Extinction law variations and dust excitation in the spiral galaxy NGC 300

Sd galaxy
D = 2.1 Mpc
i = 50°
D25 = 21.9′ = 13.4 kpc
SFR ~ 0.15 $M_\odot$/yr

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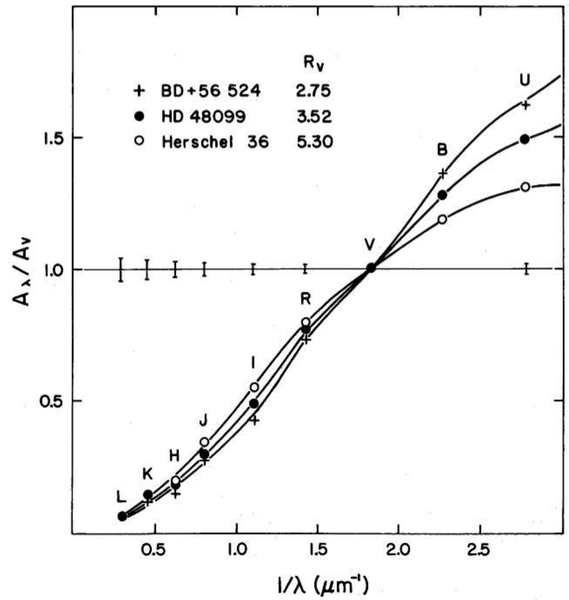
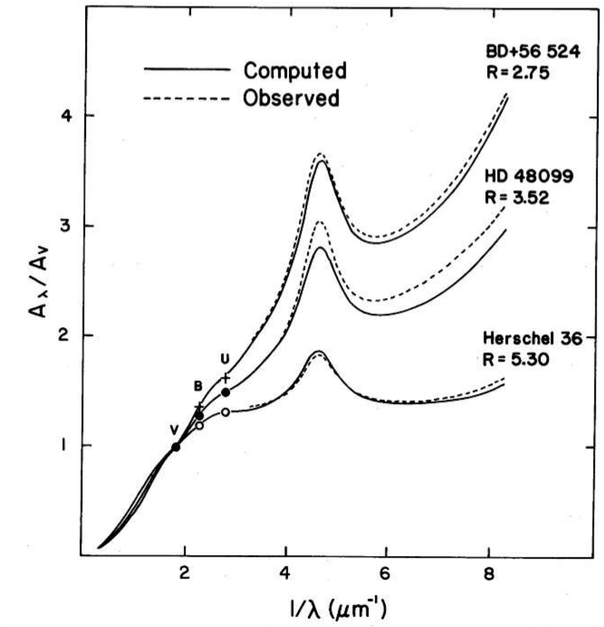
extinction laws:





Cardelli et al. 88-89:

family parameterized by $R_V = A(V) / E(B-V)$

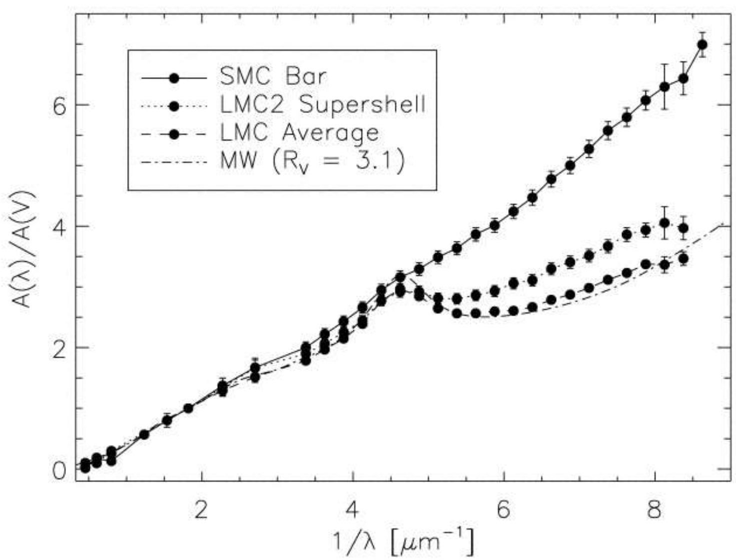
diffuse Galactic ISM: $R_V = 3.1$ on average

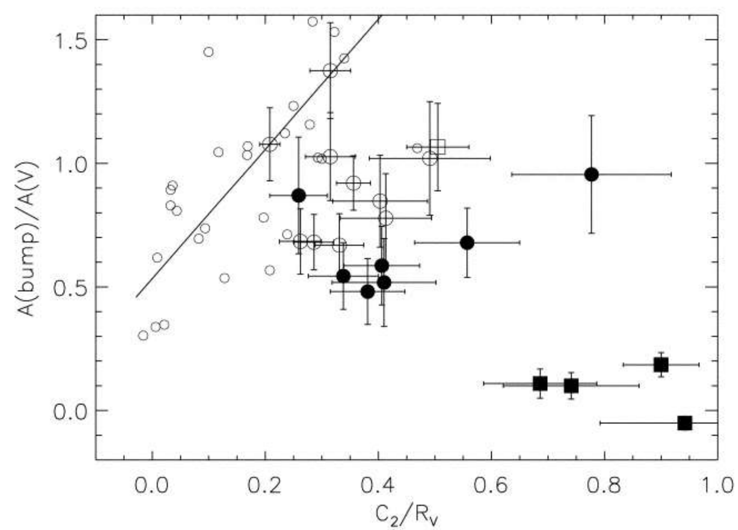
denser ISM: R_V up to ~ 6

→ grain coagulation

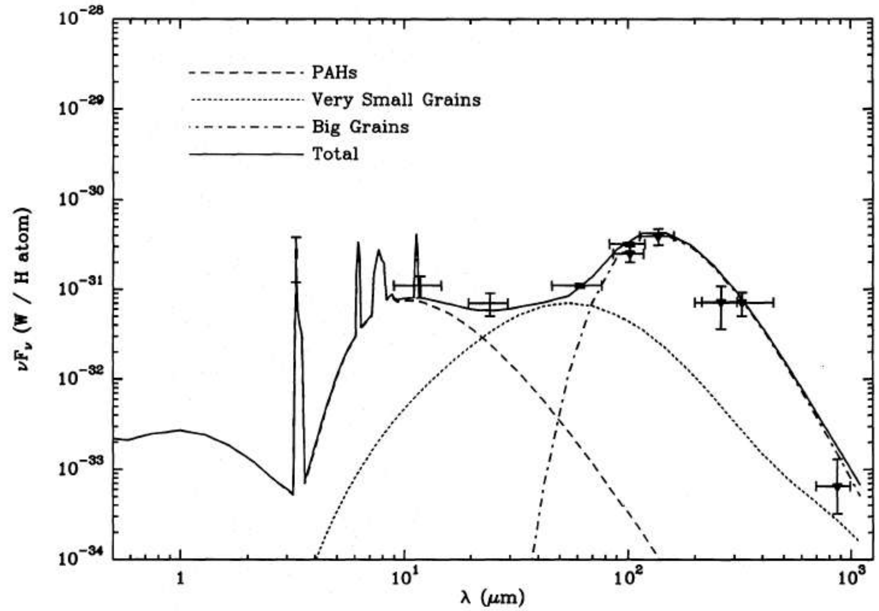
Gordon et al. 03: second parameter needed: N(HI) / A(V) ?

