Radiative transfer models for infrared emission from starbursts and AGN

- ingredients for radiative transfer models for ir sources
- cirrus models for local quiescent galaxies
- models for starbursts, ULIRGs
- models for AGN dust tori, HLIRGs
- applications to Spitzer galaxies, submm galaxies
- what powers AGN ? - IRS spectra and their interpretation

ingredients for models for spectral energy distributions of infrared sources

• model for interstellar grains [Mathis et al 1977, Draine and Lee 1984, Rowan-Robinson 1992, Desert et al 1990, Siebenmorgen and Krugel 1992, Dwek 1998]

• assumed density distribution for dust [$\rho \sim r^{-\beta}$, HII region physics (Yorke 1977, Efstathiou et al 2000)]

• dust geometry [spherically symmetric, axisymmetric (Efstathiou and RR 1990, 1991, 1995, Pier and Krolik 1992, Granato et al 1994, 1997, Silva et al 1998), clumpy (Rowan-Robinson 1995, Hoenig et al 2006)]

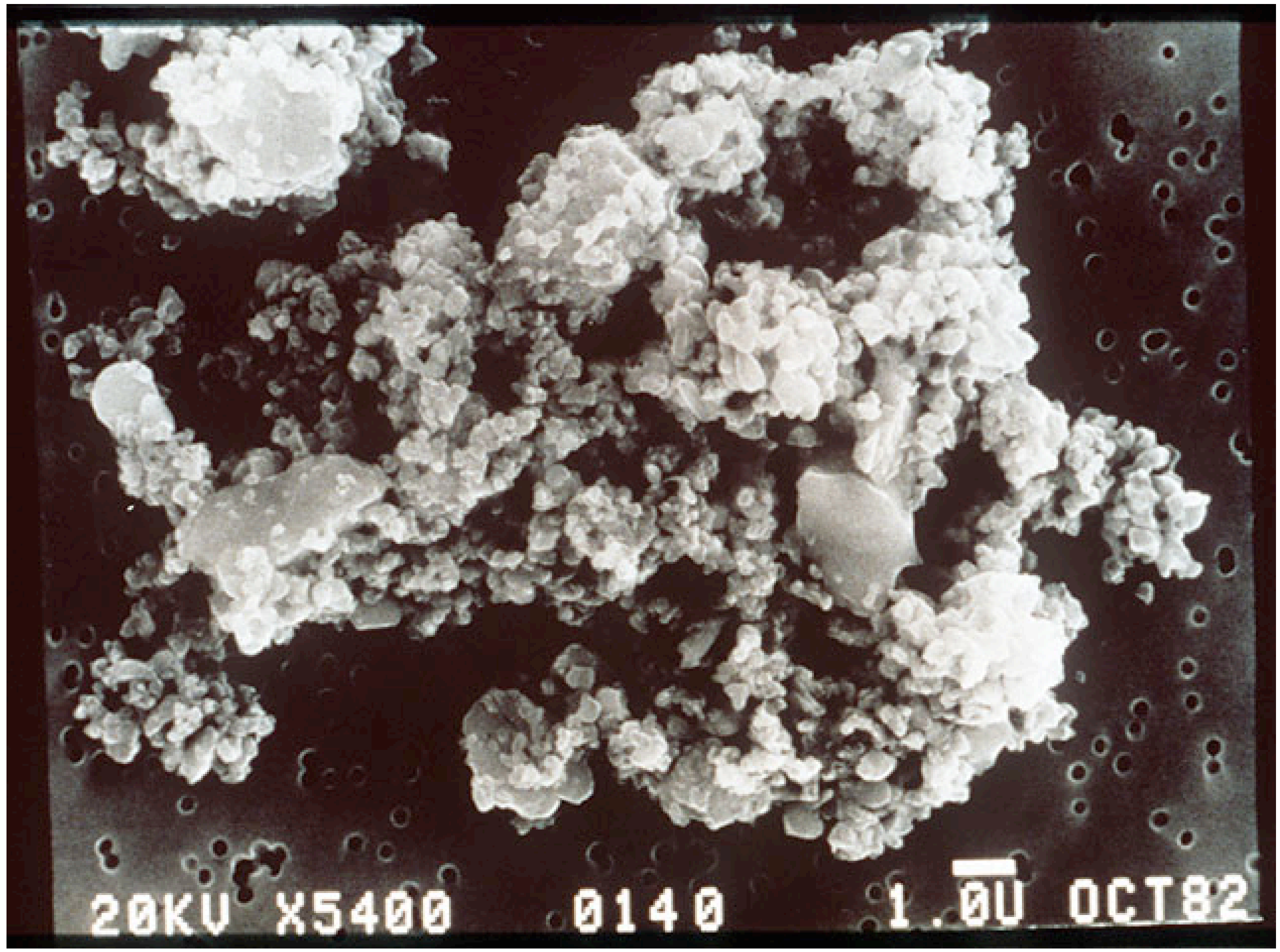
• radiative transfer code [Rowan-Robinson 1980, Efstathiou & RR 1990, Pier and Krolik 1992, Krugel and Siebenmorgen 1994, Granato et al 1997, Silva et al 1998, Popescu et al 2000, Hoenig et al 2006, Xilouris]

interstellar dust grains

size 50 A - 0.1 μm
(and larger ?)

composition:

amorphous C
graphite
amorphous silicates
crystalline silicates
SiC
PAHs



Brownlee particle

discovery of PAHs

Leger and Puget, 1984,
AA 137, L5

Astron. Astrophys. 137, L5–L8 (1984)

ASTRONOMY AND ASTROPHYSICS

Letter to the Editor

Identification of the "unidentified IR emission features of interstellar dust?

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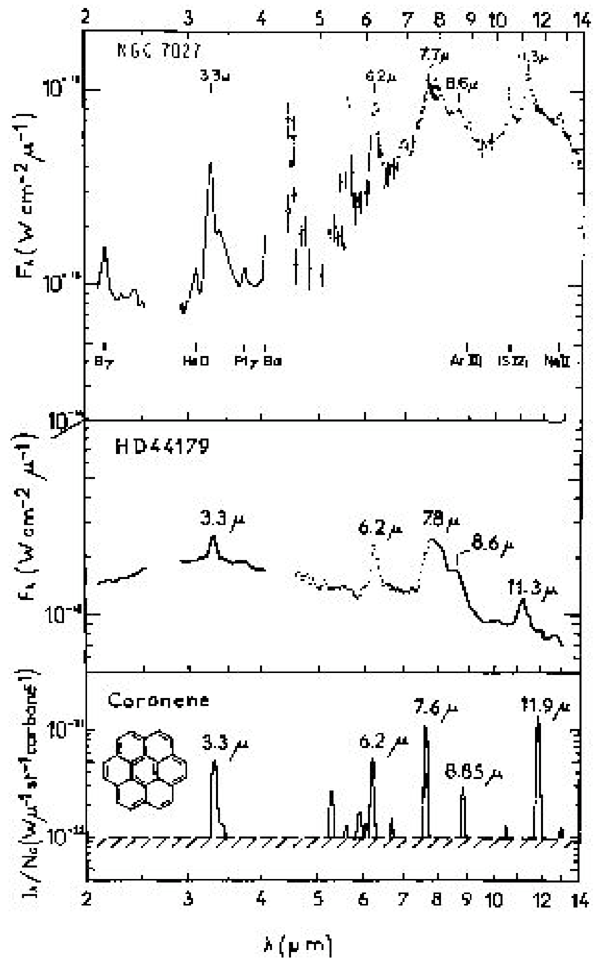


the radiative transfer equation

The intensity of radiation $I_\nu(\mathbf{r},\theta)$ satisfies the equation

$$dI_\nu/ds = - n(r)\, C_{\nu,ext}\, I_\nu + n(r)\, C_{\nu,abs}\, B_\nu\, [T(r)] + n(r) \int_{4\pi} C_{\nu,sc}\, (\theta')\, I_\nu\, (\theta')\, d\omega/4\pi$$

where $C_{\nu,abs} = \pi a^2\, Q_{\nu,abs}$,

$$C_{\nu,sc} = \pi a^2\, Q_{\nu,sc}\, \zeta(\theta')$$

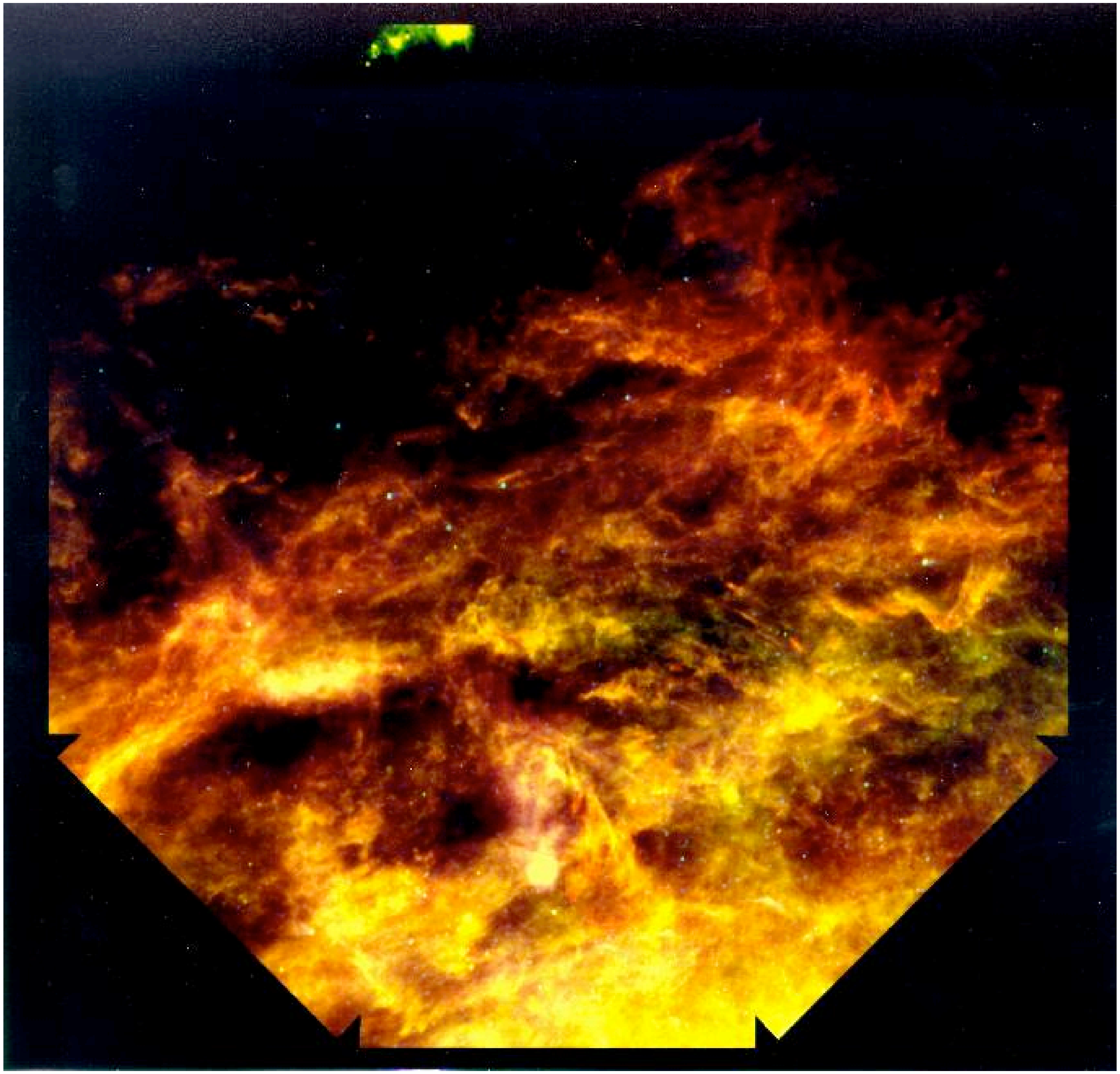
$$C_{\nu,ext} = C_{\nu,abs} + \int_{4\pi} C_{\nu,sc}\, (\theta')\, d\omega/4\pi$$

Radiative transfer models for infrared sources

- spherically symmetric dust clouds
  - first accurate code 1980 (R-R, ApJS 234, 111)
    - circumstellar dust shells 1981-3
    - starbursts and ULIRGs (RRE, 1993, MN 263, 675; ERRS, 2000)
    - cirrus galaxies (ERR, 2003)

- axially symmetric dust clouds
  - first accurate code 1990 (Efstathiou and R-R, MN 245, 275)
    - protostars 1991
    - AGN dust tori 1995

