 µm). PAHs are virtually absent in strong AGN ... and ...

Spitzer/IRS spectra of PAHs

Flux (mJy)

... also much reduced in star-forming regions below 12+logO/H ~ 8.1 (remember 30 Doradus?)...



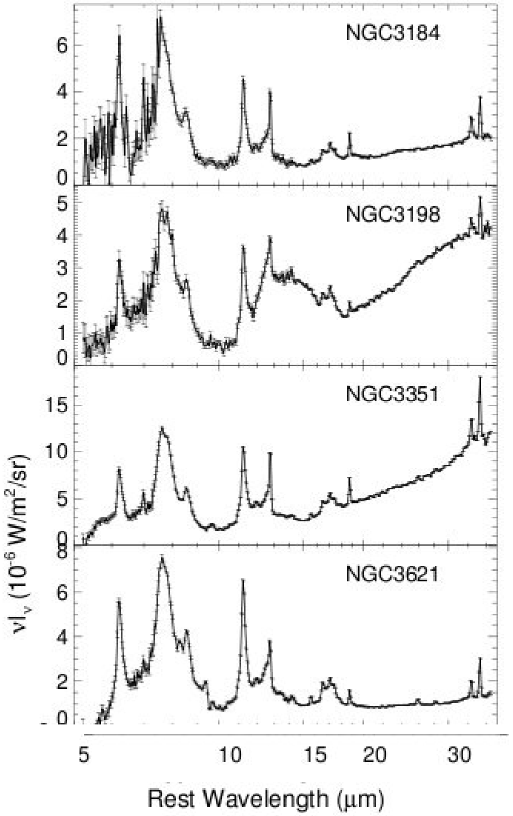
12+logO/H=7.76

12+logO/H=7.94

12+logO/H=7.85

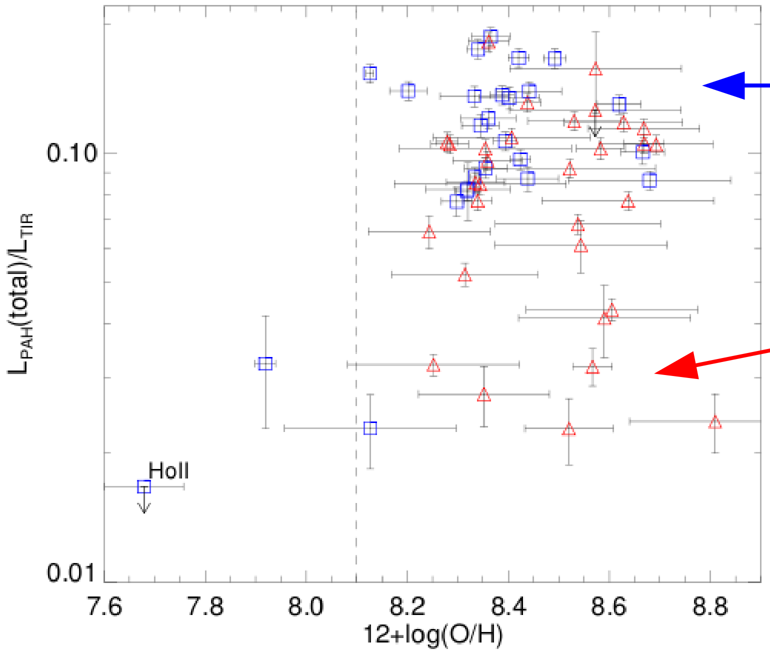
Hunt et al. (2009)

SINGS galaxies



Smith et al. (2007)