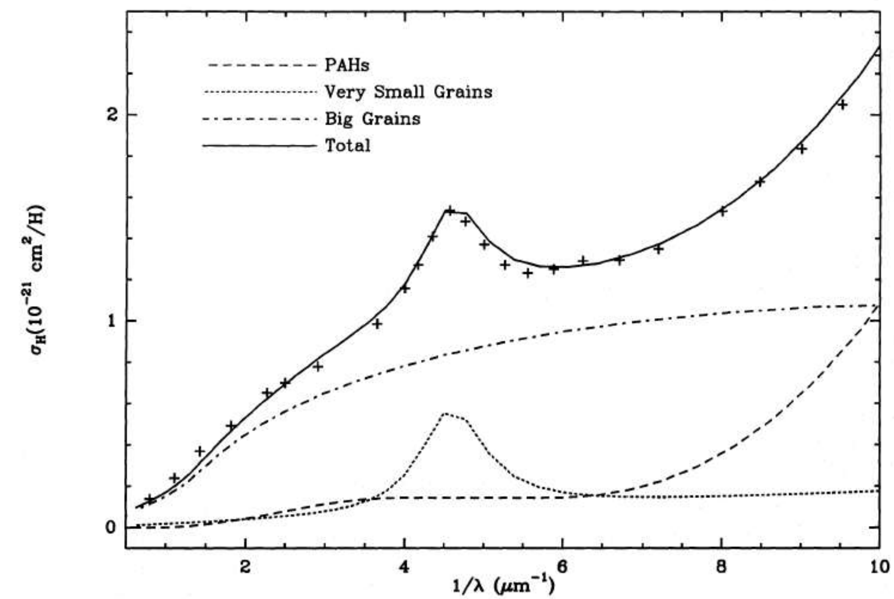
local record of grain formation / destruction processes





dust populations and identification of absorption features:





Désert et al. 90

consistent dust models for UV-optical extinction and IR emission:

– 3 dust populations: big grains (coated silicates)
very small grains (carbon-based)
aromatic compounds → mid-IR emission bands

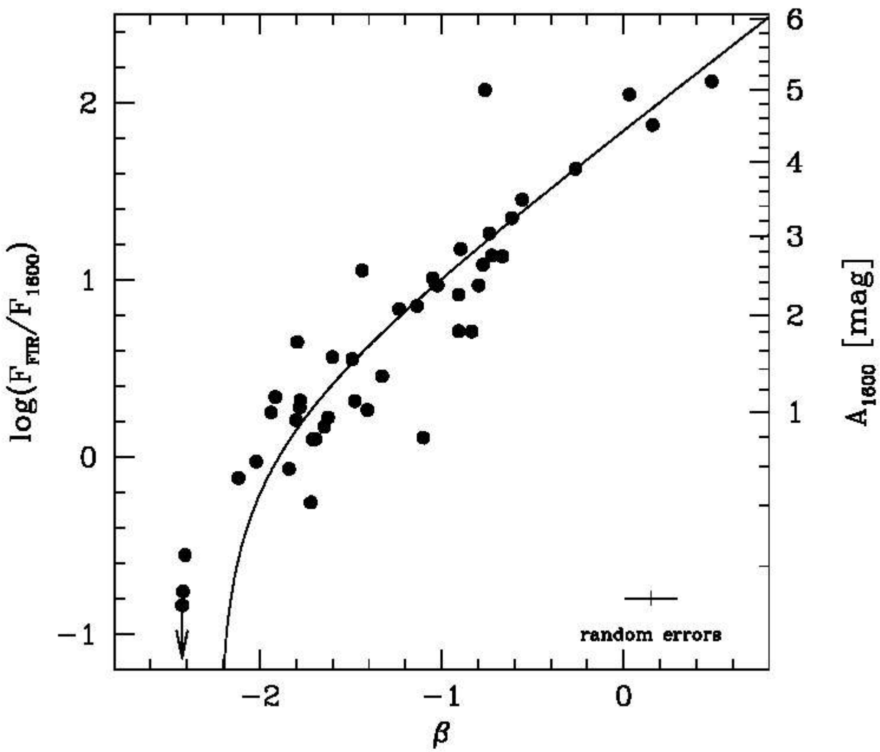
– extinction: no definite identification of 2175 Å bump and FUV rise

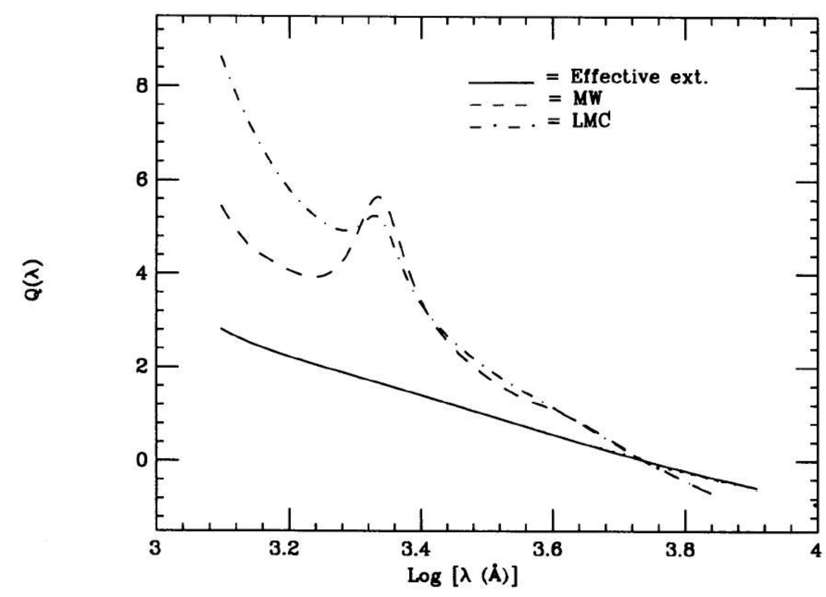
Désert et al. 90: aromatics responsible for FUV rise, not correlated with bump
Vermeij et al. 02: aromatic band ratios correlated with bump strength in LMC

UV extinction correction in galaxies:

collection of stars: attenuation law (extinction + scattering into sight line) depends on dust nature + dust/stars geometry

recipe for starburst galaxies:
starburst → UV spectral slope (β) insensitive to exact SF history
energy balance between UV absorption and FIR re-emission
→ linear relation between A(UV) and β (UV reddening)
(expected for foreground screen geometry)