IRAS - cirrus



south celestial pole

Cirrus models for local galaxies

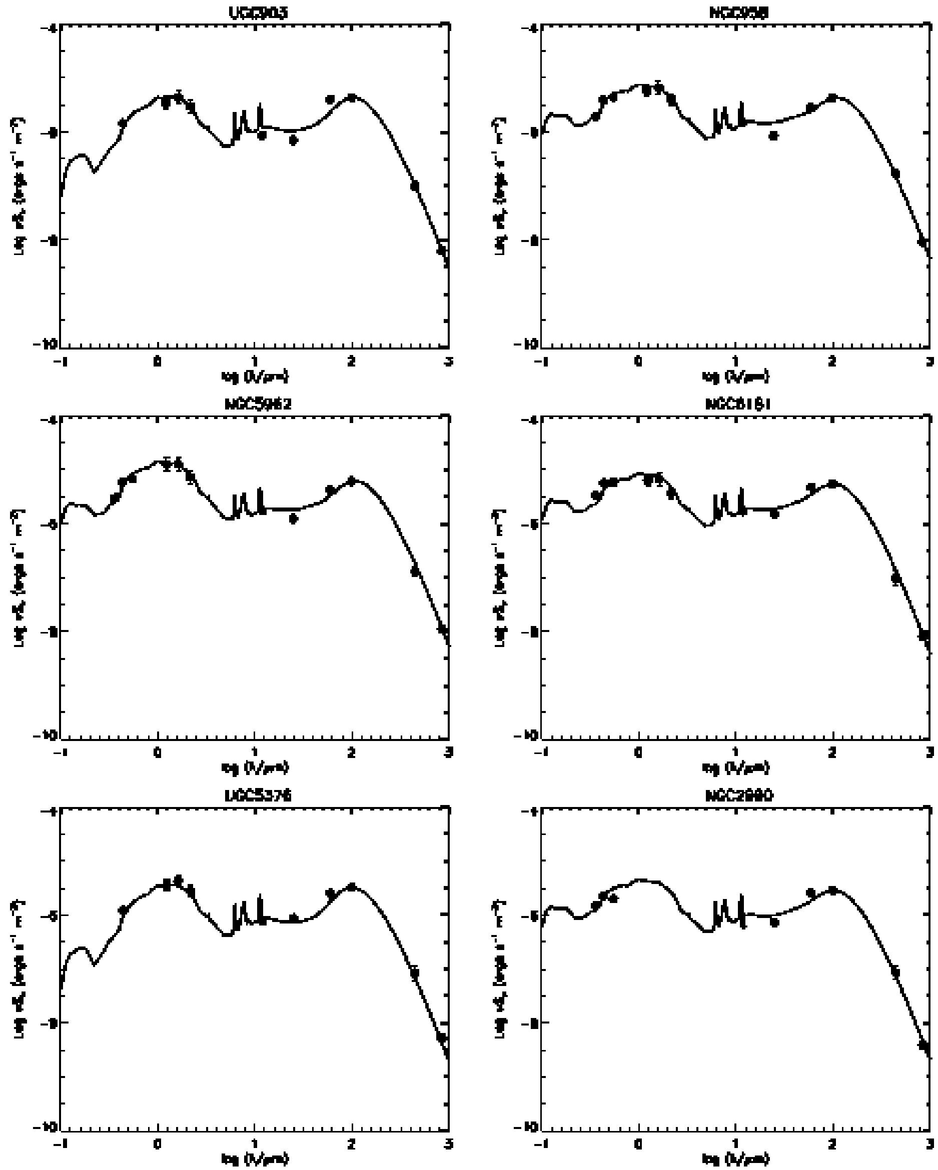
• assume optically thin ism, extinction A_V (<1, 0.4-0.9)

• Bruzual & Charlot starburst models, age t_*, exponential decay time τ

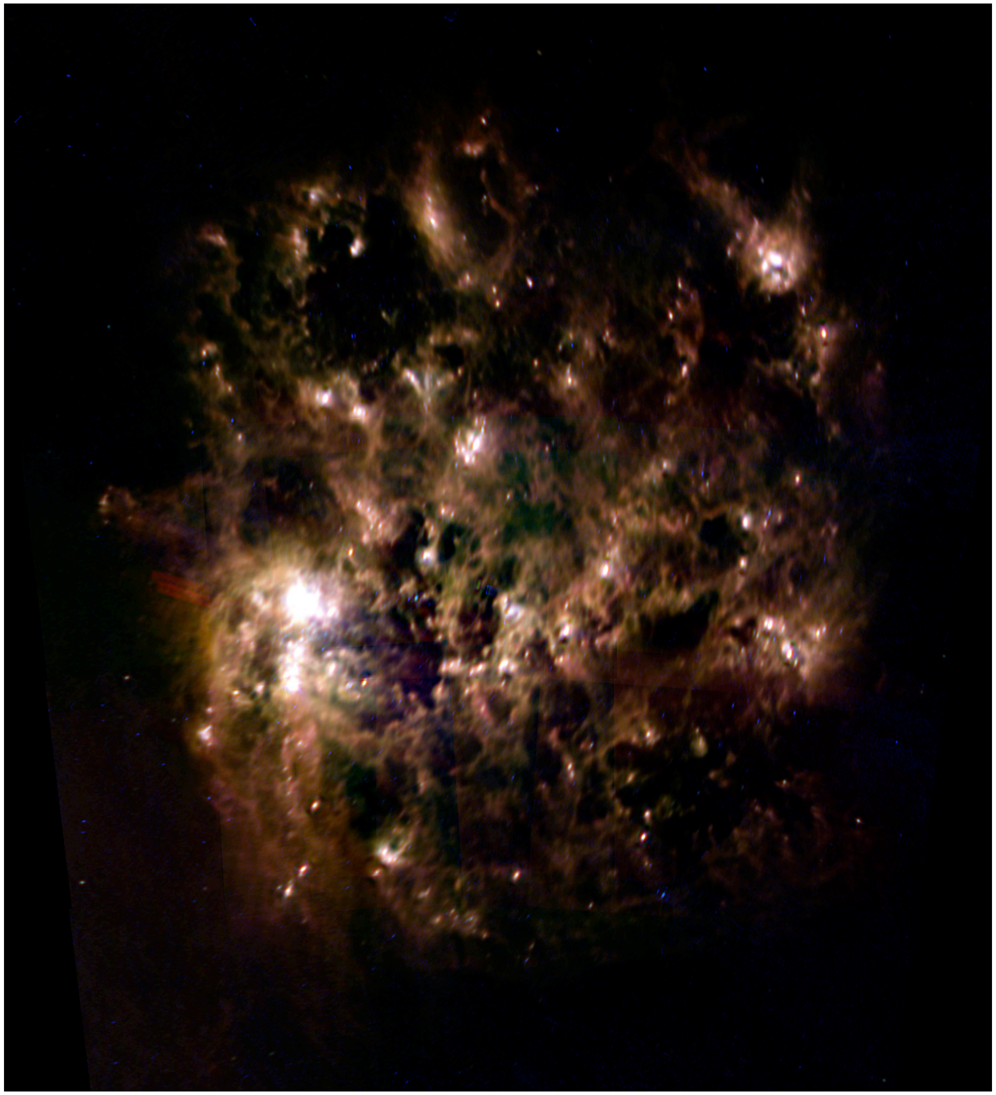
• characterise galaxies by single mean intensity, ψ = bolometric intensity/solar neighbourhood intensity (~2-5)

• for local galaxies, t_* = 0.25 Gyr, τ = 5-11 Gyr

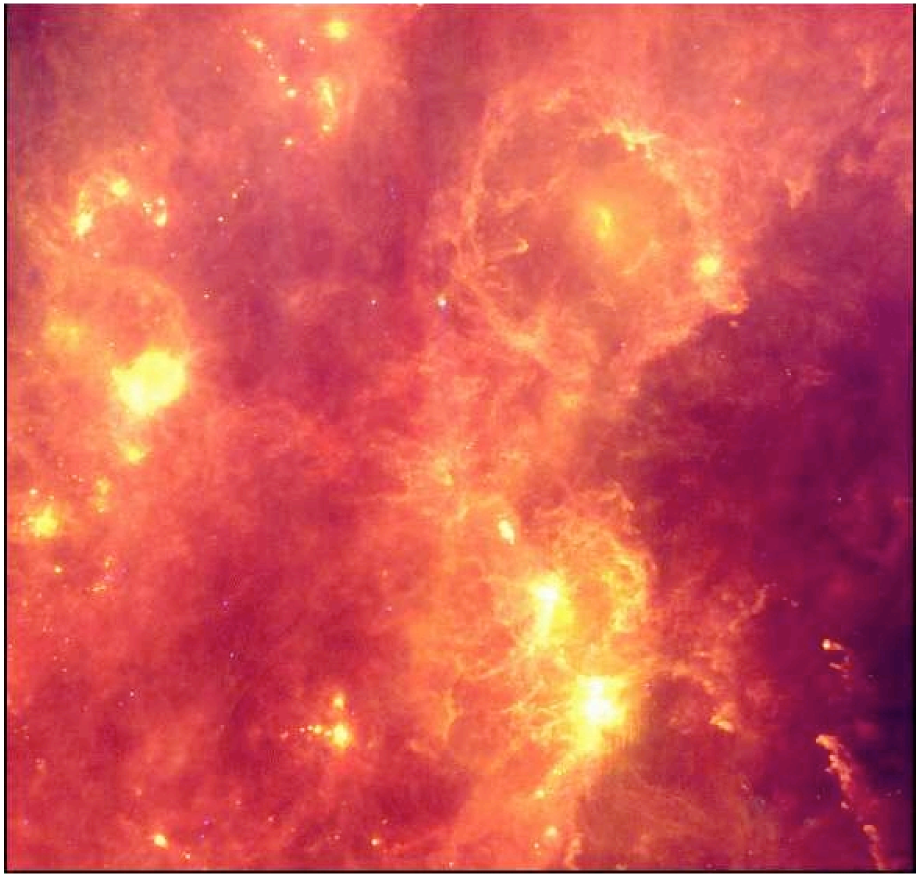
(Efstathiou and Rowan-Robinson 2003, MN 343, 322)