PAHs comprise about 10% of the total IR luminosity

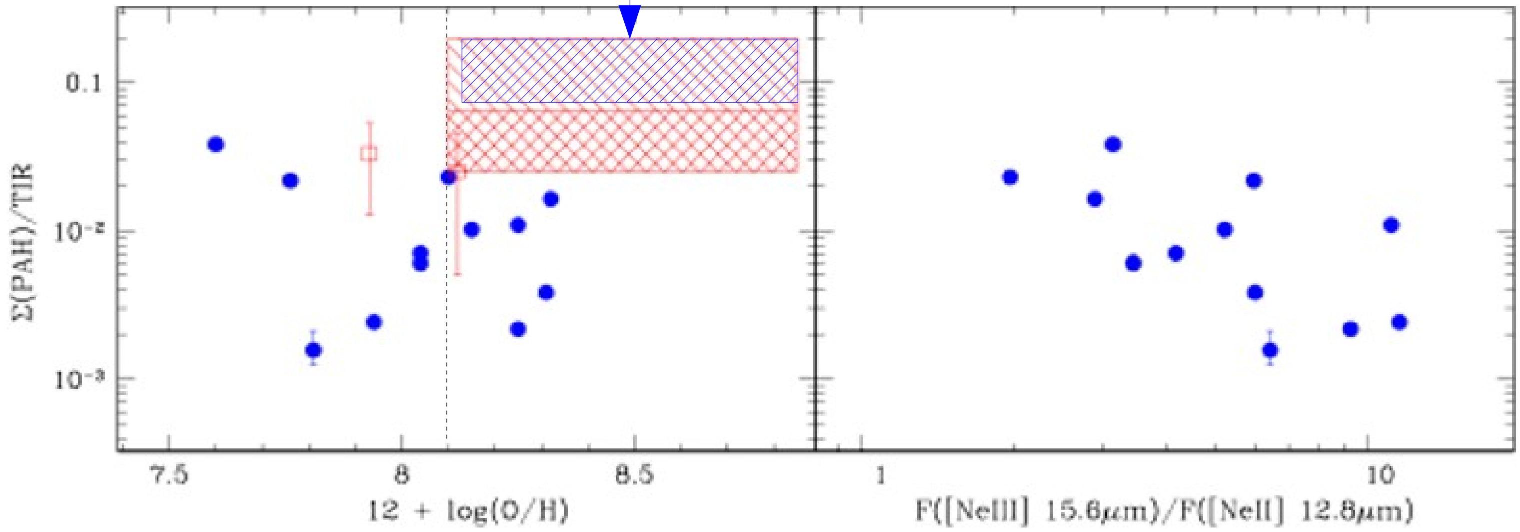


SINGS
Normal spirals

AGN

Roughly constant PAH/TIR enables luminosity estimates at high z!

In metal-poor compact dwarf galaxies: PAH component varies with ISRF hardness, not as well with O/H

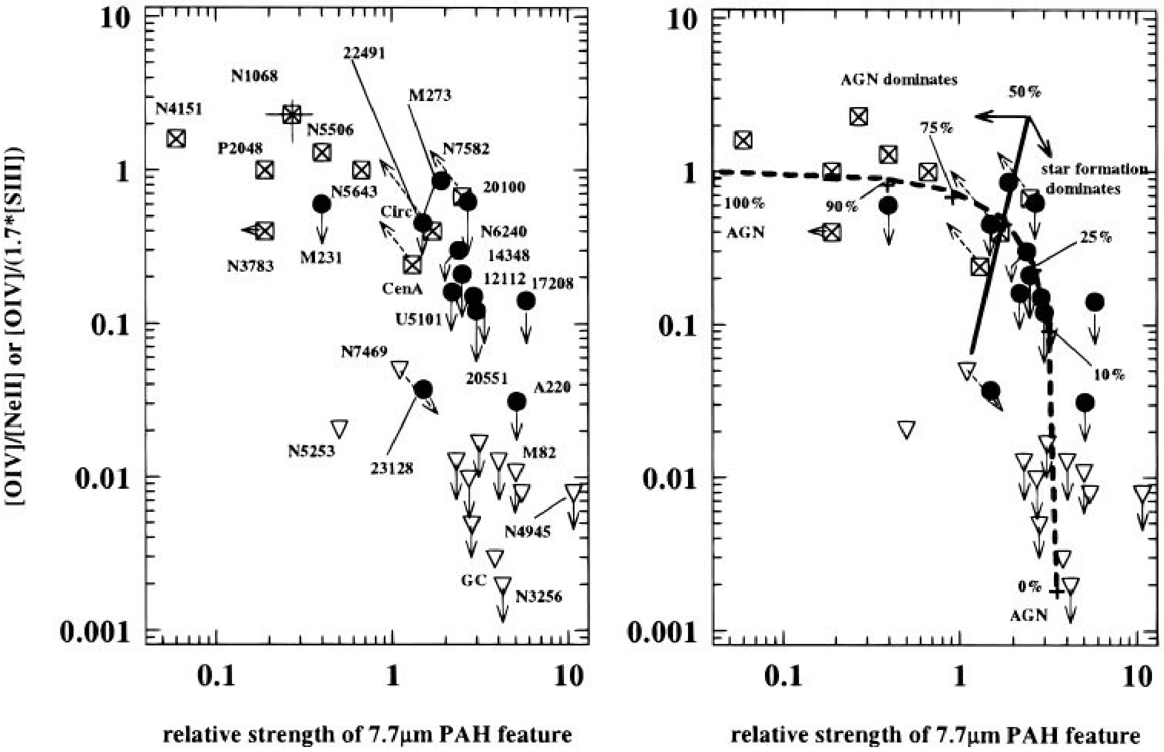


Smith et al. (2007), Hunt et al. (2009)

Mid-infrared diagnostics for ULIRG AGN (1)

Ubiquity of PAHs in starbursts (except for metal-poor ones) and the lack of them around an AGN has led to a plethora of AGN diagnostics.