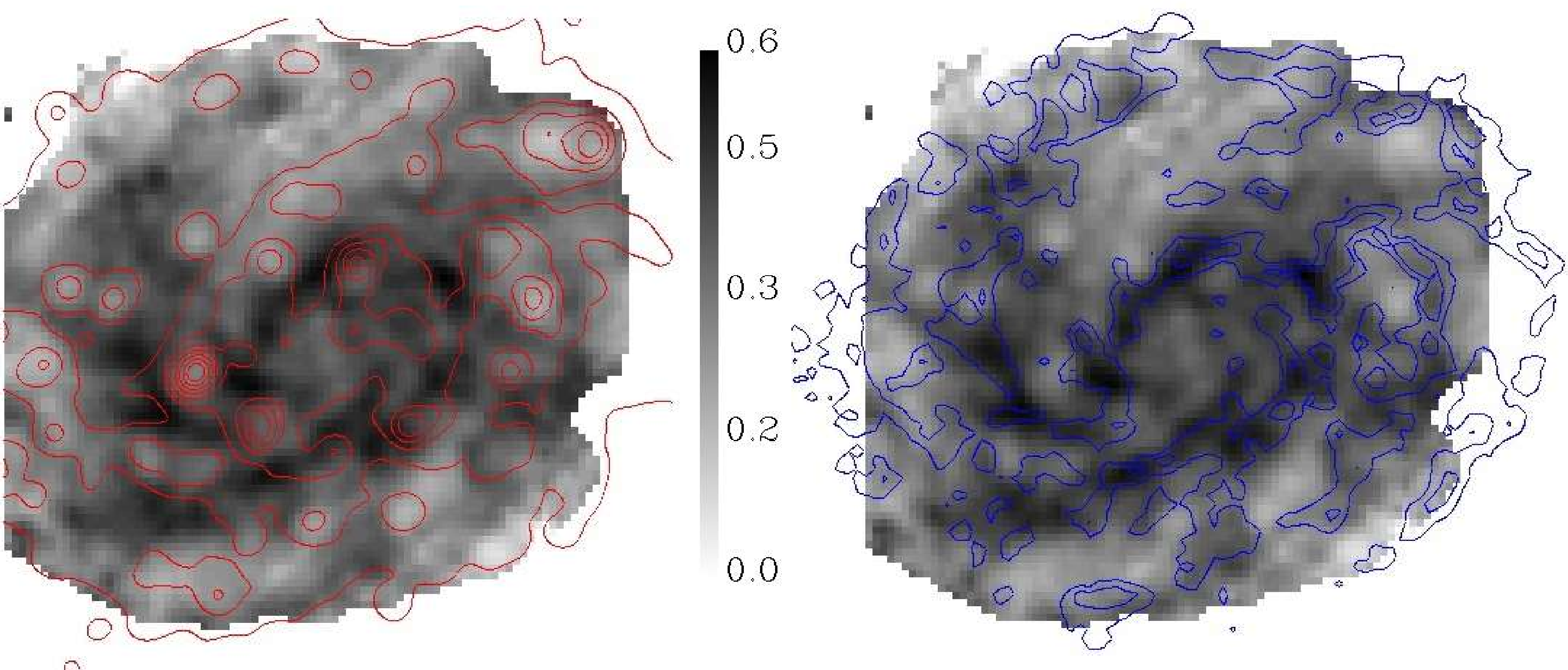




study of a normal galaxy at high spatial resolution

Spitzer early release observations: 3.6 / 4.5 / 5.7 / 8 / 24 / 71 / 156 μm
Galex nearby galaxy survey: FUV (1516 Å) and NUV (2267 Å)
UBVI (courtesy S.C. Kim 04), R, Hα and Hβ
UV to 8 μm: FWHM ≤ 50 pc

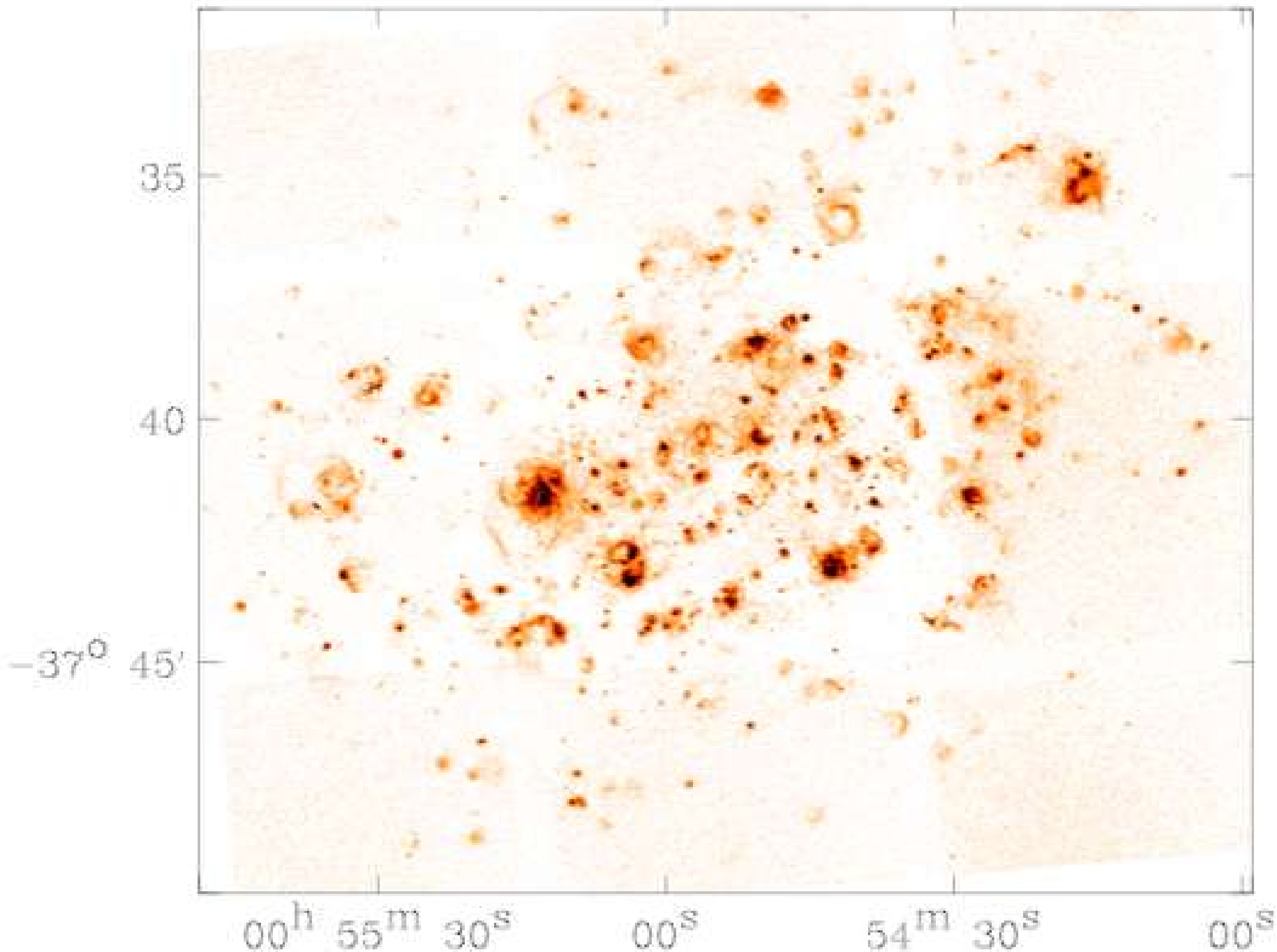
energy budget at the 160 μm resolution (FWHM = 38″ = 390 pc):
global A(FUV) map



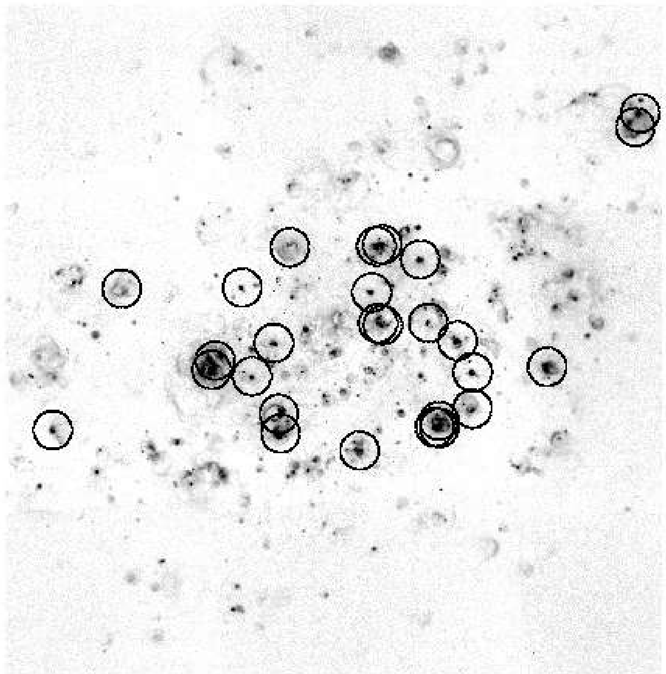
Deharveng 88: 176 catalogued HII regions
metallicities: 0.4–1.4 $Z_\odot$