IRAS - star forming regions



LMC

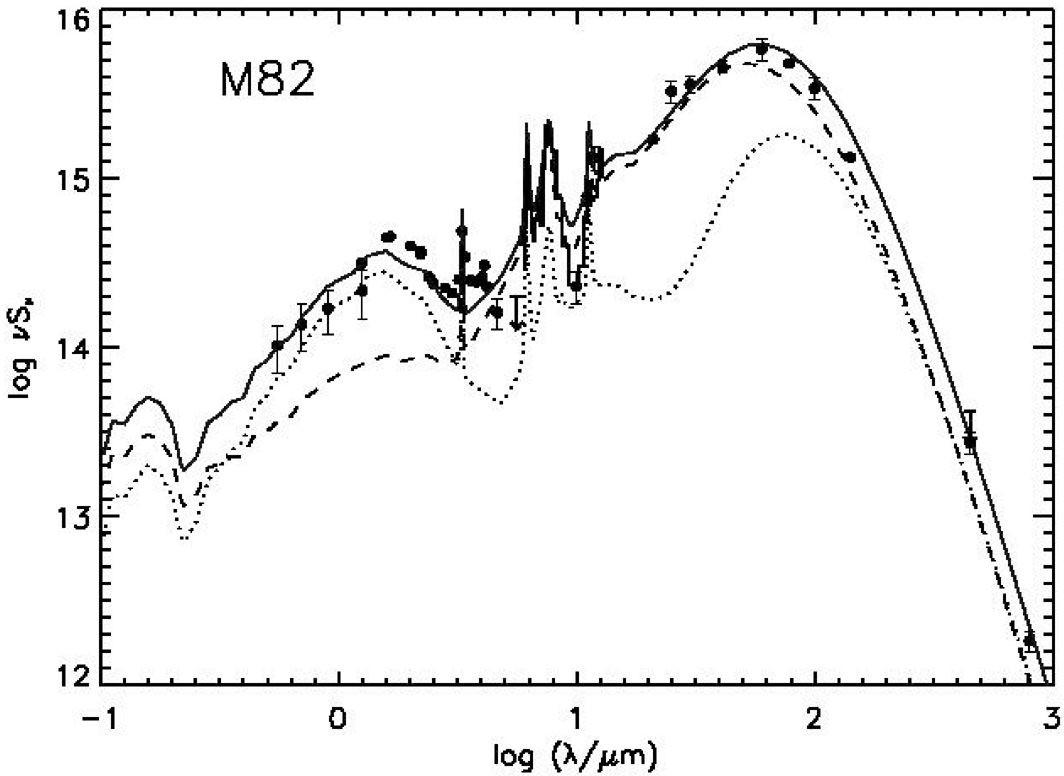


constellation Orion

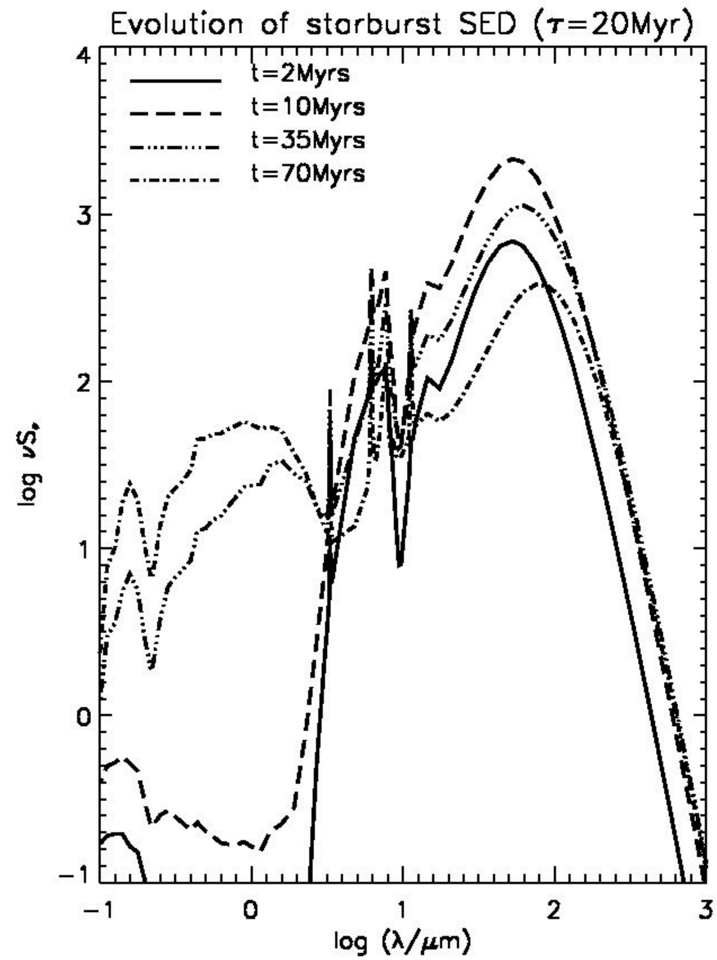
Models for starburst galaxies

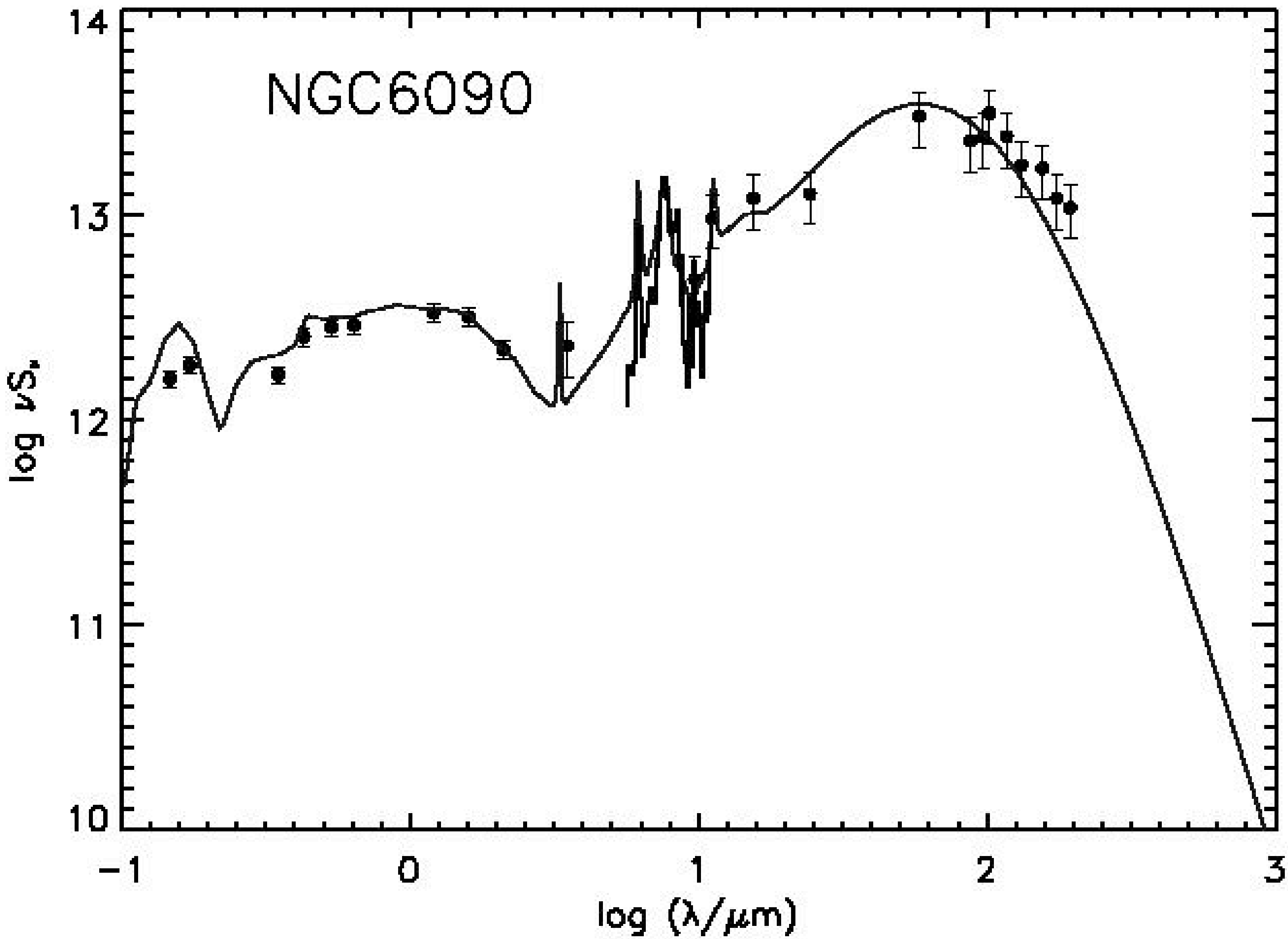
Eftstathiou, R-R, Seibenmorgen, 2000, MN 313, 734

- embedded phase, t < 10^7 yrs
- expanding neutral shell, t = 10^7-10^8 years

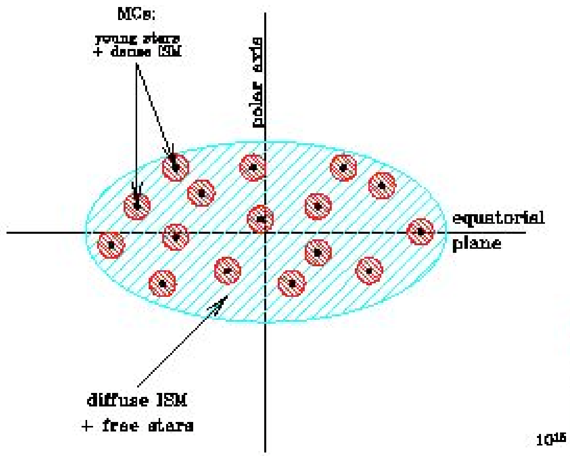


op




NGC6090
14
13
12
11
10
log νS_ν
−1
0
1
2
3
log (λ/μm)

galaxy sed model fits from GRASIL (Silva et al 1998)



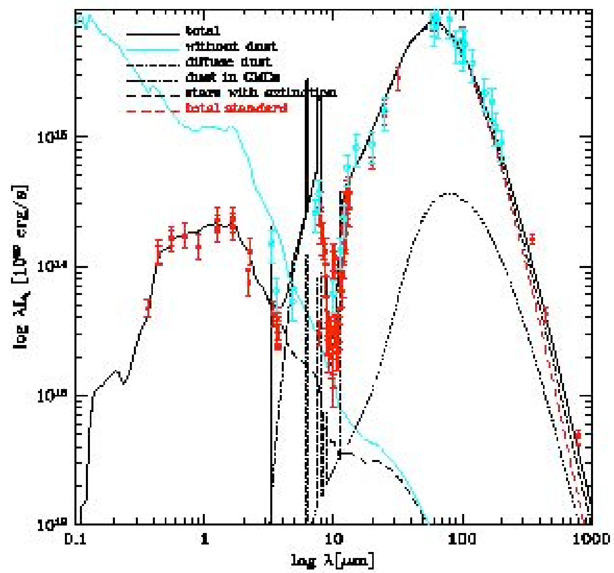


Fig. 9.— Arp 220: in this case the wavelength dependence of grain cross-section has been modified above 100μm from $\propto \lambda^{-2}$ to $\propto \lambda^{-1.6}$. The

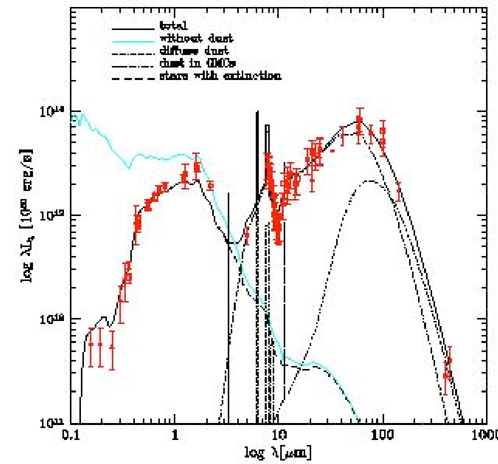


Fig. 6.— Fit to the SED of M82. Data are from Code & Welch (1982), Soifer et al. (1987), Klein et al. (1988), Cohen & Volk (1989), Van Driel et al. (1993), Ichicawa et al. (1994,1995).

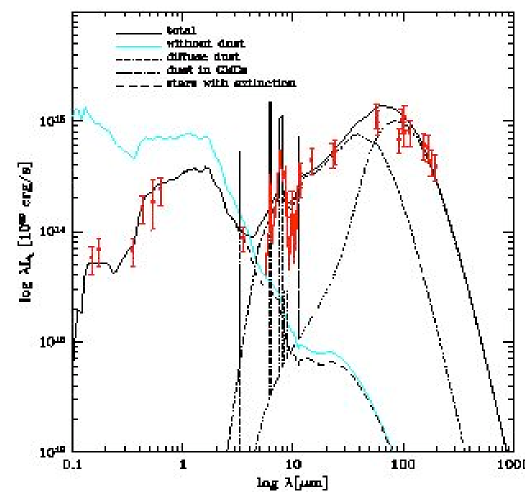


Fig. 8.— Fit to the SED of NGC 6090. Data are from Mazzarella & Boroson (1993), Acosta–Pulido et al. (1996), Gordon et al. (1997).

IRAS - ultraluminous infrared galaxies

THE REMARKABLE INFRARED GALAXY ARP 220 = IC 4553

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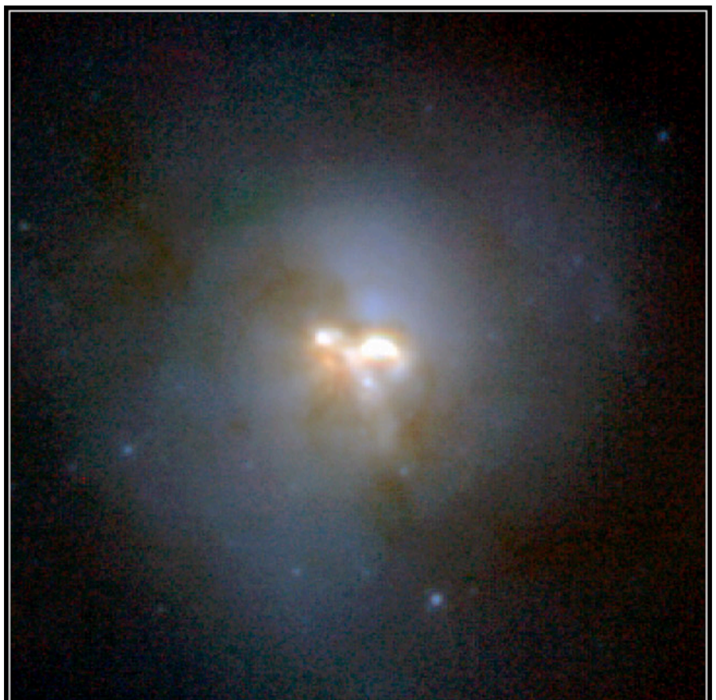
ABSTRACT

IRAS observations of the peculiar galaxy Arp 220 ≡ IC 4553 show that it is extremely luminous in the far-infrared, with a total luminosity of ~ $2 \times 10^{12}\ L_\odot$. The infrared-to-blue luminosity ratio of this galaxy is ~ 80, which is the largest value of the ratio for galaxies in the UGC catalog, and places it in the range of the "unidentified" infrared sources recently reported by Houck *et al.* in the *IRAS* all-sky survey. Other observations of Arp 220, combined with the luminosity in the infrared, allow either a Seyfert-like or starburst origin for this luminosity.