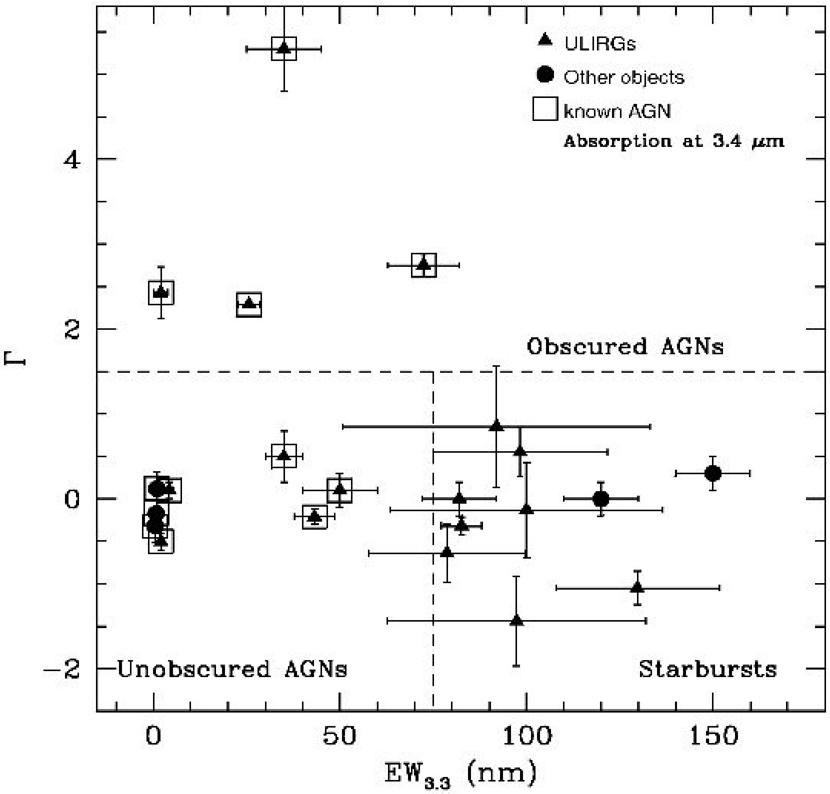
Combine high-excitation (coronal) line [OIV] with low-excitation one, e.g., [NeII] or [SiII], and compare to a strong PAH feature (e.g., 7.7μm)



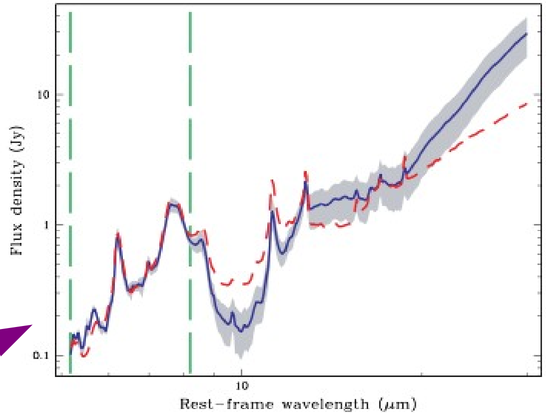
Genzel et al. (1998)

Mid-infrared diagnostics for ULIRG AGN (2)

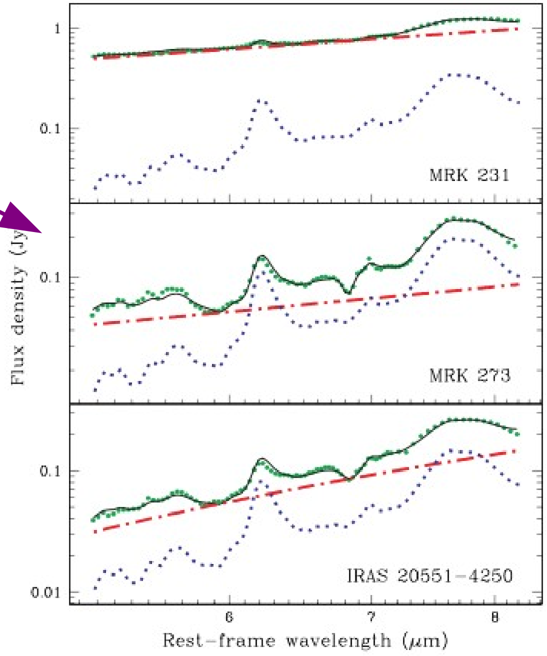
Compare 3-4µm continuum slope to 3.3µm PAH emission equivalent width (VLT/ISAAC)



6-9 µm range (Spitzer/IRS):