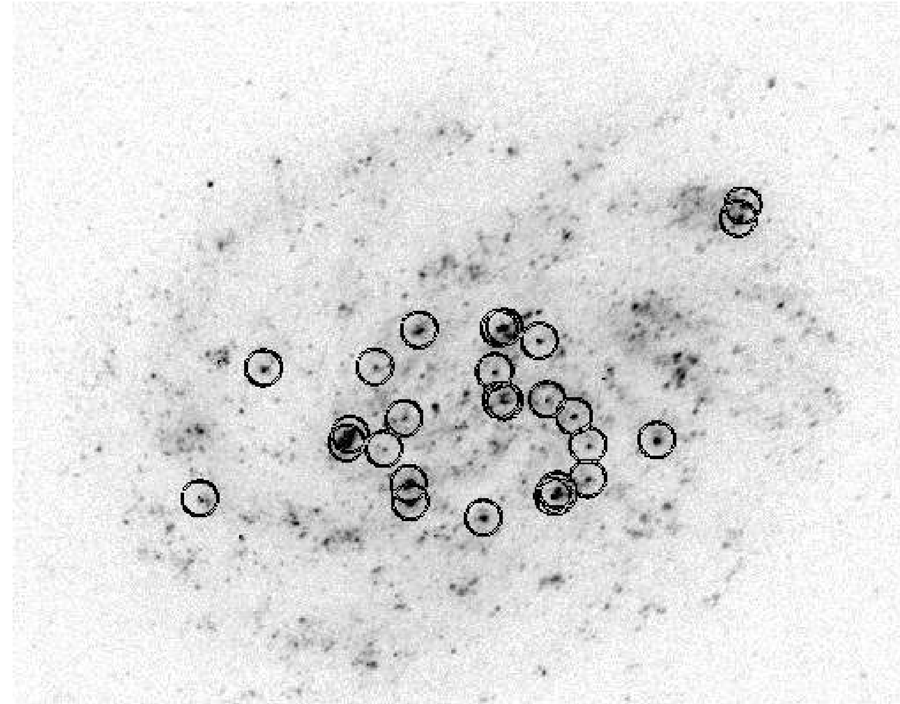
numerous SNR (Blair 97, Pannuti 00, Payne 04)
and WR (Breysacher 97, Schild 03)

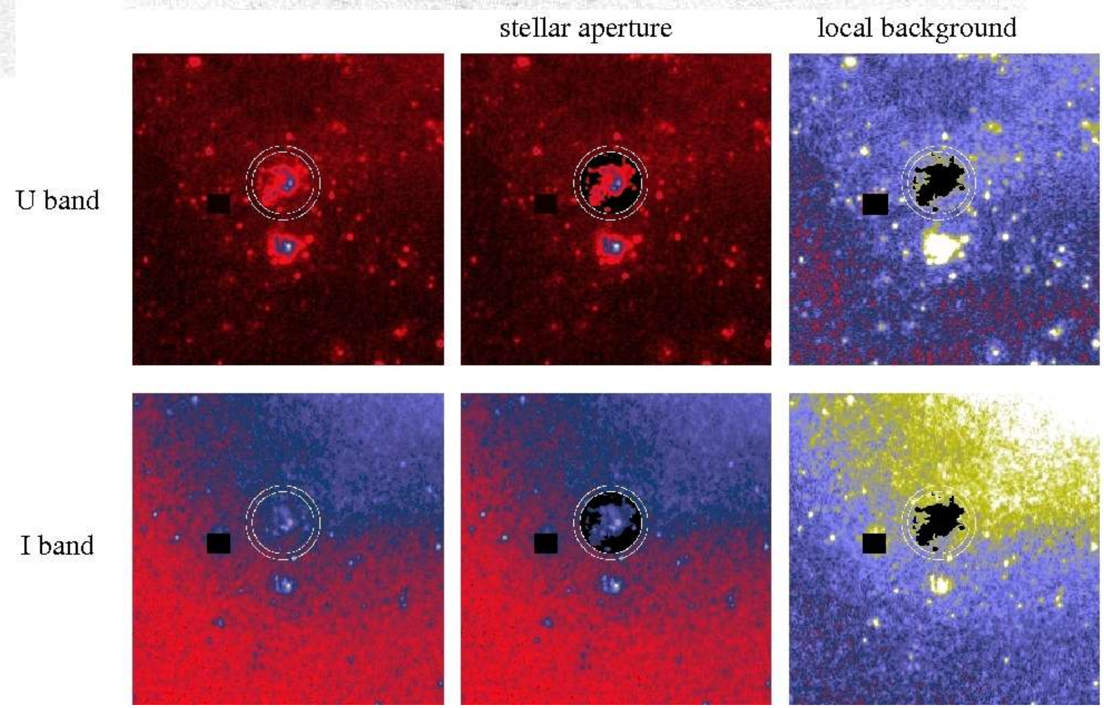
morphology of HII regions: evidence for high ISM porosity



sample of 27 ionizing stellar clusters:







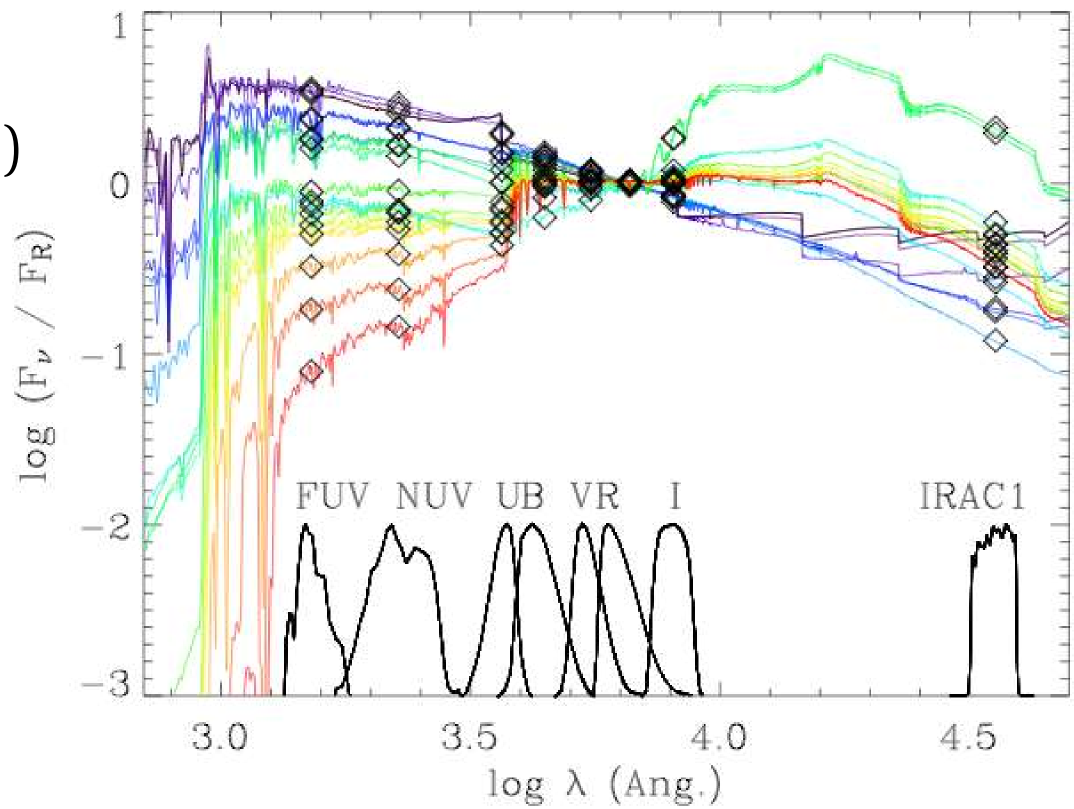
photometry:
local background b
and standard deviation σ
computed iteratively
in U band
→ apertures in all bands:
pixels < / > $(b + 3\sigma)$ in U

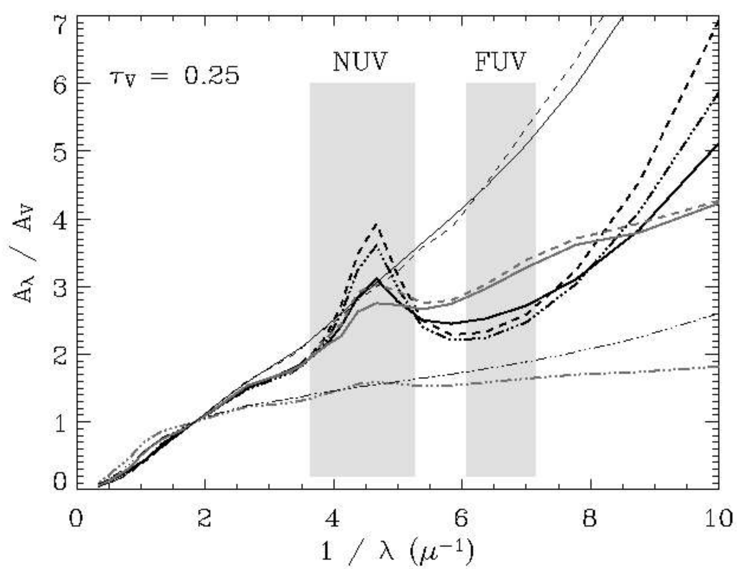
population synthesis fits:

Starburst99 model
(Leitherer et al. 99)
with Salpeter IMF (0.1–120 $M_\odot$)

discrete grids of age
and extinction at 1516 Å

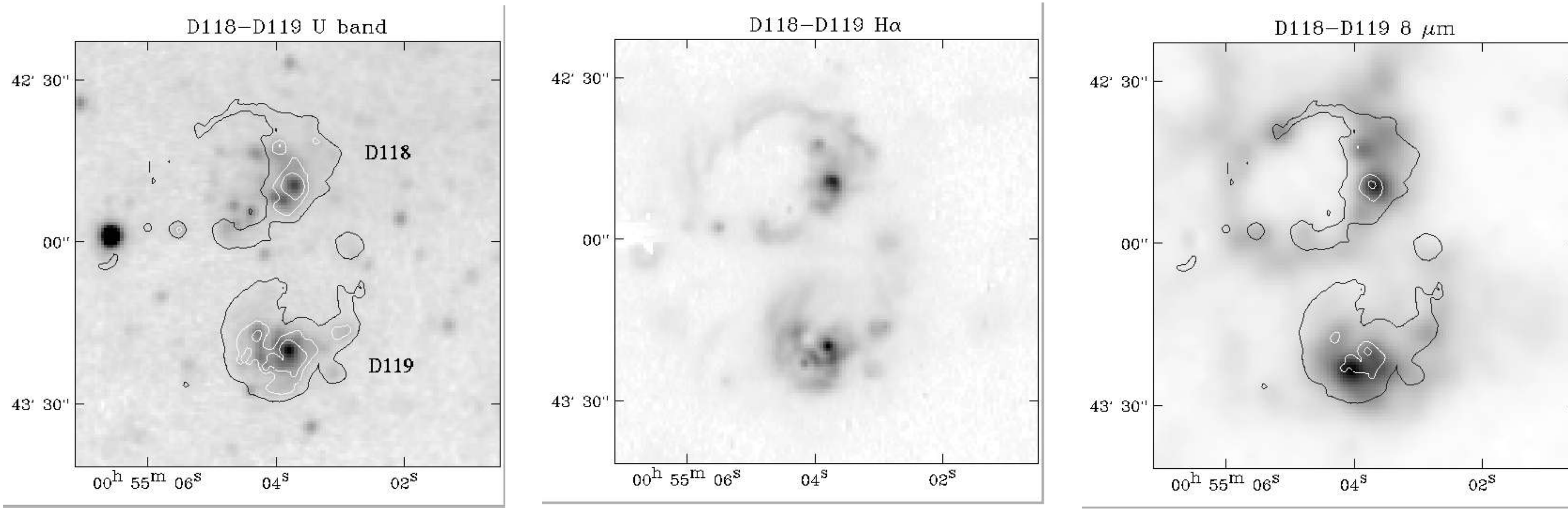
observed N_{Lyc} **not** used
as constraint (but in good
agreement with fits)





coupled with different extinction laws:

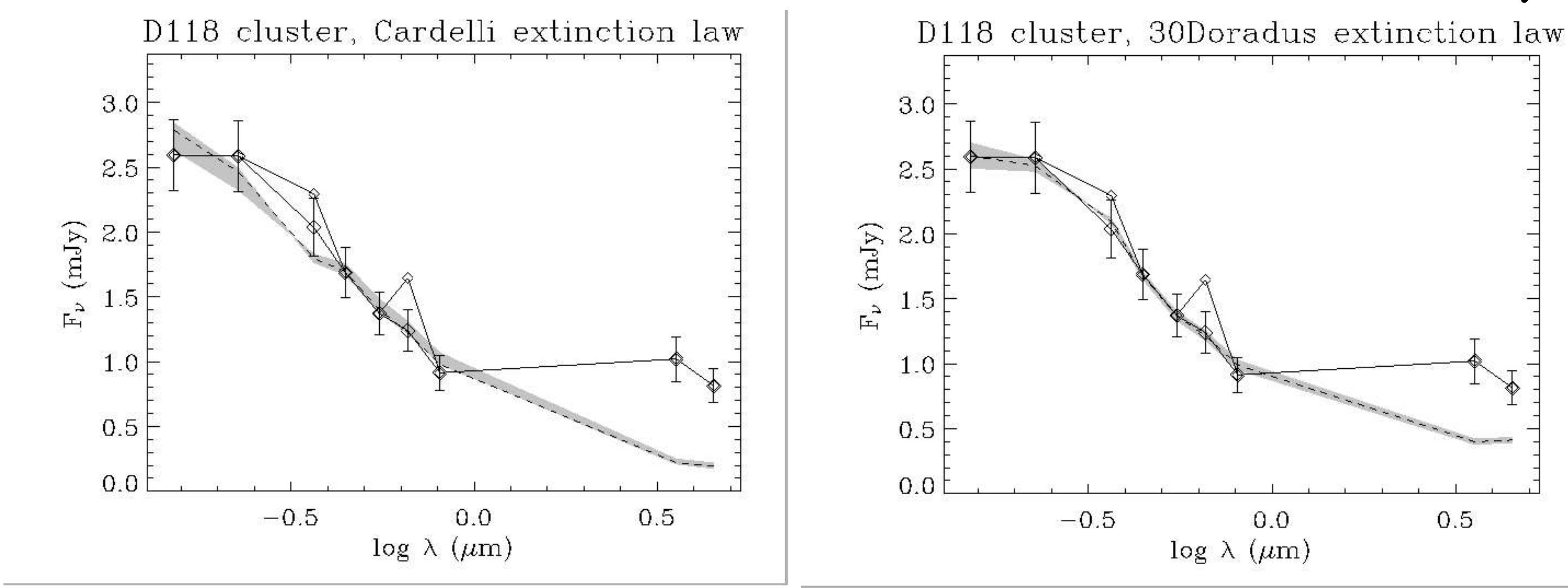
MW diffuse ISM: A(FUV)/A(NUV) =	1.00
LMC average:	1.10
30 Doradus:	1.27
Calzetti law:	1.20