Ultraluminous Infrared Galaxy Arp 220 HST • NICMOS
PRC97-17 • ST ScI OPO • June 9, 1997
R. Thompson (University of Arizona),
N. Scoville (California Institute of Technology) and NASA

Arp 220

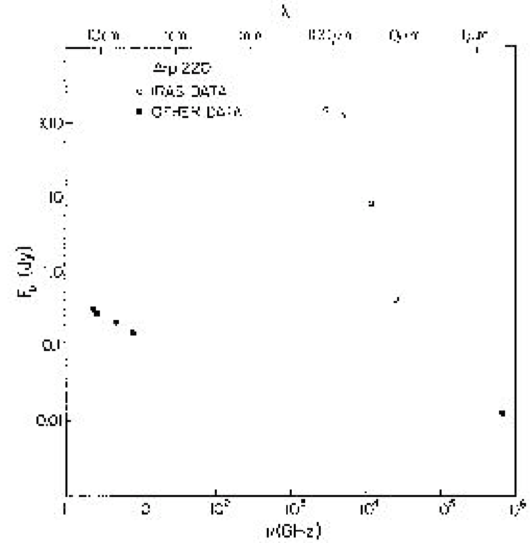
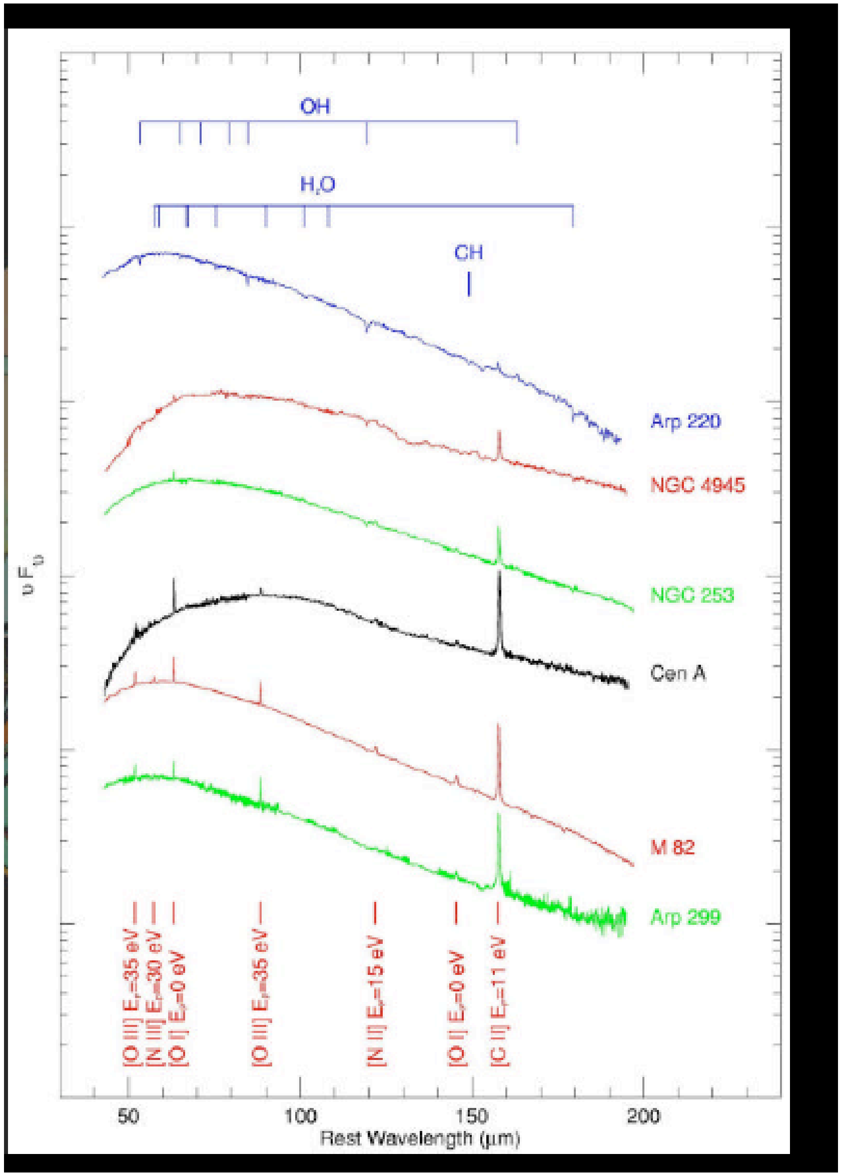


Fig. 2. The energy distribution of A220, plotted vs. frequency from the data in Table 1 and the cited references. The open circles are the *IRAS* data, while the filled circles represent data from other observations (see text).

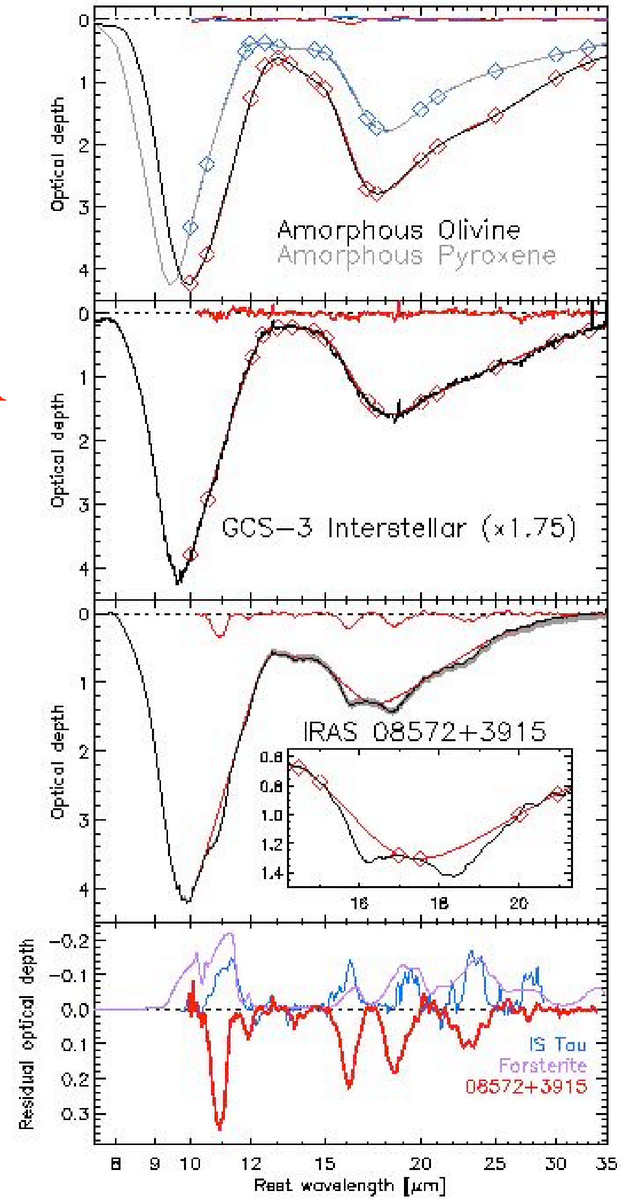
Soifer et al, 1984, ApJ 283, L1:
the remarkable infrared galaxy Arp 220

seds of ultraluminous infrared galaxies



L:ISO

R:SPITZER

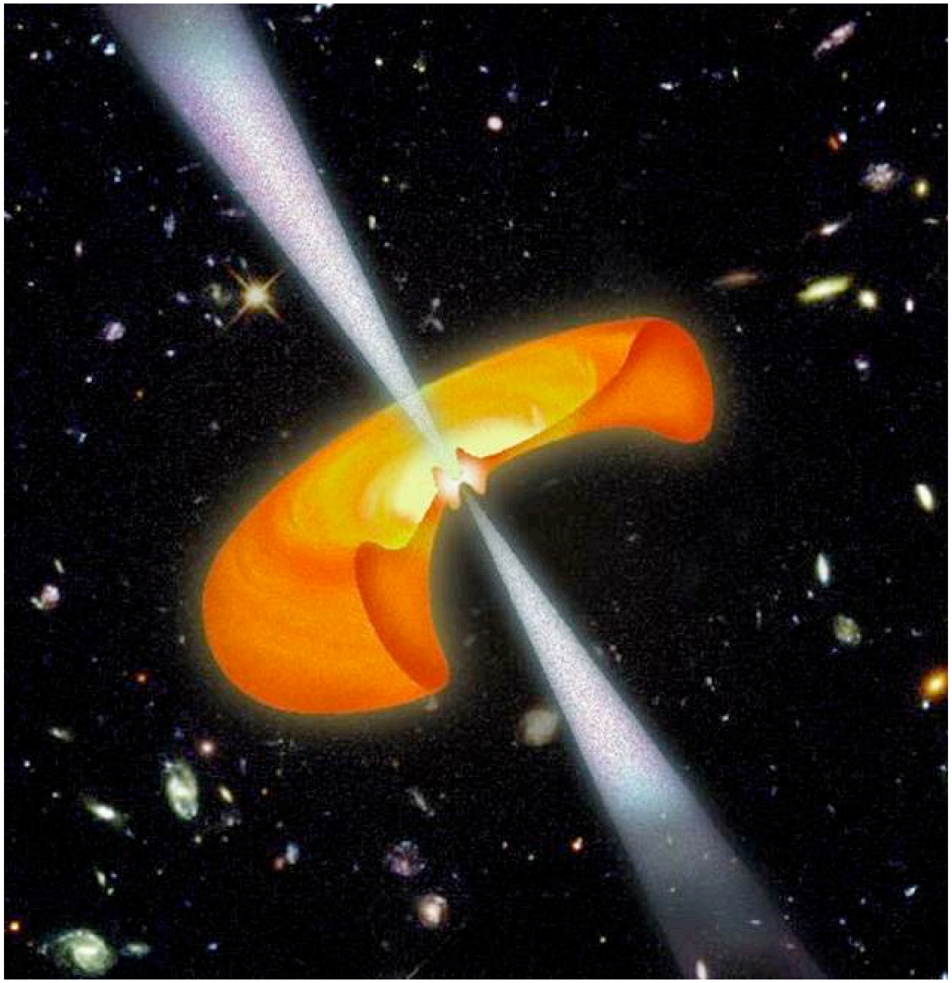


IRAS - AGN dust tori

Miley et al, 1984, ApJ 278, L79:
A 25 μm component in 3C390.3

Rowan-Robinson & Crawford, 1989:AGN mid-ir excess modelled as dust torus
(subsequent models: Pier & Krolik 1992, Granato & Danese 1994)

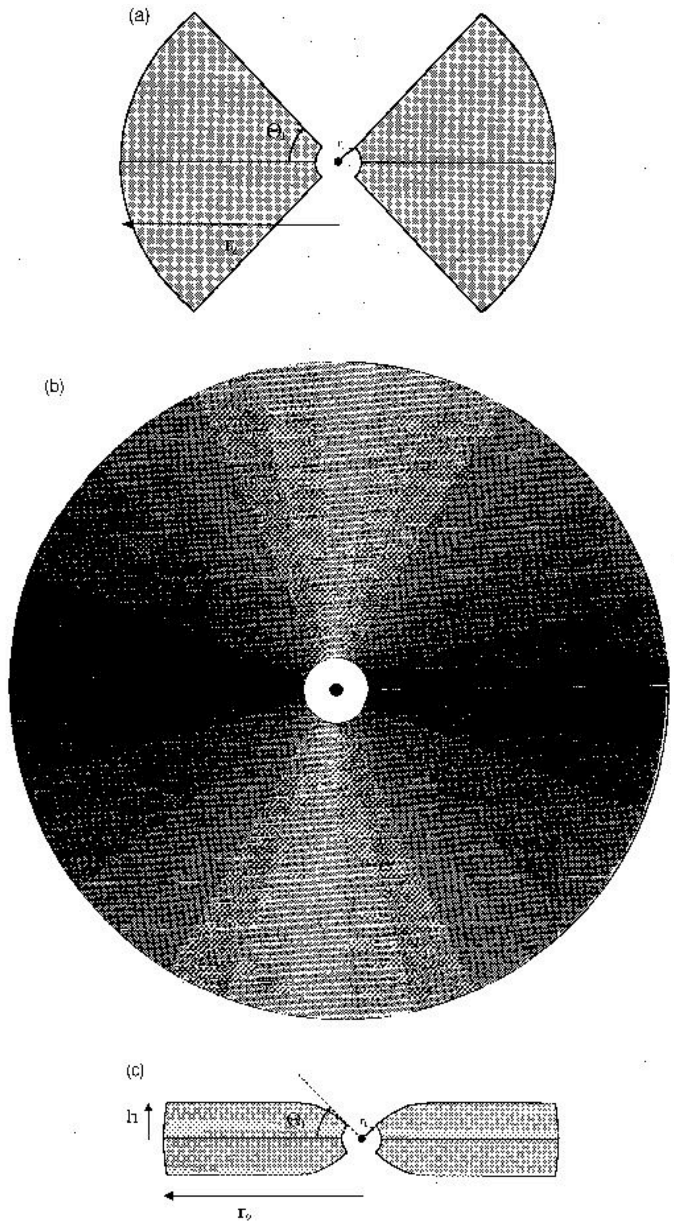
Rowan-Robinson 1995: ‘torus’ could be ensemble of small, thick clouds filling narrow-line region (1-200pc)

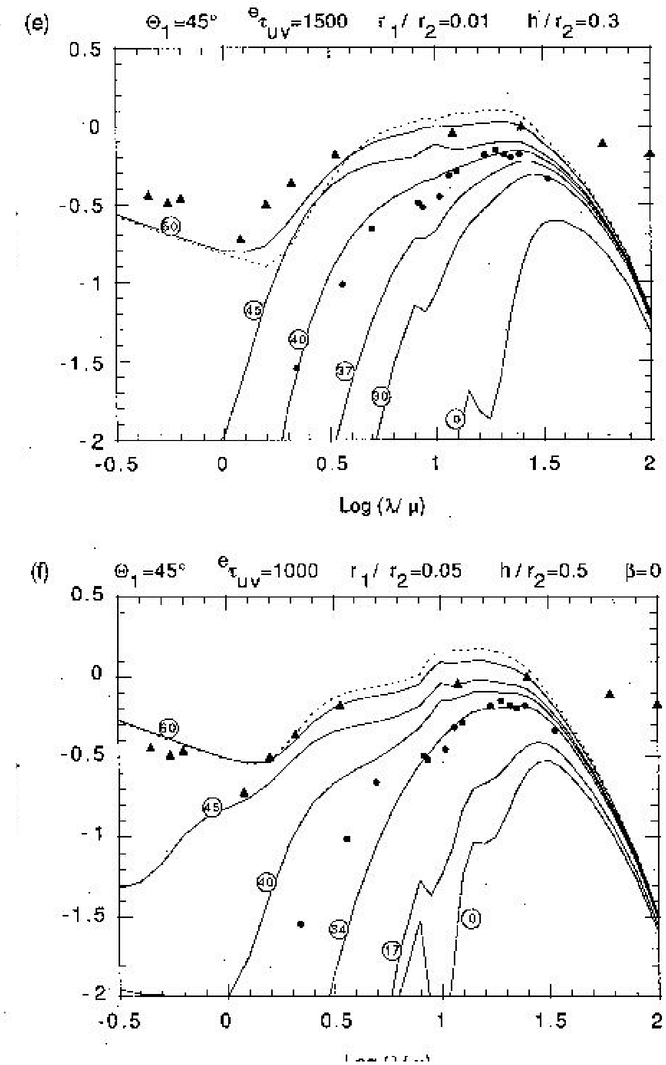


IRAS - AGN dust tori

Efstathiou & RR, 1995, MN 273, 649:

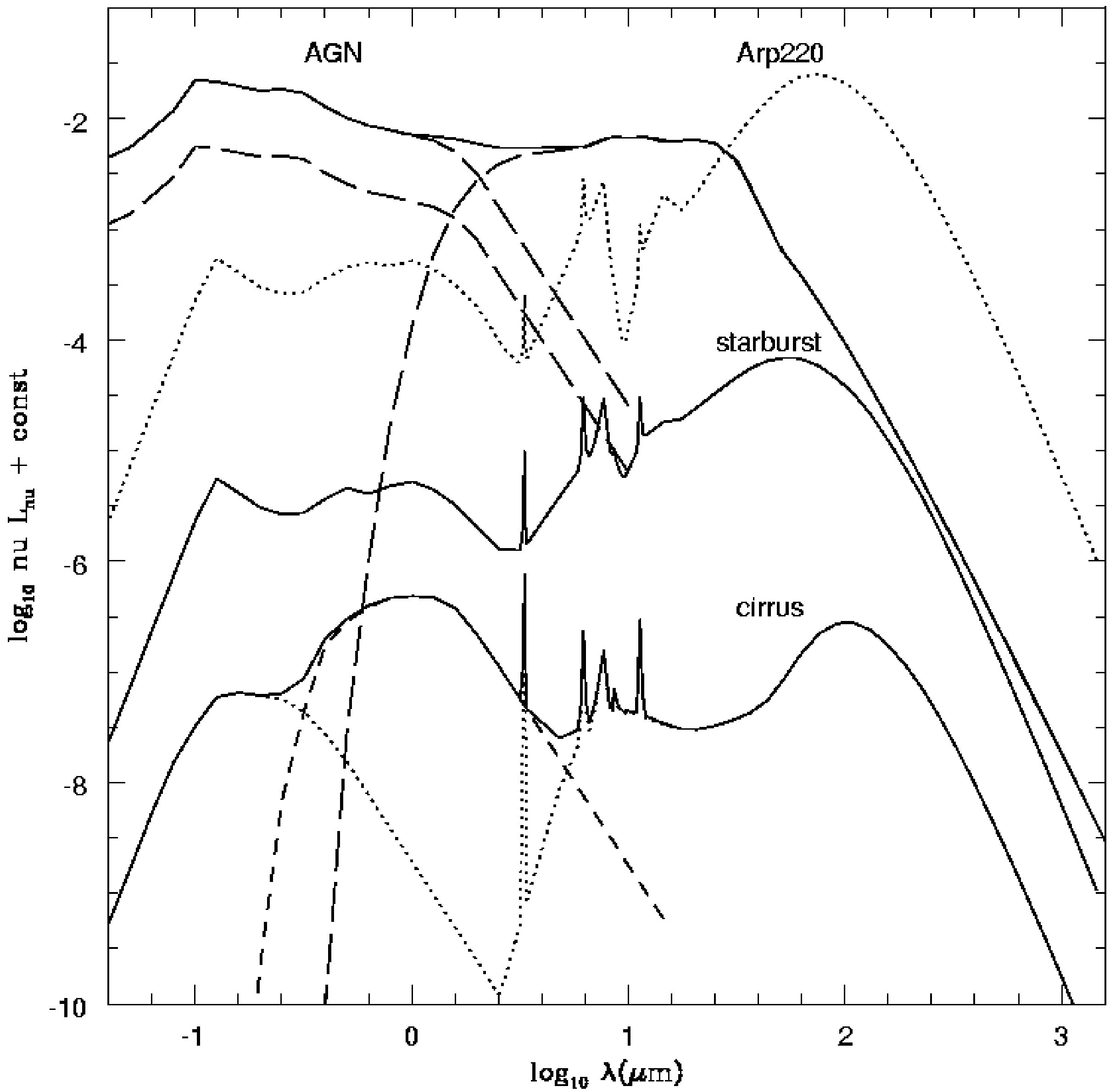
axisymmetric radiative transfer models for AGN dust tori



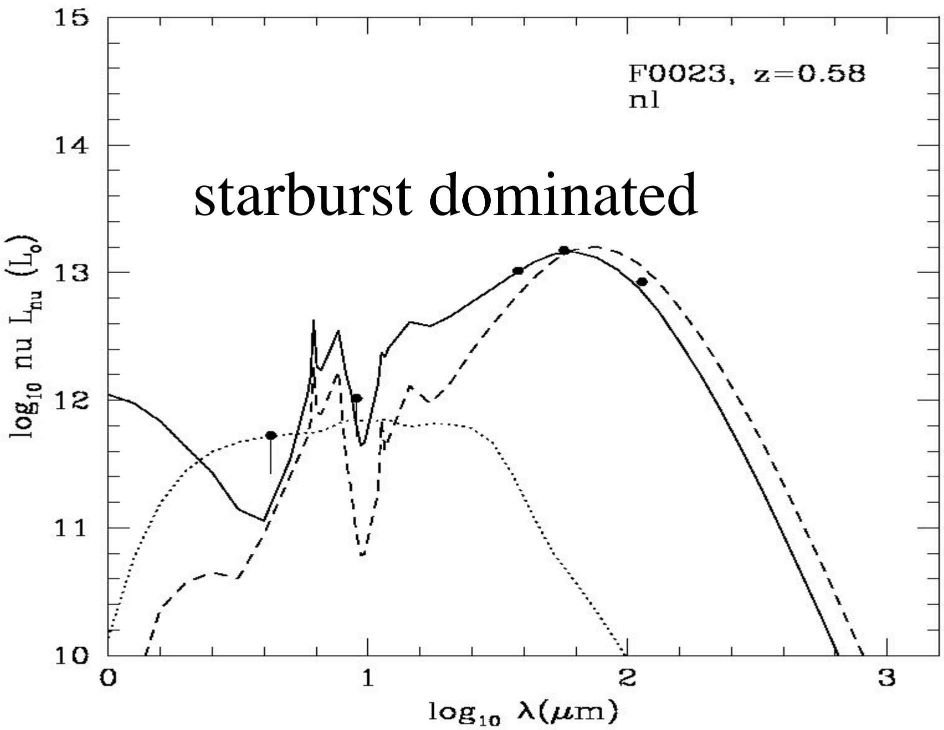


Infrared templates

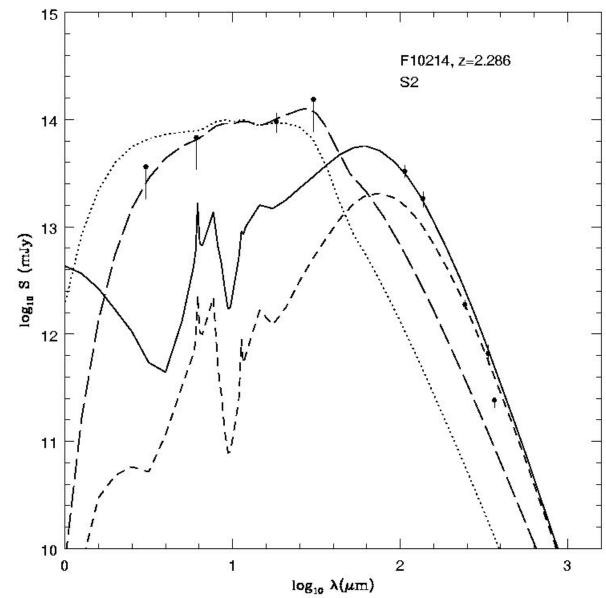
(Rowan-Robinson 2001)