Model spectrum with a starburst template and a continuum (with some extinction) to decompose into AGN and starburst components



Risaliti et al. (2006), Sani et al. (2008), Nardini et al. (2008)

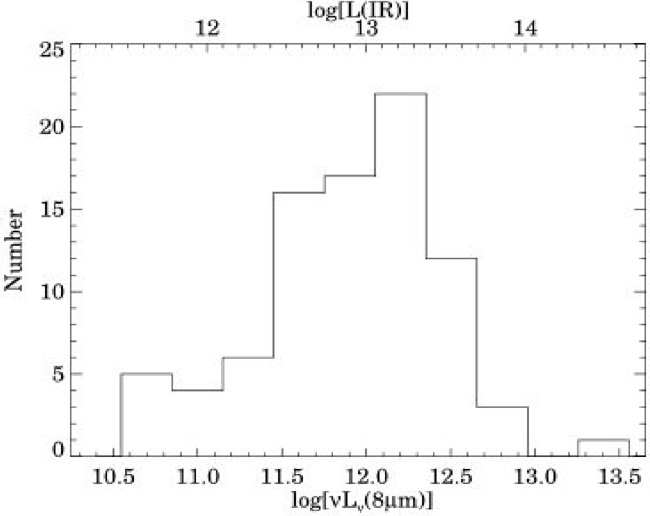
Spitzer and a census of the high-redshift universe

Because PAHs redshift into Spitzer/MIPS 24µm for z~2, deep fields (e.g., Boötes, GOODS, COSMOS, ...) observed in optical and at 24µm ***reveal new IR galaxy populations:***

F(R)/F(24µm) <~ 1000 (R >~ 24, F(24) ~ 1mJy)

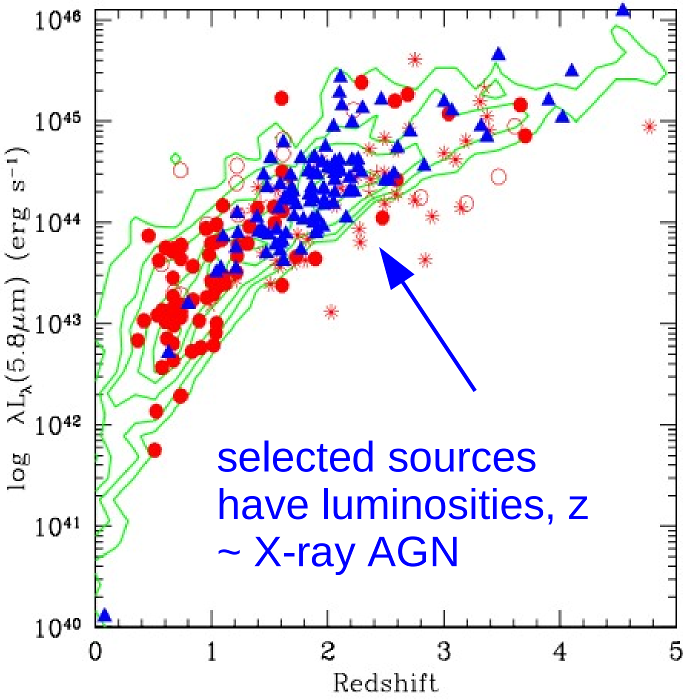
24µm flux limit to find ULIRGs OR red optical/NIR (R-K>~5) for AGN

Dusty Obscured Galaxies
(DOGs, Dey et al. 2008)



z~2, ULIRG-like, warmer dust than SMGs, may represent the AGN-growth phase, progenitors of massive present-day galaxies

Obscured Compton-Thick AGN
(Fiore et al. 2008) at z~2-3

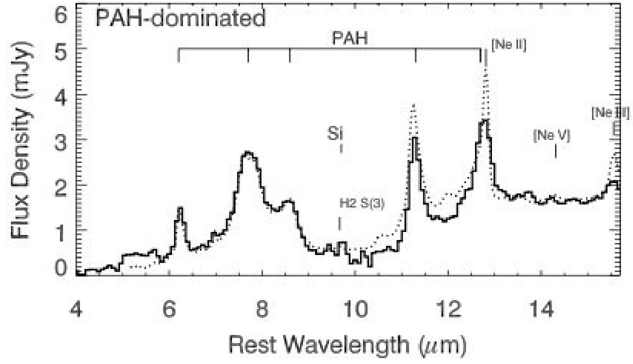


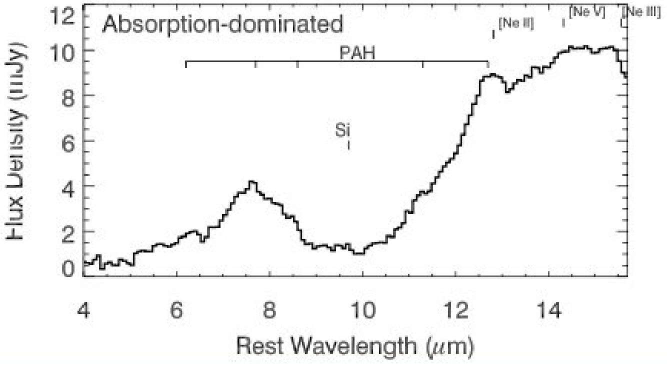
selected sources have luminosities, z ~ X-ray AGN