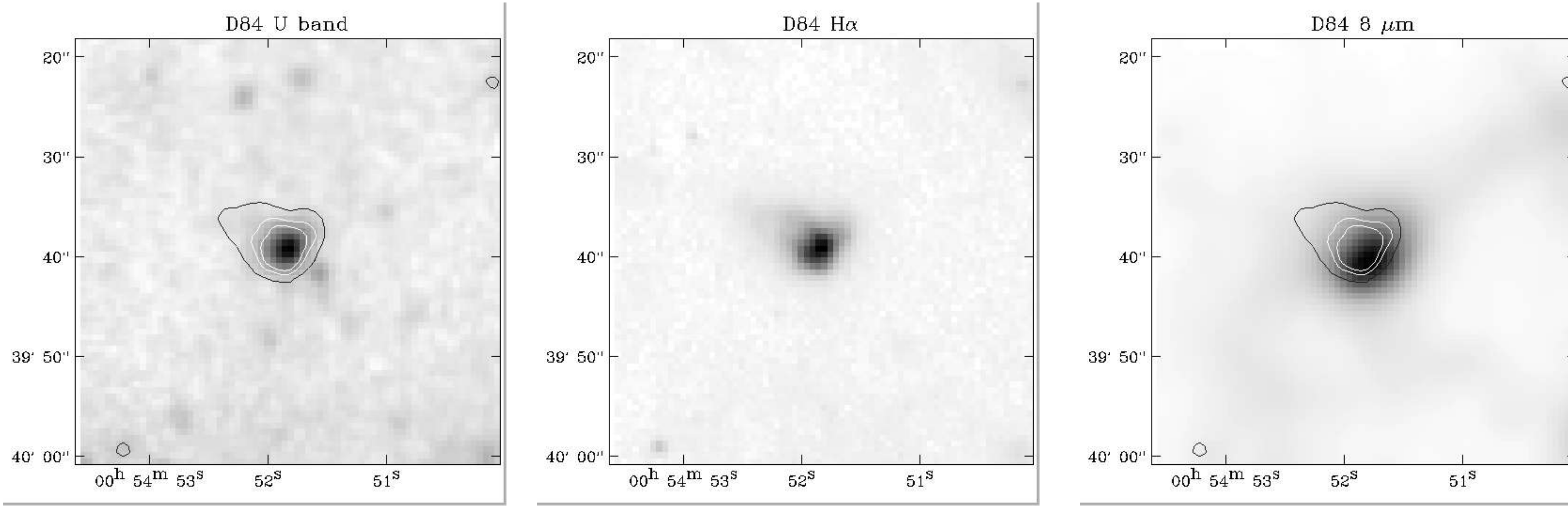


D118: complex and diffuse HII region best fit: 30 Dor law

age ~ 3 Myr, A(1516 Å) = 0.7 ± 0.1, M = (31 ± 2) x 10^3 $M_\odot$

Calzetti law: degenerate with 30 Dor law, but overpredicts N_{Lyc}

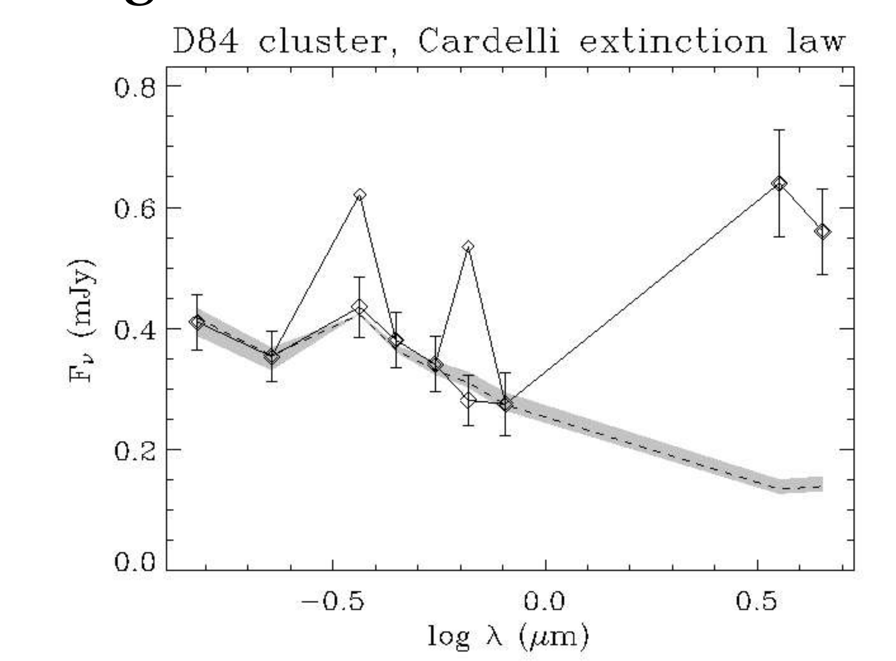


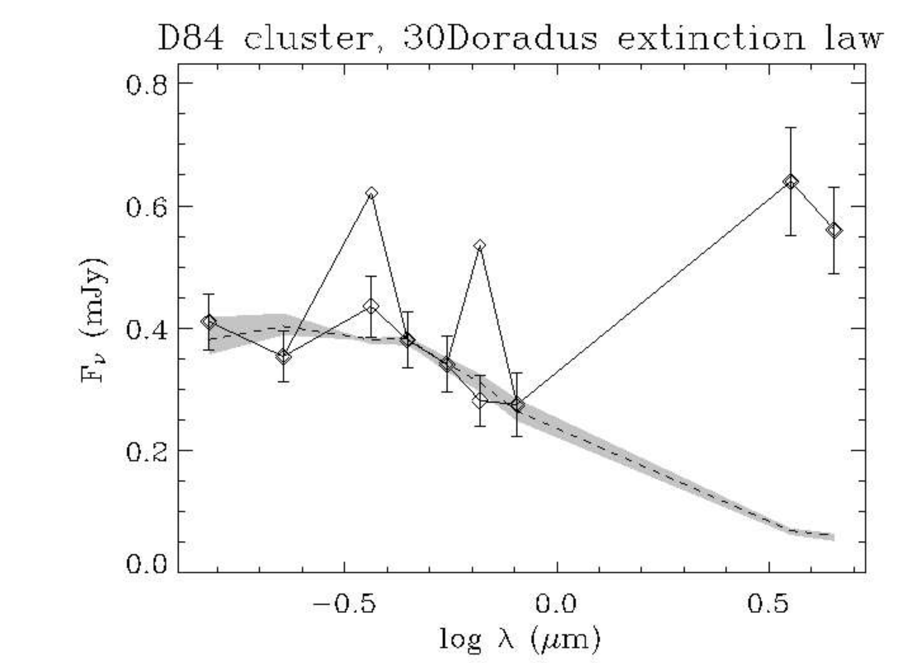


D84: compact HII region best fit: MW law ($R_V = 3.1$)

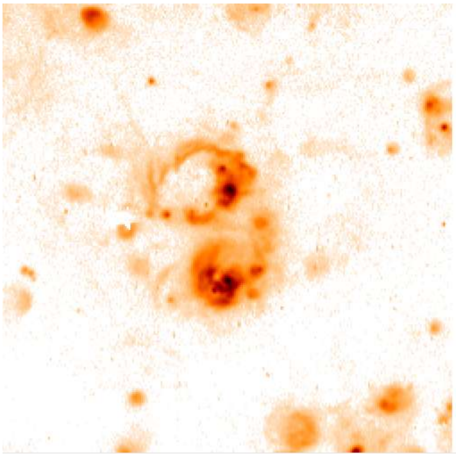
age ~ 3 Myr, A(1516 Å) = 1.5 ± 0.2, M = $(10.3 \pm ^{1.3}_{0.5}) \times 10^3\ M_\odot$