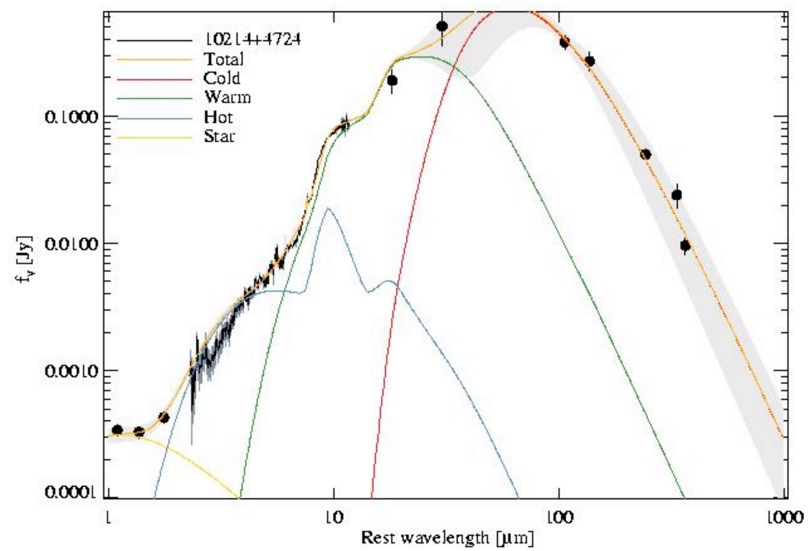
Hyperluminous infrared galaxies



Rowan-Robinson, 2000, MN 316, 885



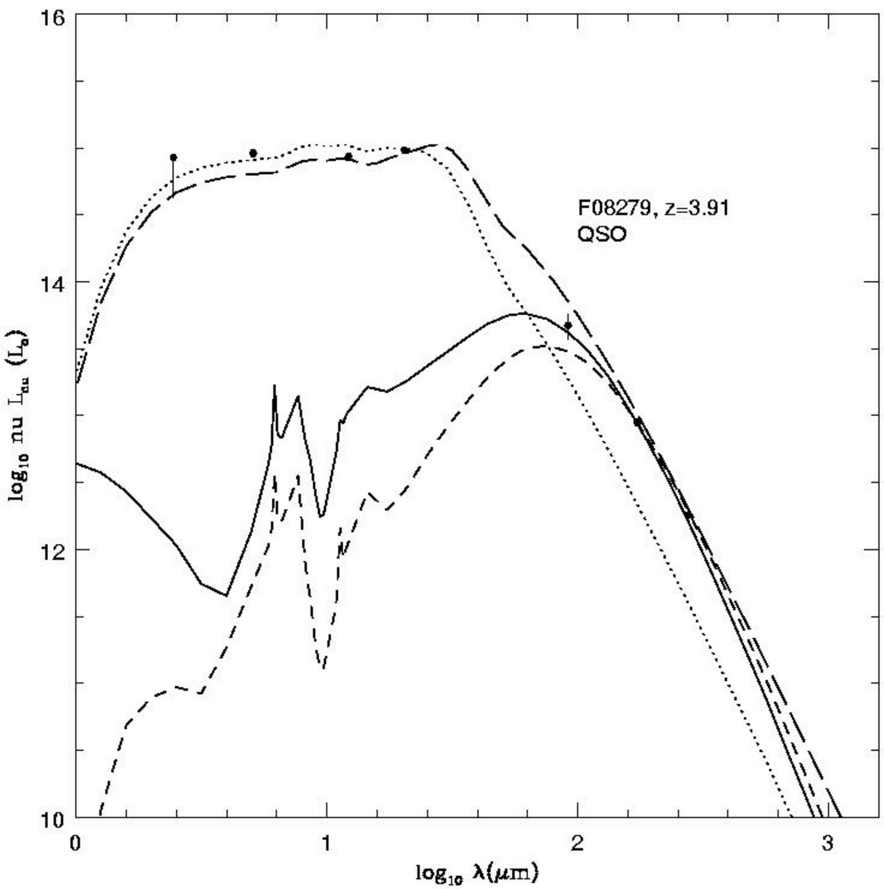
IRAS F10214, z=2.3 galaxy

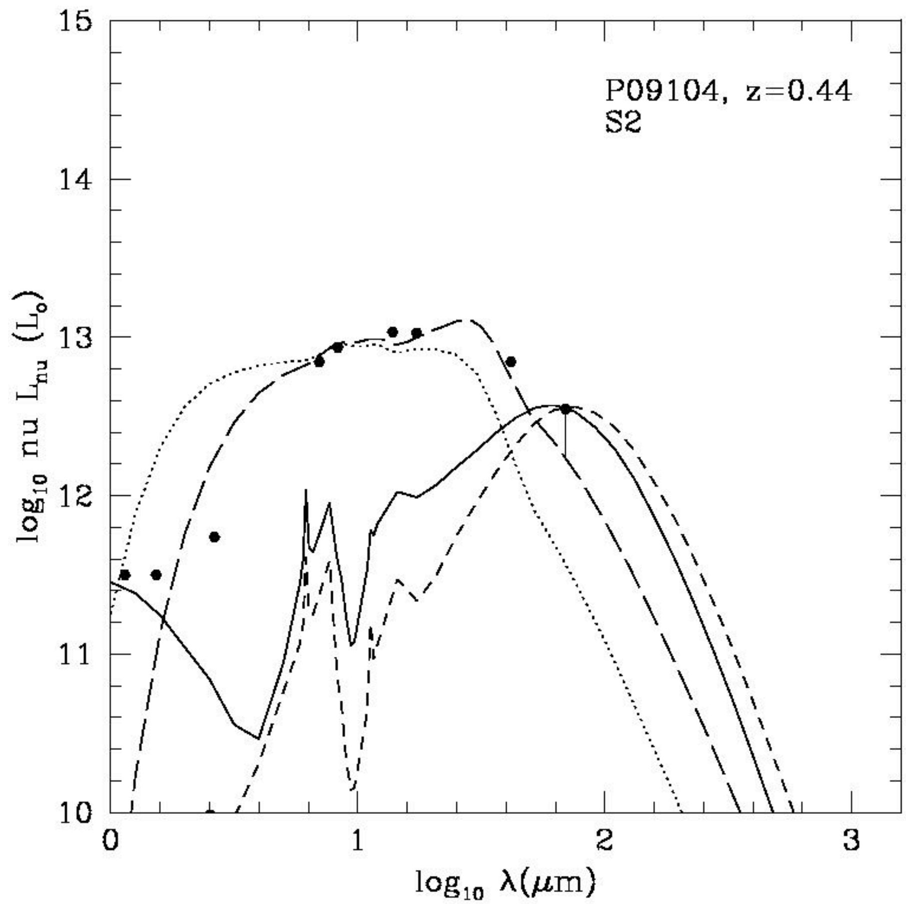


Teplitz et al 2006

Fig. 2.— The semi-empirical dust model fit to the SED of FSC 10214+4724. The IRS mid-IR spectrum was extended with other data as described in the text. The components of the model (cold, warm, and hot dust, and stellar 3500K black body) are indicated in color. The shaded grey region indicates the 1σ uncertainty in the fit.

dust torus dominated

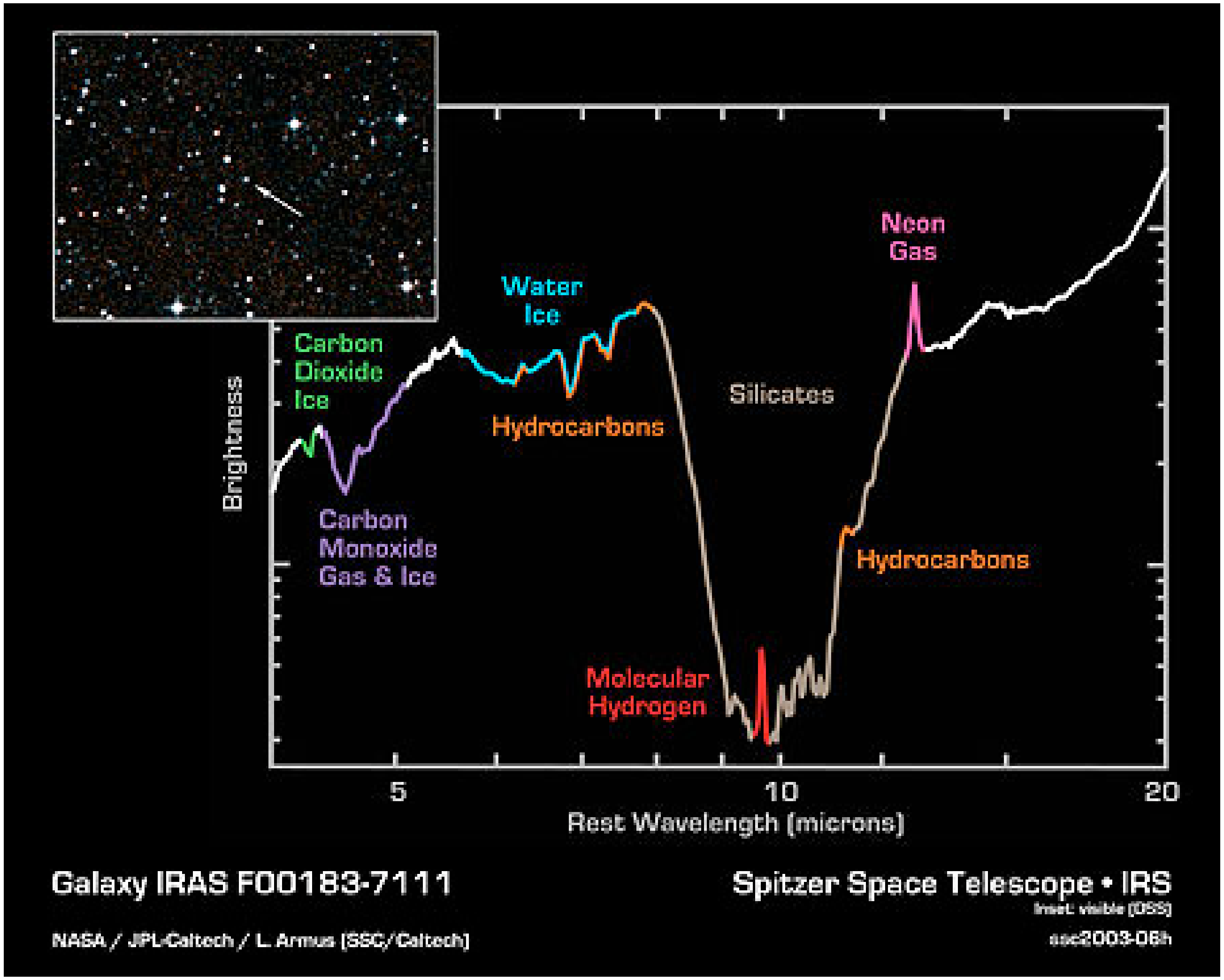




SPITZER-IRS: IRAS F00183-7111, hyperluminous infrared galaxy

•IRS spectrum of the hyperluminous ir galaxy F00183-7111 = IRAS P00182-7112 (Spoon et al 2004)

• z = 0.327 (narrow line object), lg L_{sb} = 13.25

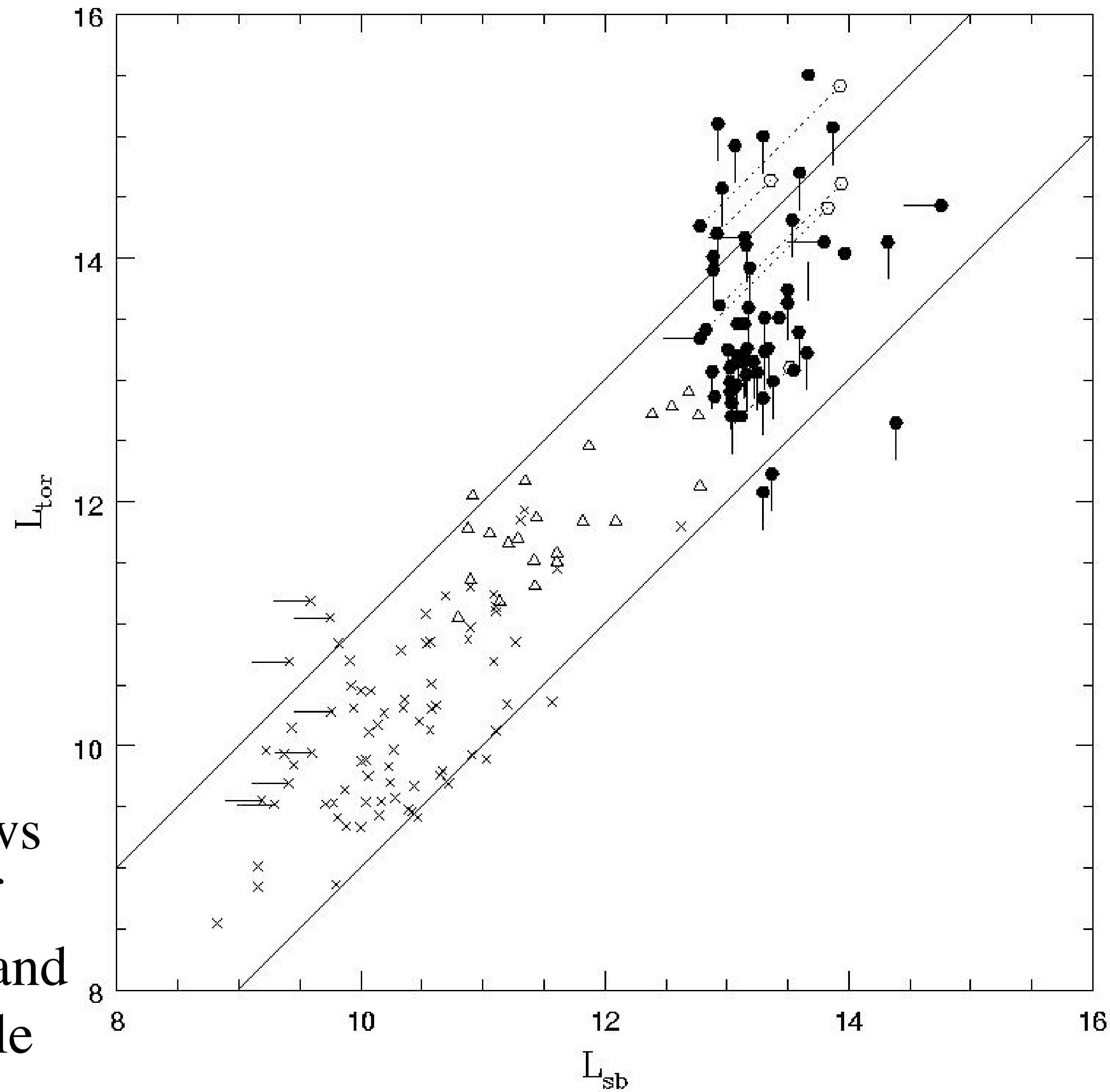


L_{tor} v. L_{sb}

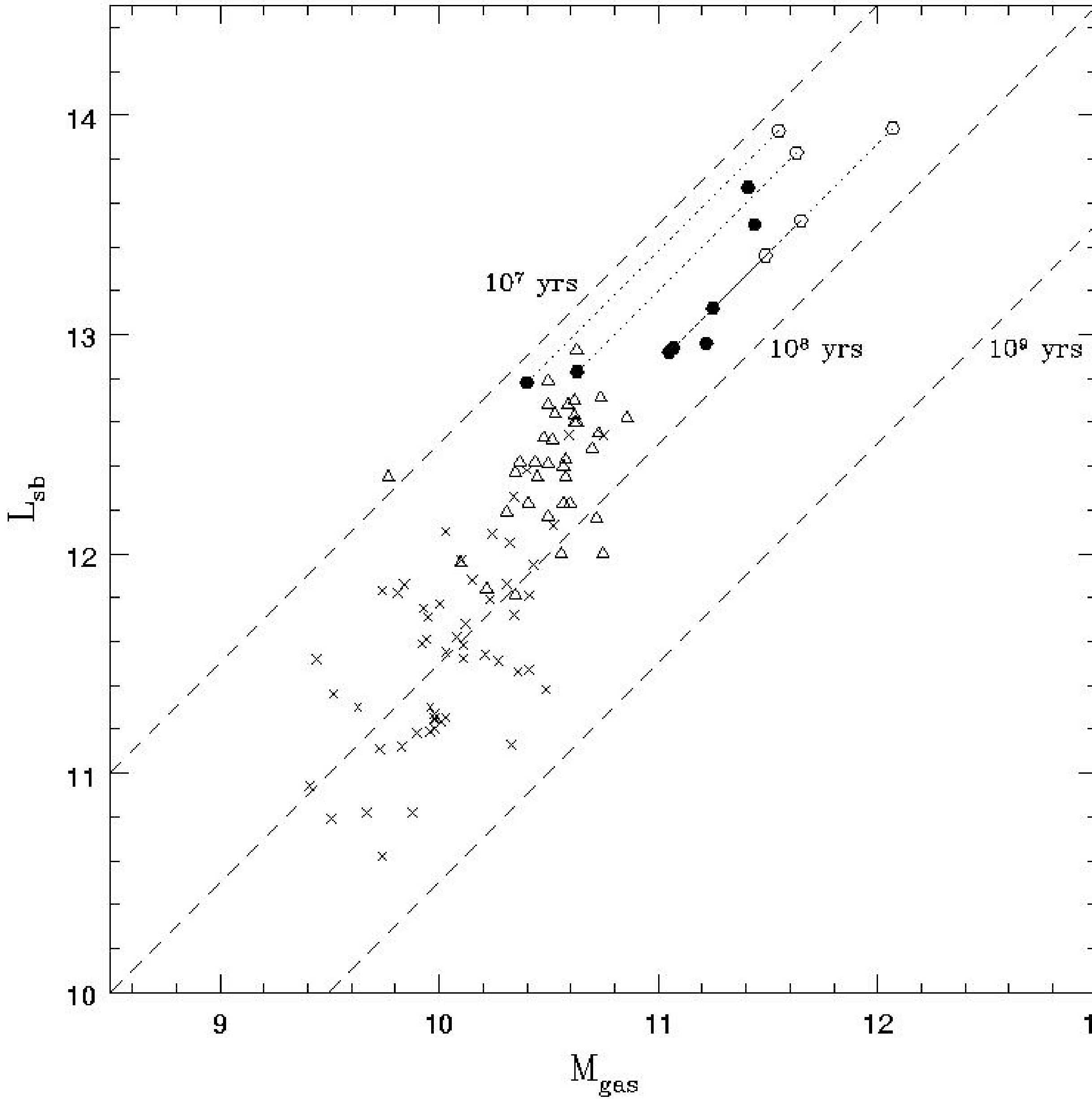
dust torus luminosity is related, via covering factor, to black-hole accretion rate

starburst luminosity is a measure of the star-formation rate

broad correlation shows link between supply of gas for star formation and for growth of black hole