The redshift zoo

Boötes field observed in optical and at 24µm (>1mJy) and **70µm (>30mJy)** with Spitzer/MIPS, with relaxed F(R)/F(24µm) criterion (slightly less red):

ULIRGs with z <~ 1.3, PAHs 4-7x10^{11} Lsun (Brand et al. 2008)

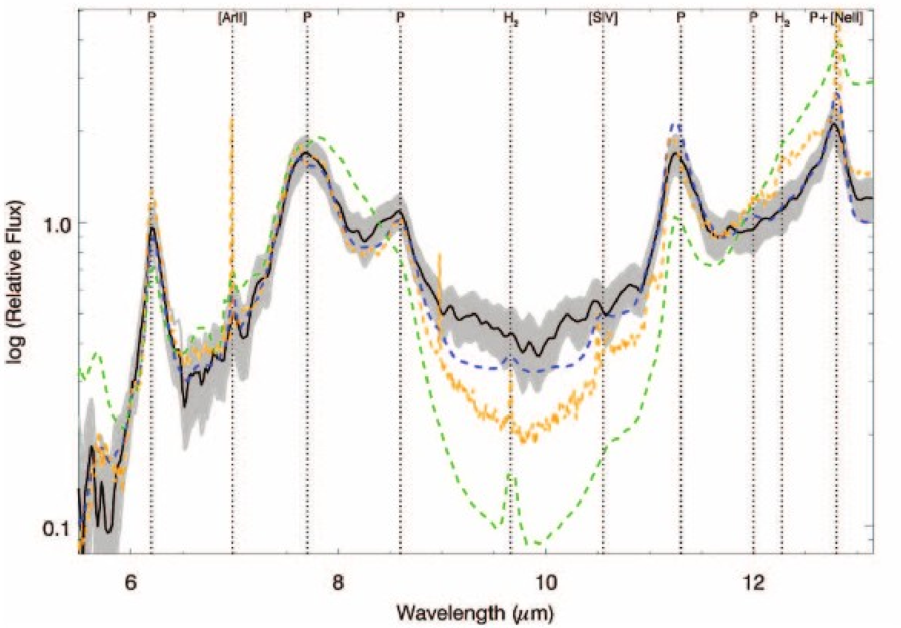




SWIRE field selected **via stellar photospheric bump** (Spitzer/IRAC) at 1.6µm, 24µm >0.5mJy with Spitzer/MIPS:

ULIRGs with z ~ 1.7, with TIR ~ $10^{13\text{-}14}$ Lsun (Farrah et al. 2008)

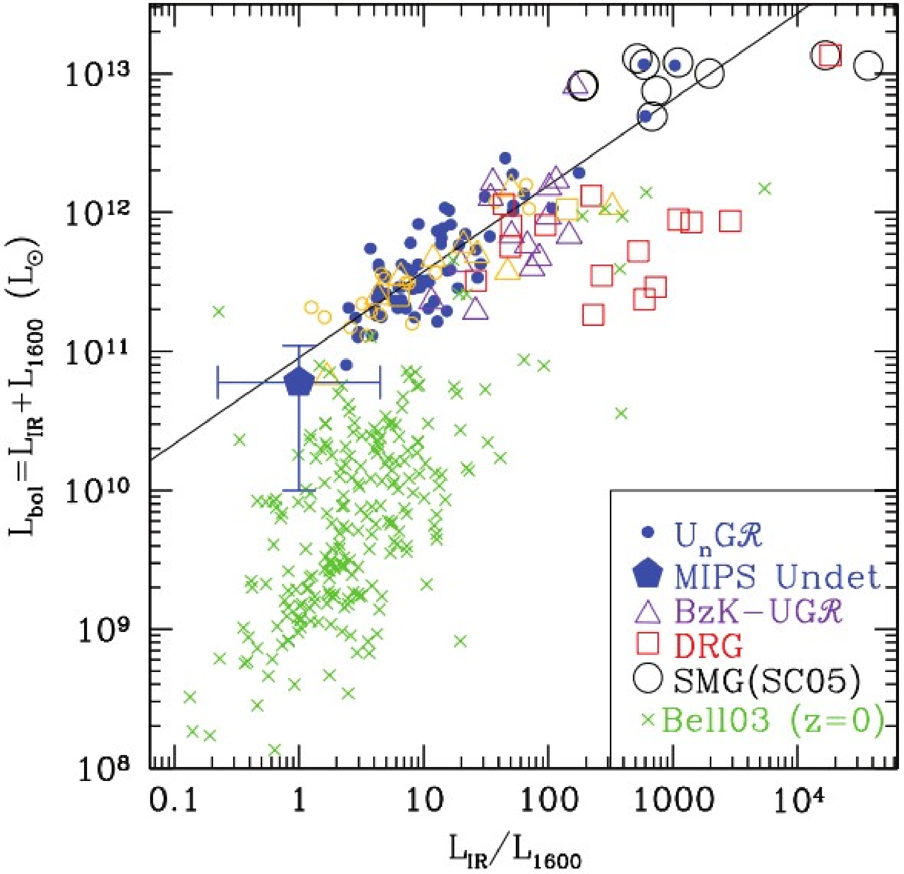
BUT with weak silicate absorption, more similar to local LIRGs (10^{11} Lsun) than ULIRGs (inevitably associated with strong PAHs and strong silicate absorption)



Dust obscuration, luminosity, and redshift

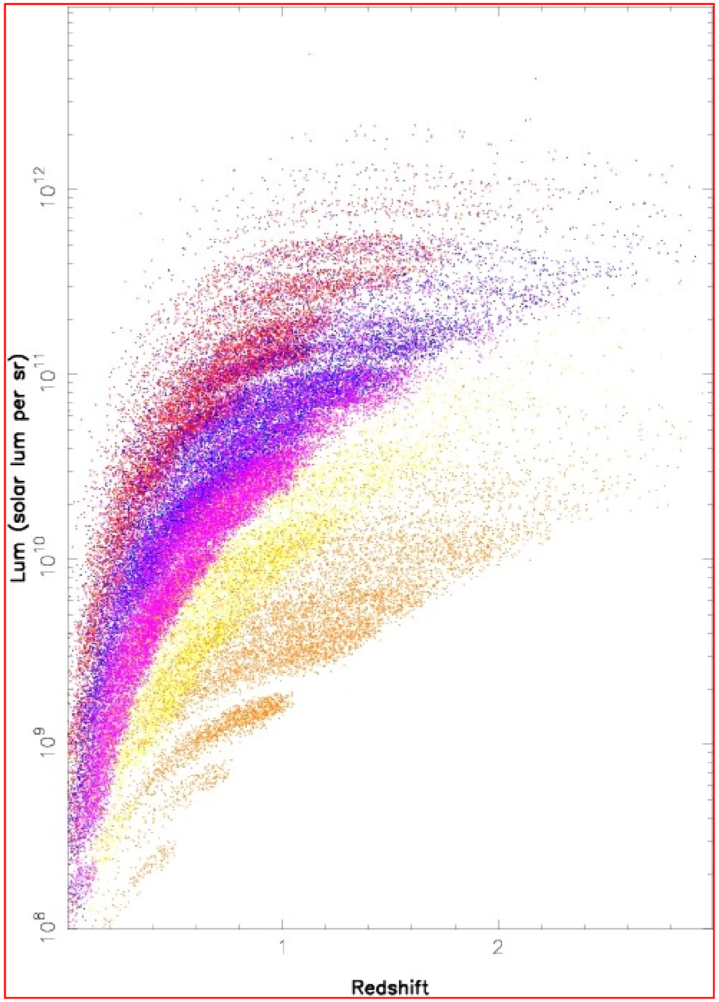
Reddy et al. (2006) uses MIPS 24 µm in GOODS fields for galaxies z~2 to estimate restframe 5-8.5µm luminosities and thus LIR (MIR/LIR constant to within a factor of 2 or 3).

Obscuration increases with luminosity but for a given bolometric luminosity is a factor of 8–10 reduced at z ~ 2 than at the present epoch (Reddy et al. 2006, see also Adelberger & Steidel 2000)



Although a larger fraction of star formation at high redshifts occurs in dustier systems, dust obscuration for a given Lbol has less of an impact on observations of high-redshift galaxies than expected from present-day extrapolation.