L_{sb} v. M_{gas}



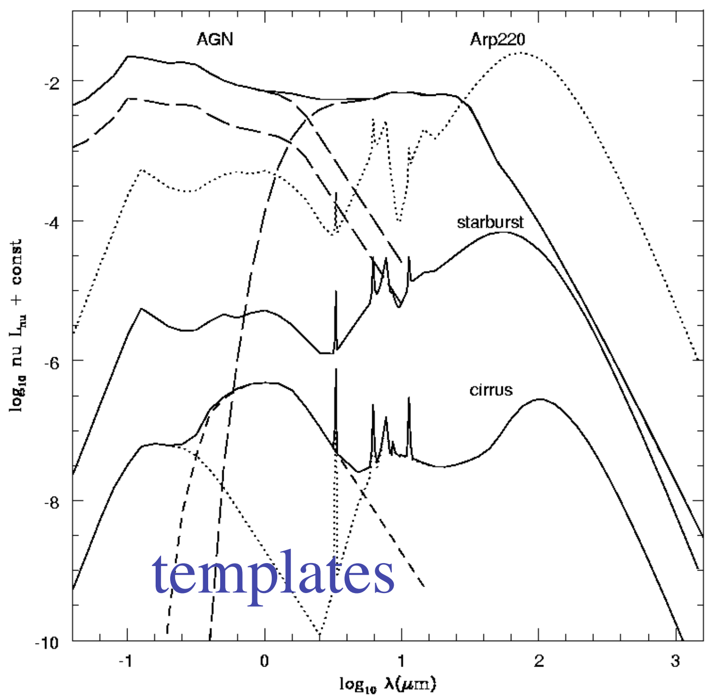
broken lines show time-scale to convert gas mass into stars

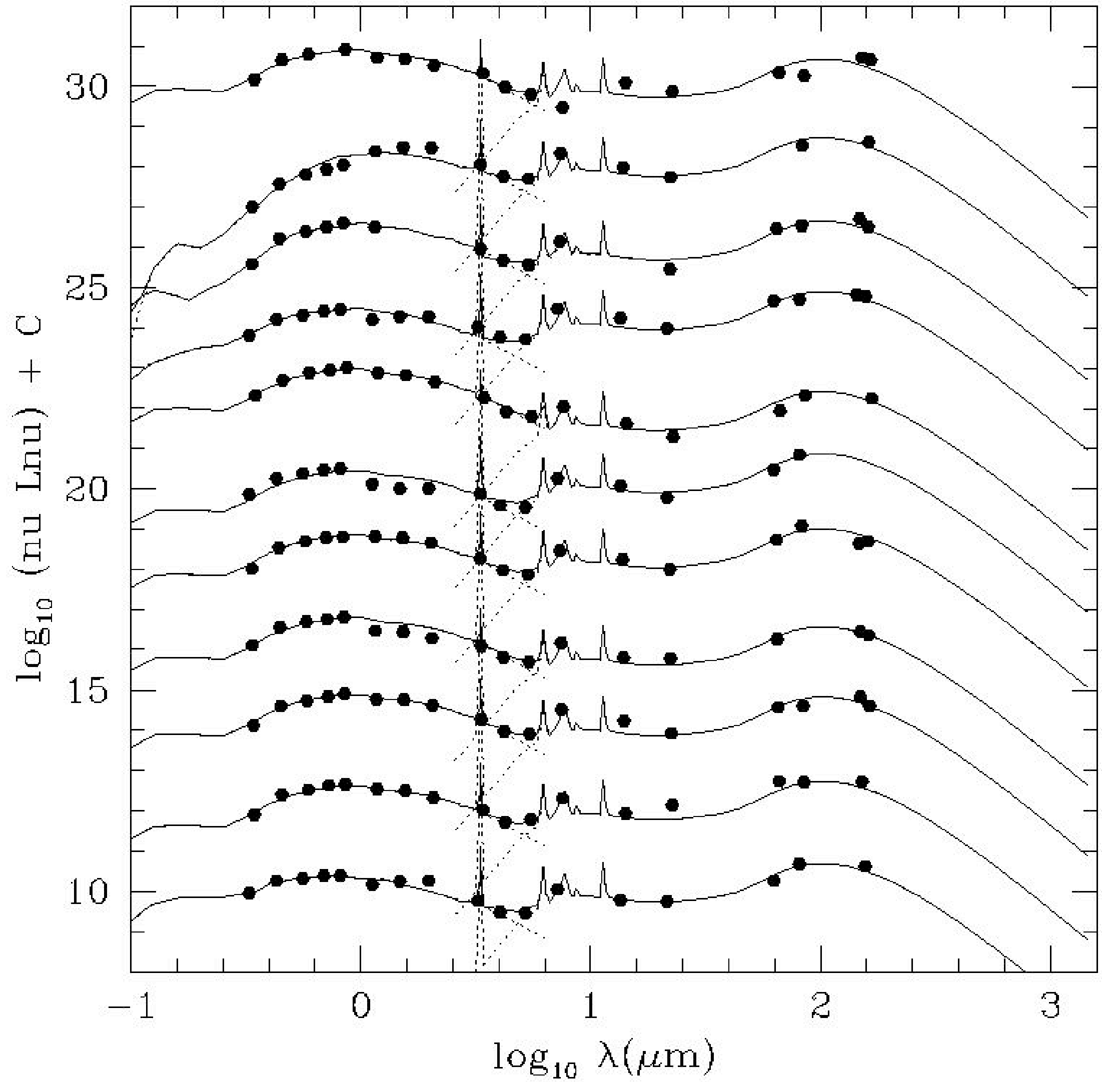
ULIRGs and HLIRGs have bursts on shorter time-scale, or need truncated IMF

z<0.12 galaxies with cirrus seds

Rowan-Robinson et al, 2005, AJ 129, 1183

sources with good ISO-ELAIS and SPITZER-SWIRE data

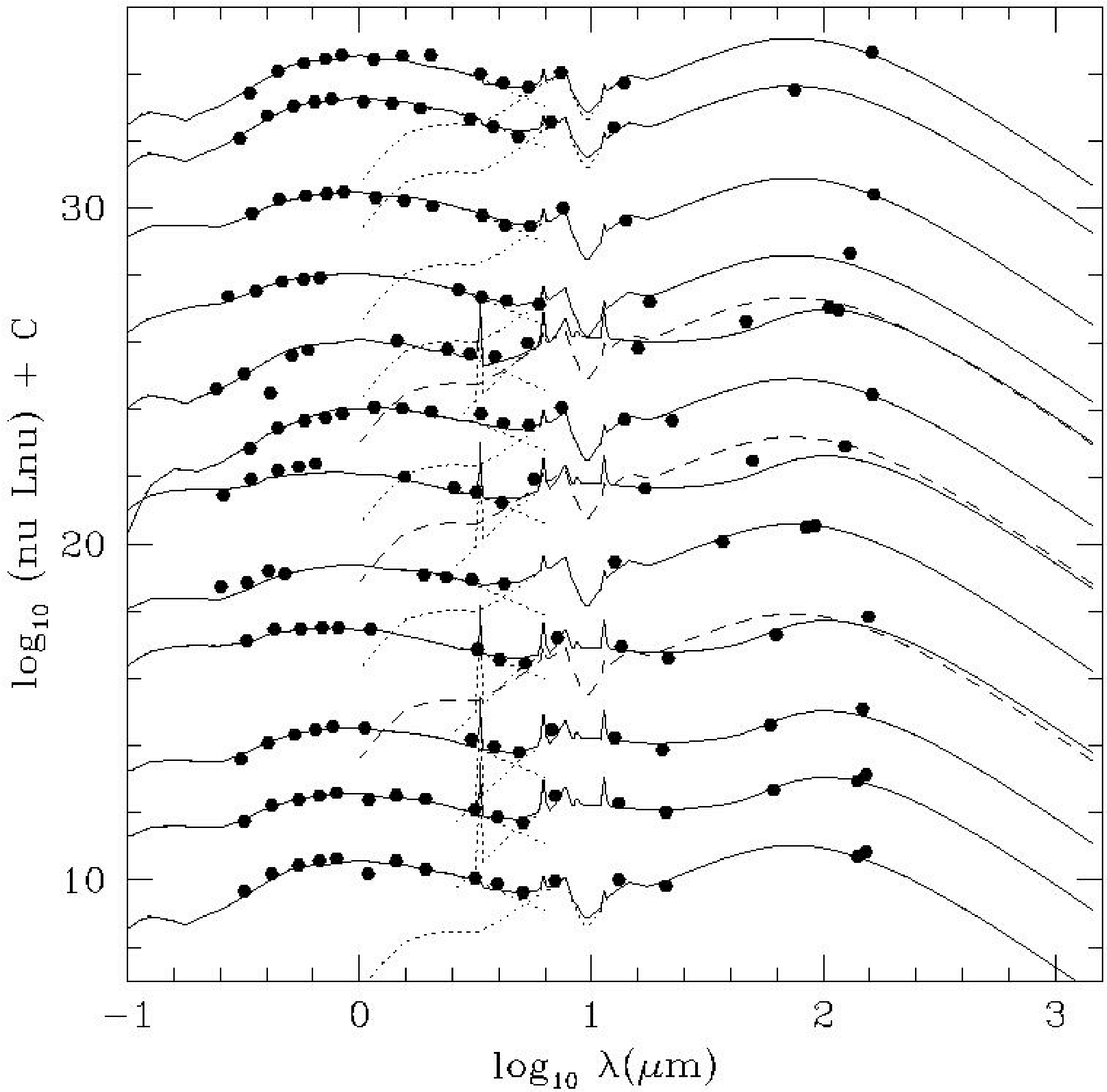




z=0.1-0.9 galaxies

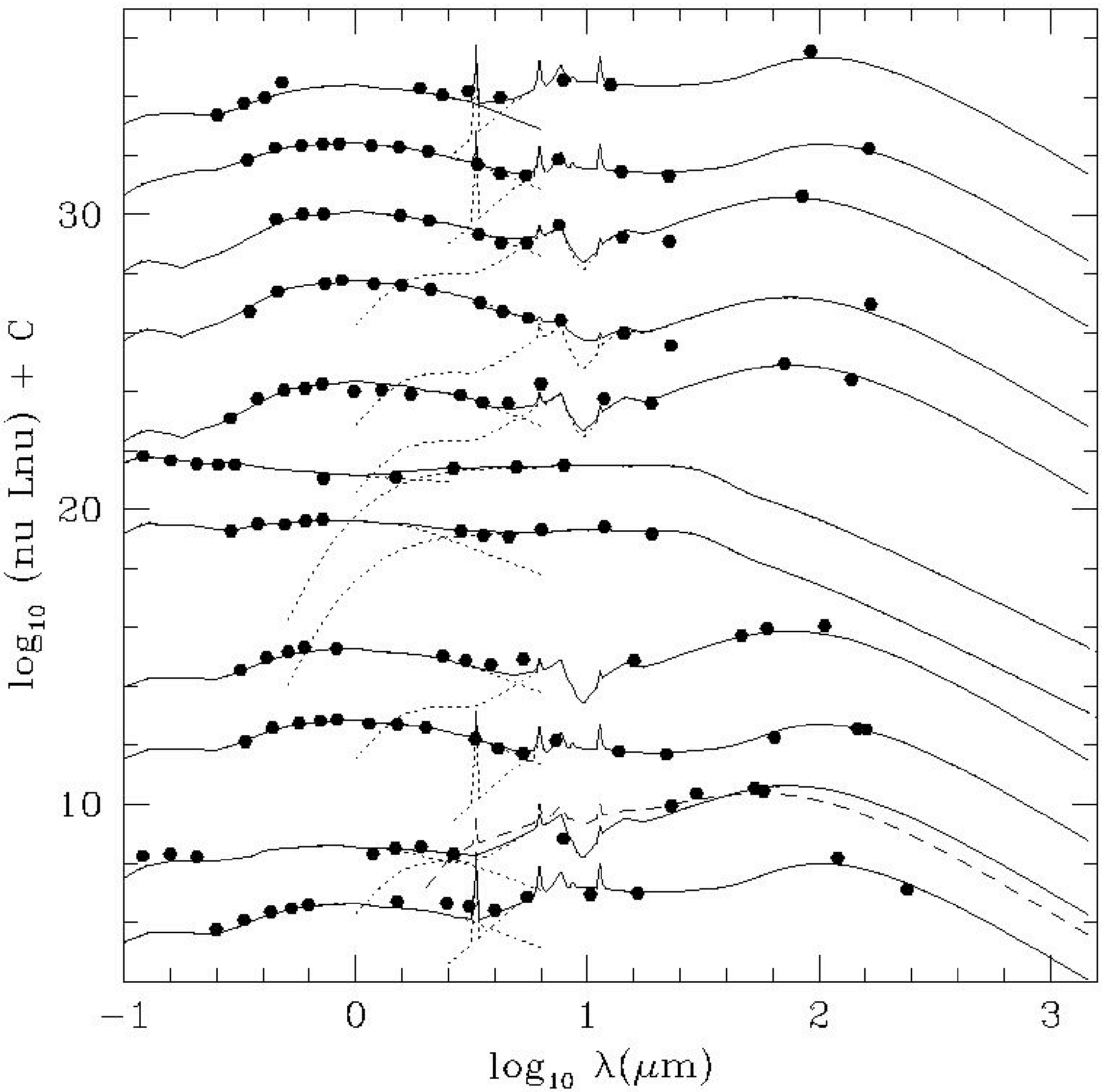
fitted with cirrus
or A220 template

A220 model:
A_V = 200, t* = 26 Myr
(Efstathiou and
RR 2001)