Future prospects with Herschel



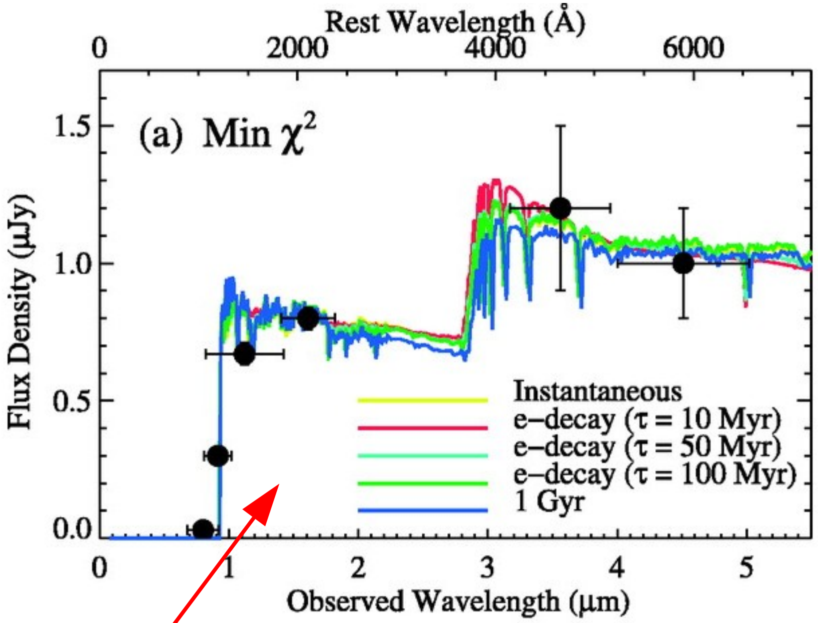
HERMES (Guaranteed Time):
PACS and **SPIRE** continuum survey
(PI Seb Oliver, 900 hrs)

Redshift-luminosity space probed in a 4-tier wedding cake survey. Yellow: 0.25 square degrees, 1.7 mJy 5σ threshold at 120 μm (PACS); red, blue, and magenta: 0.9, 9, and 90 square degrees, with 5σ thresholds of 10, 31, and 100 mJy at 250 μm (**SPIRE**). The **PACS** and first **SPIRE** surveys would be confusion-limited.

ISO could observe 10^{11} Lsun to z~1; **Spitzer** could observe 10^{11} Lsun to z~2.

Herschel will observe 10^{11} Lsun to z~3! to better constrain the bolometric luminosity of galaxies, and distentangle AGN and starburst components.

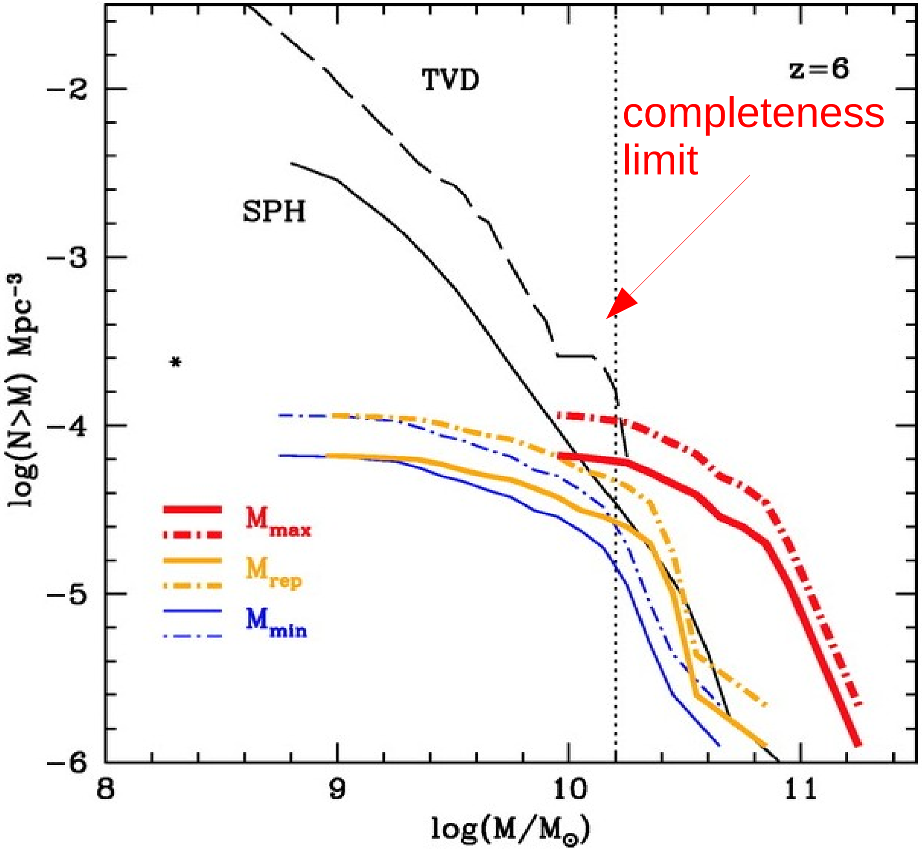
Mid-infrared constraints on galaxy formation epoch



Egami et al. (2005) used IRAC to detect a **galaxy at z~6.7**, lensed by a foreground cluster, and estimate a stellar mass of 10^9 Msun, and an age of at least 50Myr.