seds of z=0.1-2.2 galaxies/quasars

fitted with cirrus, A220 starburst and AGN dust torus templates

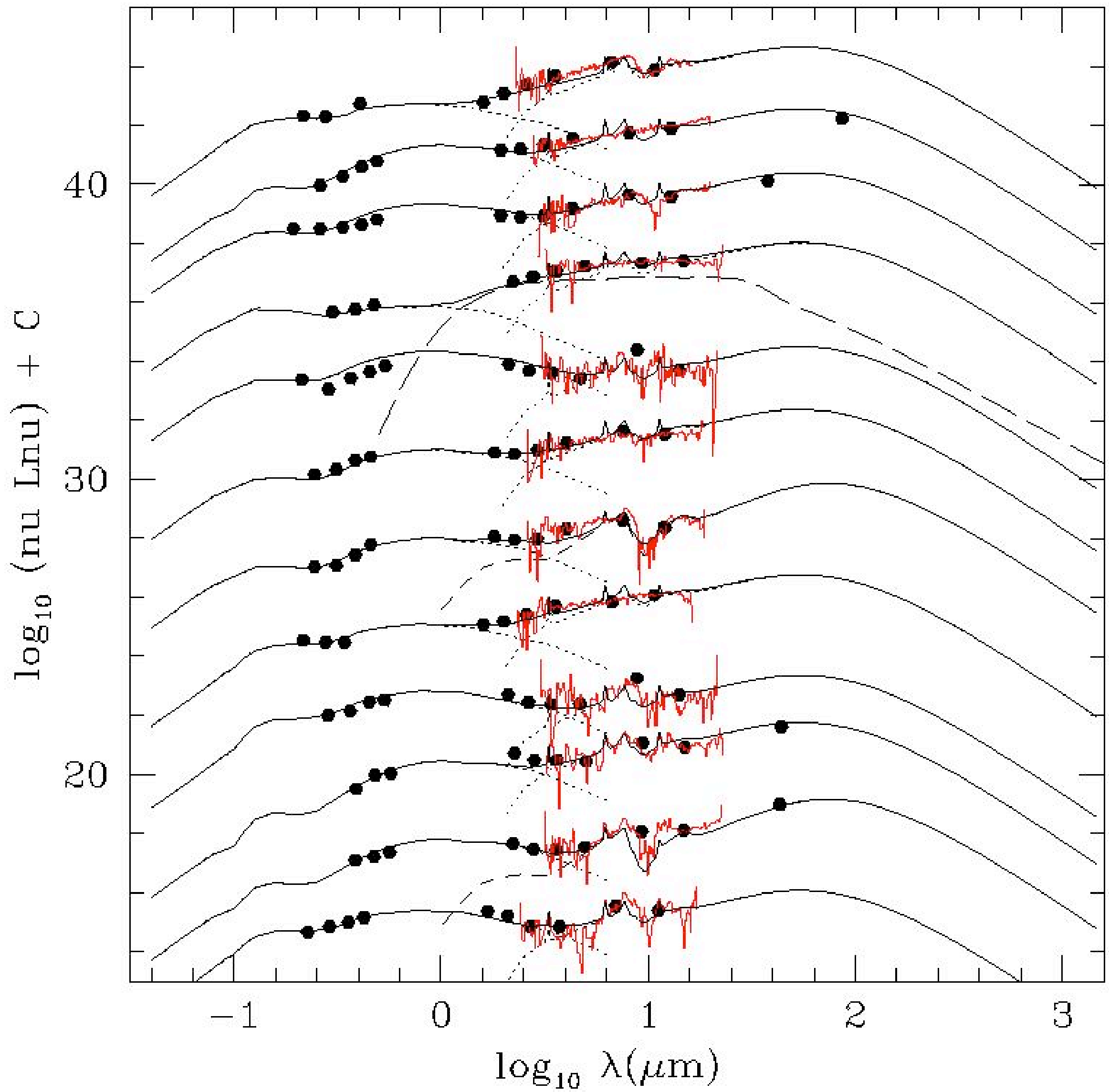


SPITZER-IRS spectra of ELAIS sources

- IRS spectra for 70 ELAIS-N1 and -N2 sources with S15> 1mJy validate the template fits
- most are ULIRGs, with z =1-3
- Filled circles: optical, ISO, SWIRE

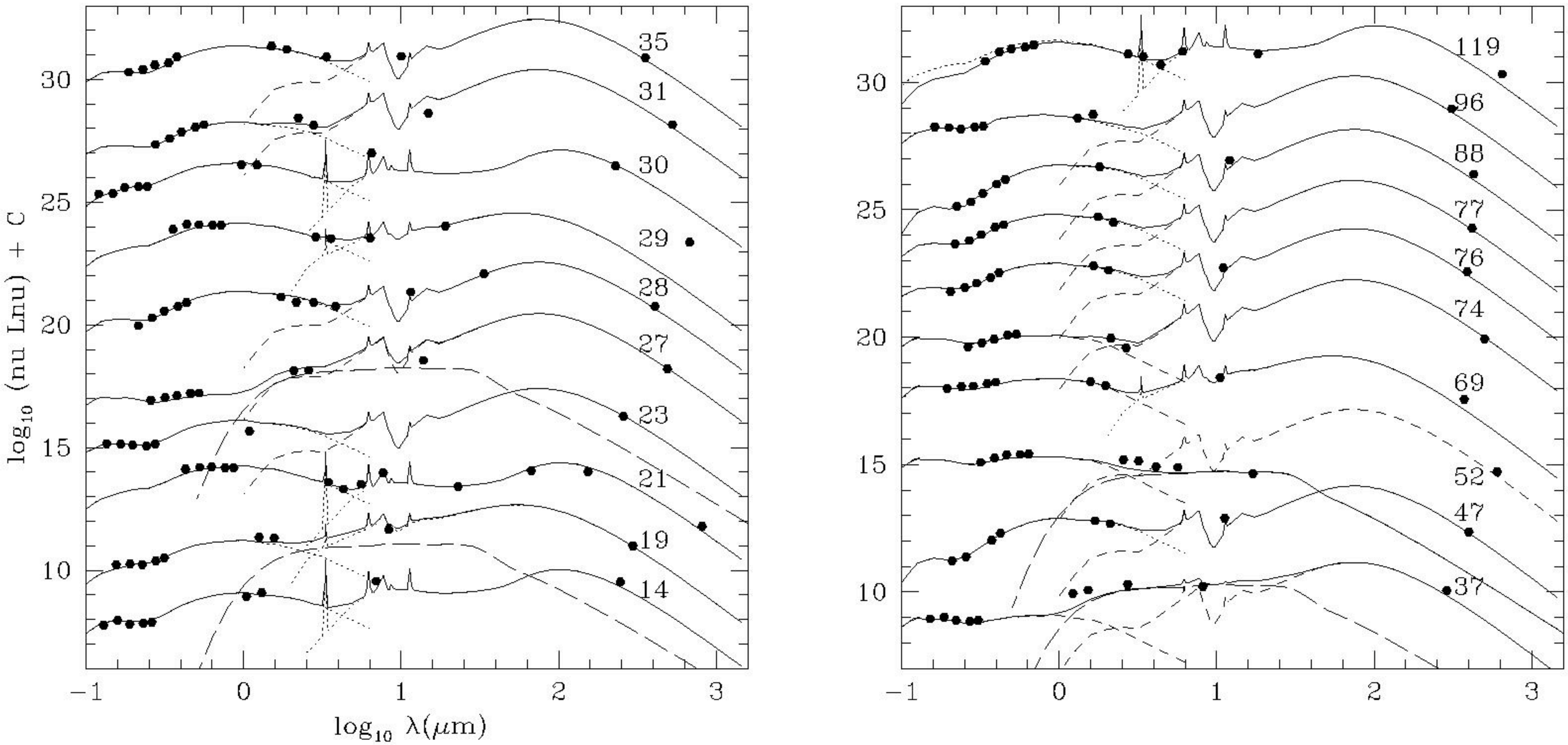
  (and MAMBO) data
- Solid curves: model seds
- Red curve: calibrated IRS data

(Hernan-Caballero et al 2006)

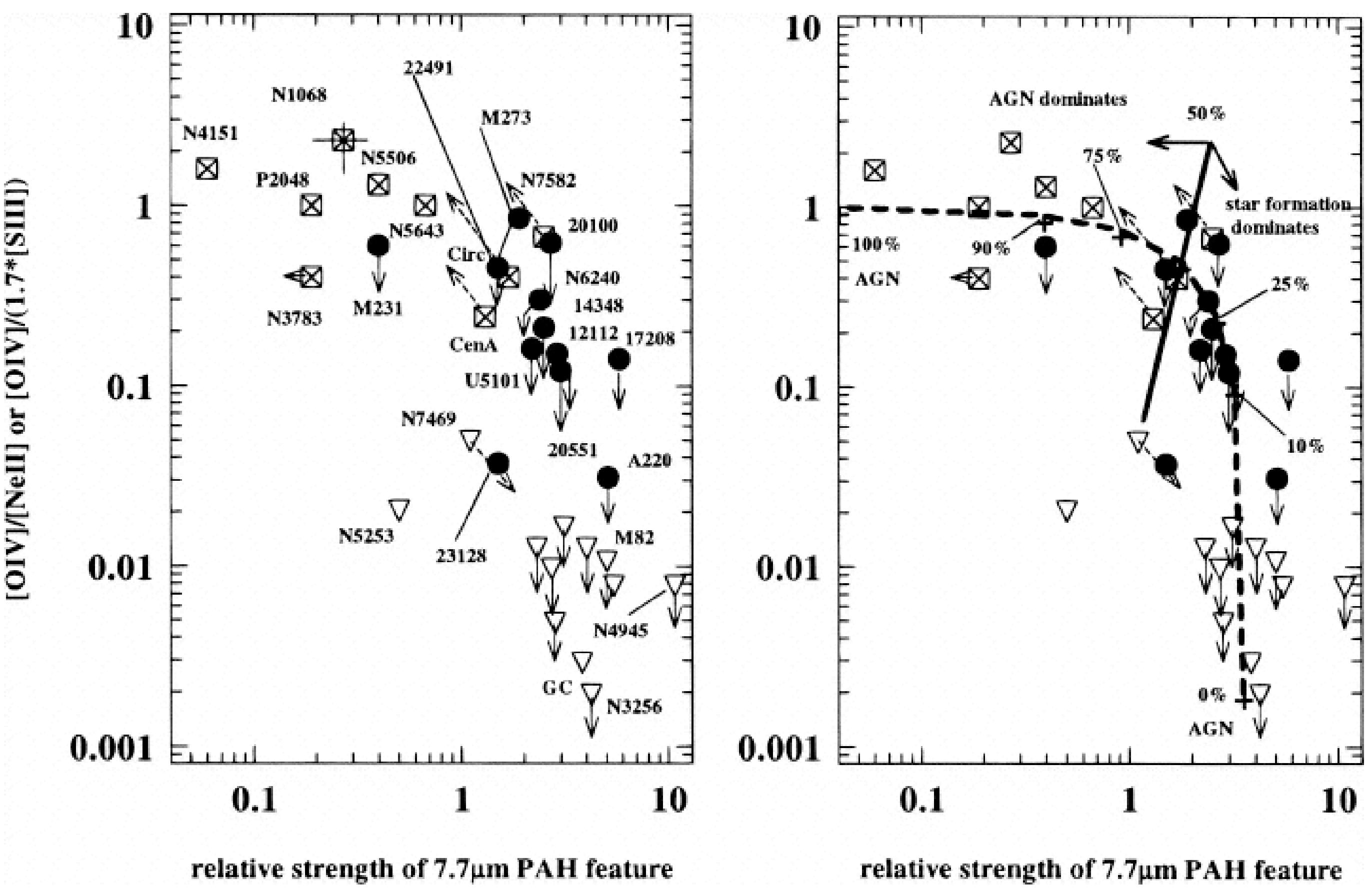


seds of submillimetre galaxies

SHADES SXDS Clements et al 2007



what powers ultraluminous infrared galaxies (ISO) ?



Genzel et al, 1998, ApJ 498, 579

what powers ultraluminous infrared galaxies (Spitzer) ?

Spoon et al, 2007, astro-ph/0611918