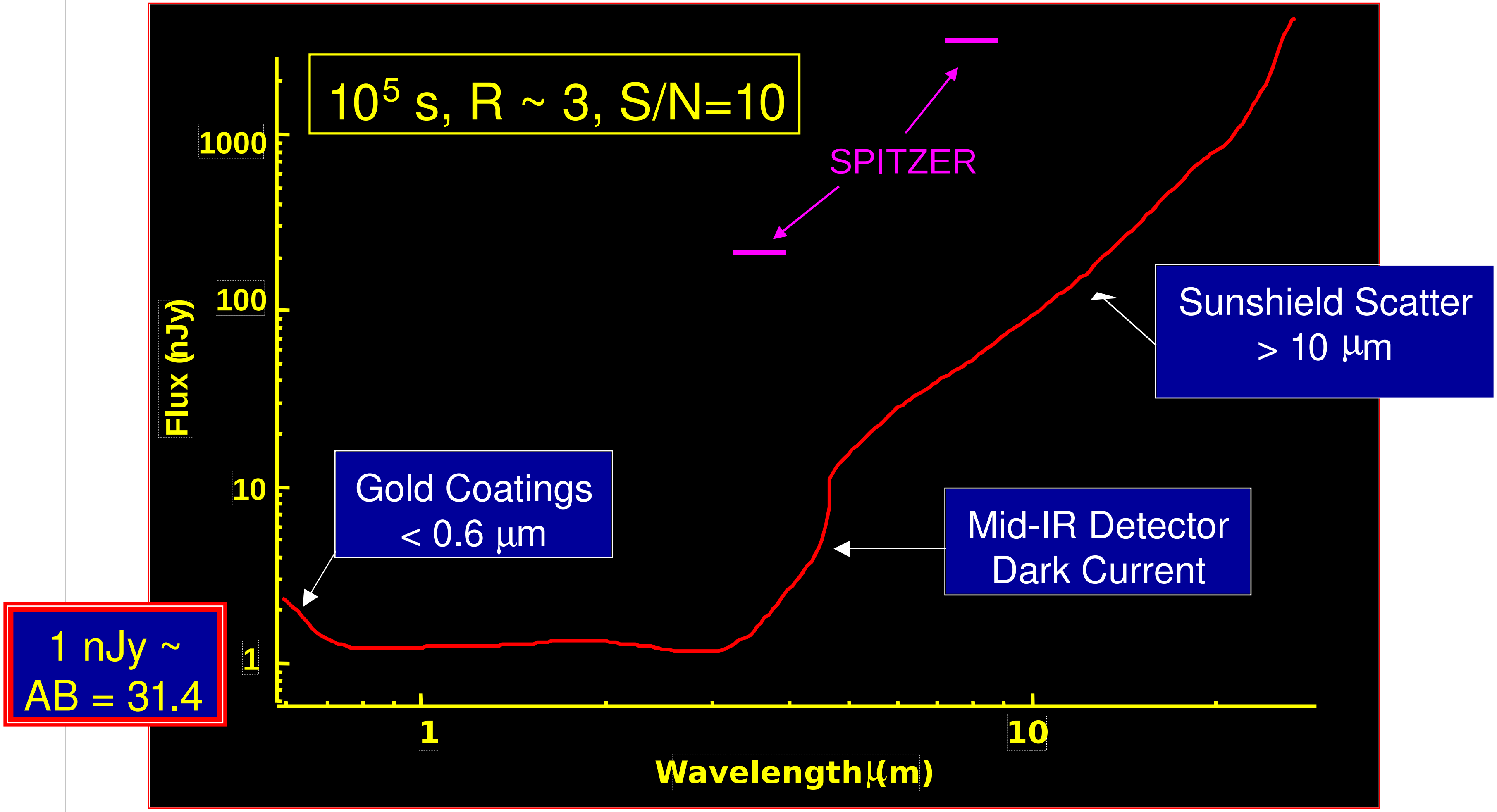
Yan et al. (2006) used IRAC to detect 53 i(775W) dropouts in GOODS fields; **mass locked up in stars at z~6** implies higher SFR prior to this epoch.

Spitzer/IRAC's sensitivity at 3.6 and 4.5μm enables detection of galaxies at z~6-7.



completeness limit

Looking toward the future with JWST



Courtesy: Roberto Maiolino

JWST/NIRCAM, MIRI will improve Spitzer/IRAC sensitivity by an order of magnitude, thus enabling a probe of galaxy ages and masses toward the epoch of reionization.

Dust obscures the most powerful starbursts...

"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

Thank you...