strong near-IR excess from ISM

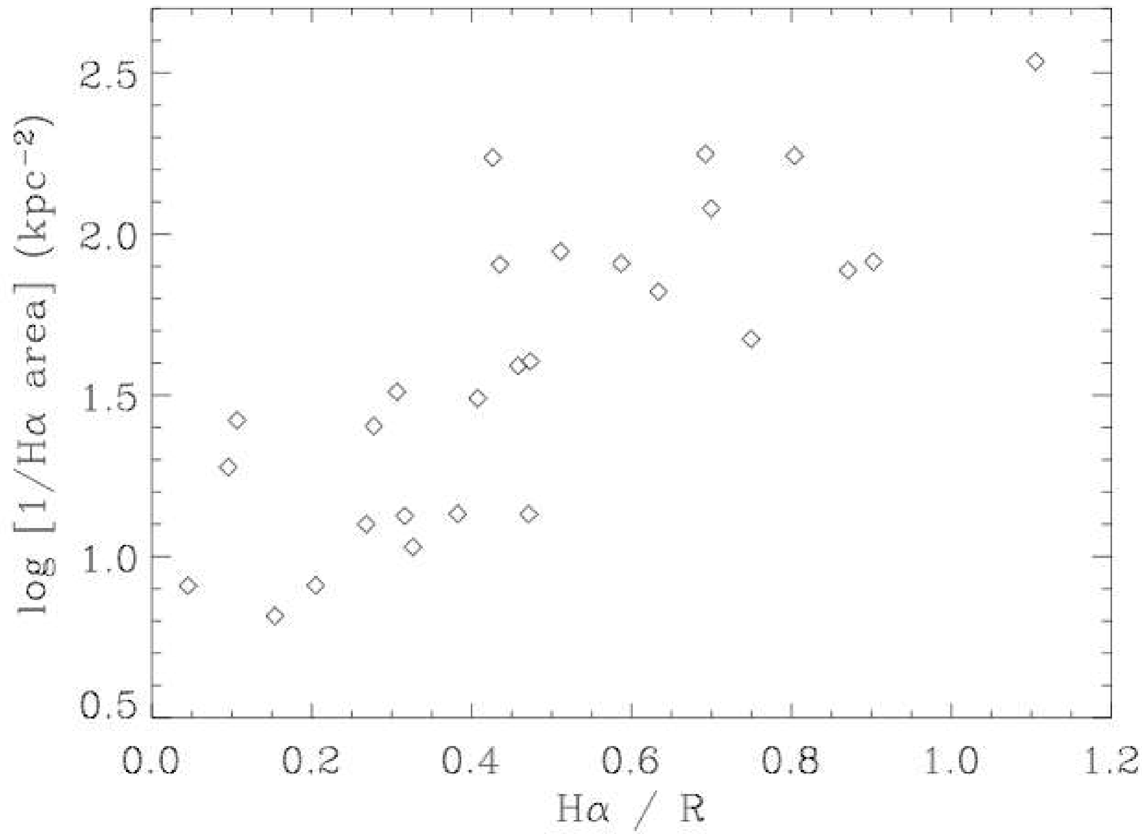


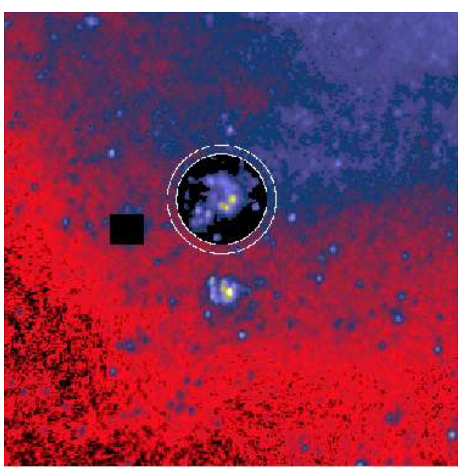


compactness of HII regions:



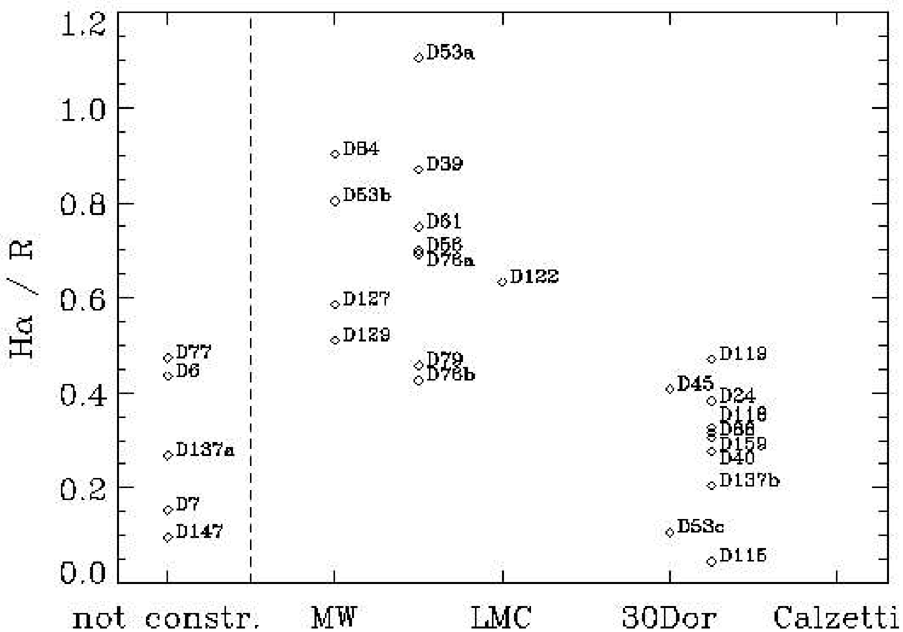
inverse area of (Hα > 6σ)

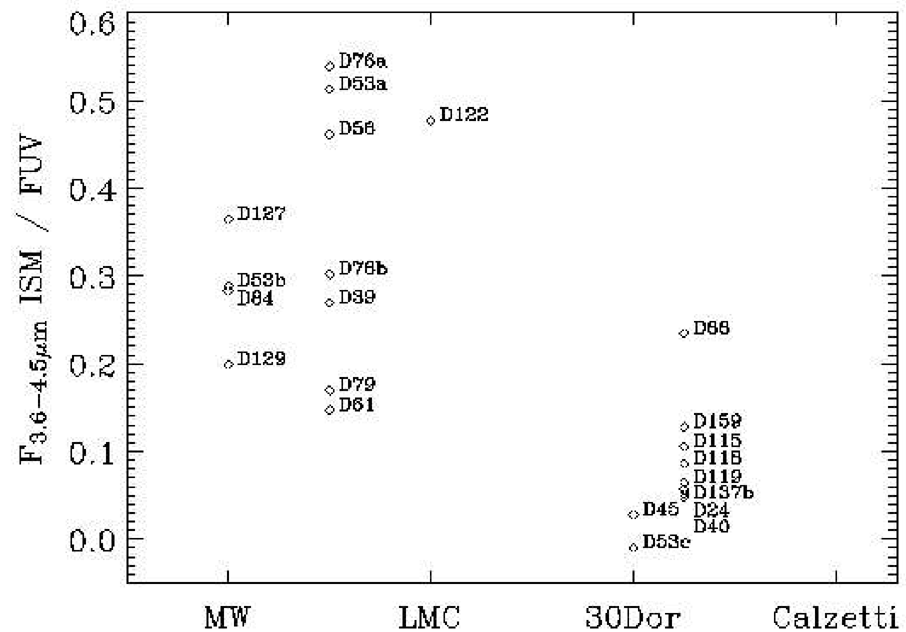




Hα / R ratio inside stellar aperture

systematic variation of the extinction law:



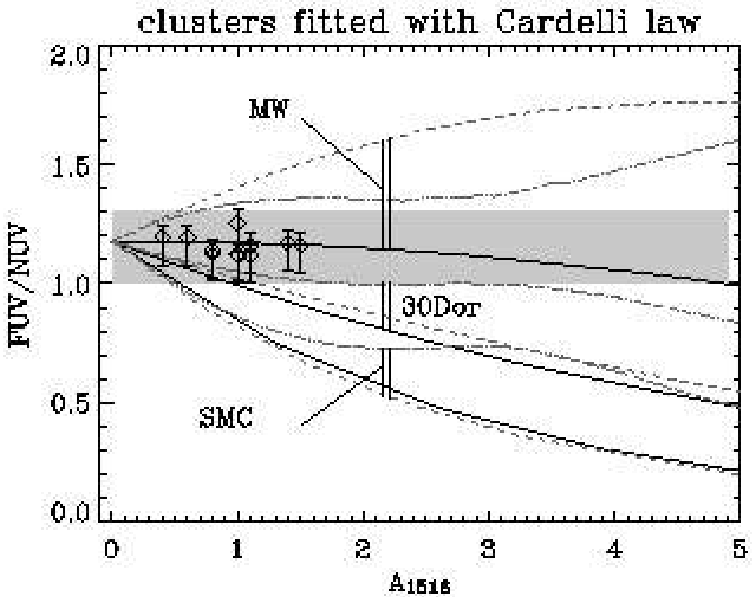


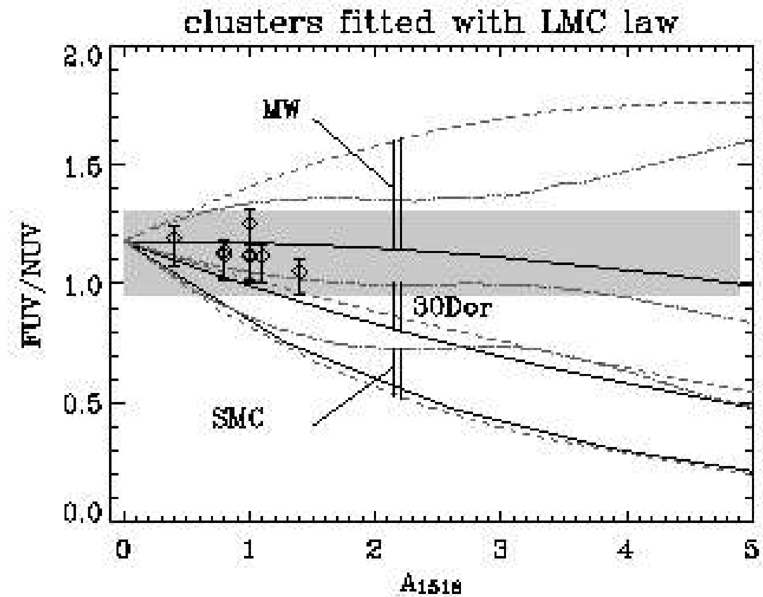
shape of best-fit extinction law correlated with both:

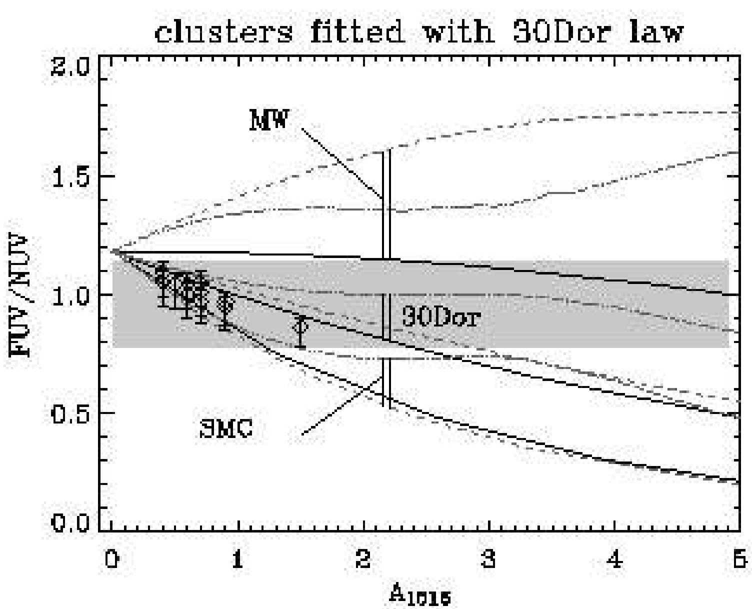
– local ISM geometry (HII region compactness)

– column density of 3-5 μm emitting dust
(emission in excess of stellar fit, normalized by FUV)

radiative transfer effects:







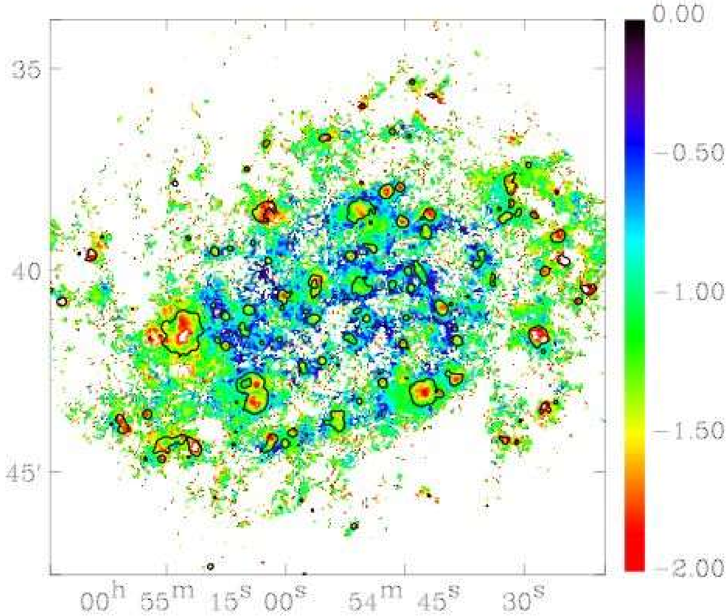
predictions of DIRTY (Witt 00, Gordon 01, Misselt 01):

observed FUV/NUV = f ($A_{1516\,\text{Å}}$)

for 3 Myr-old cluster

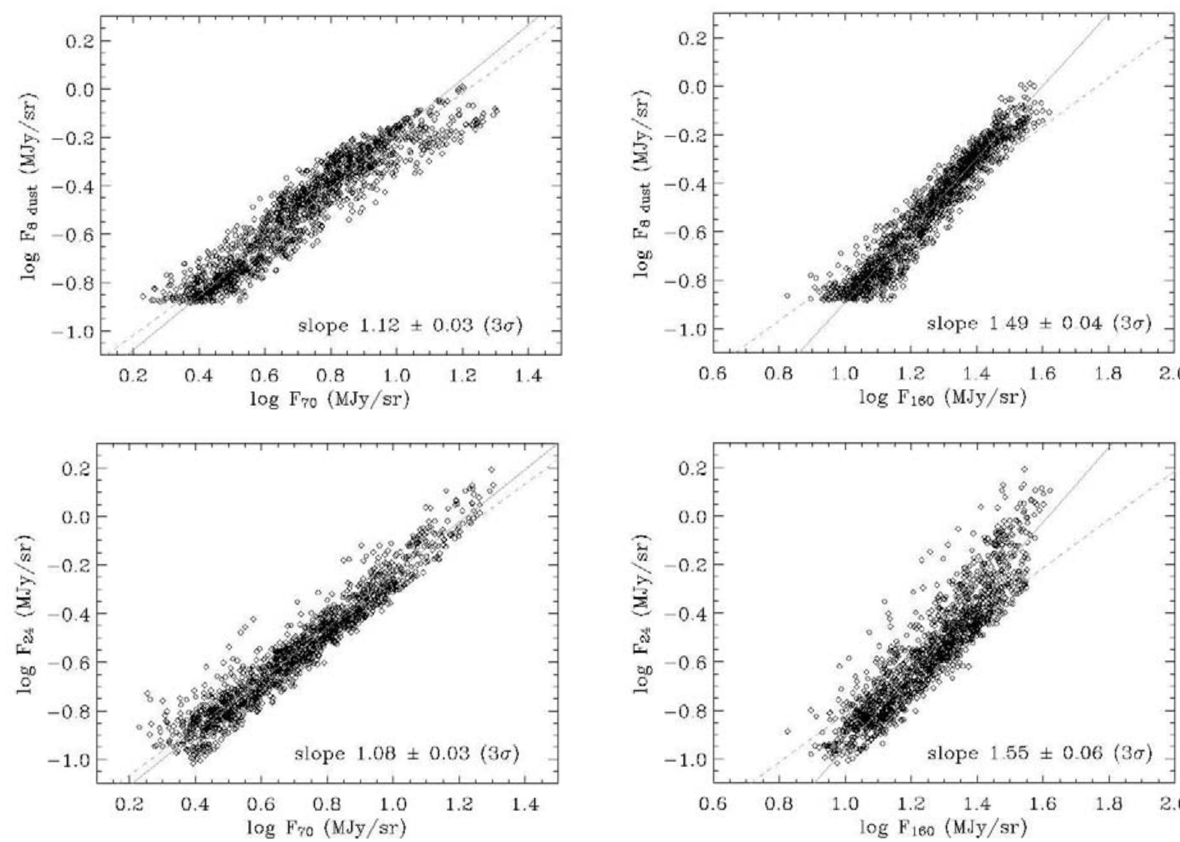
error bars: allow age from 1 to 5 Myr

on the excitation of aromatic bands:



8 μm / Hα map: aromatics depleted inside HII regions (cf Galactic studies showing association with PDRs)

but aromatics associated more closely with warm dust (24 and 70 μm) than cold dust (160 μm)



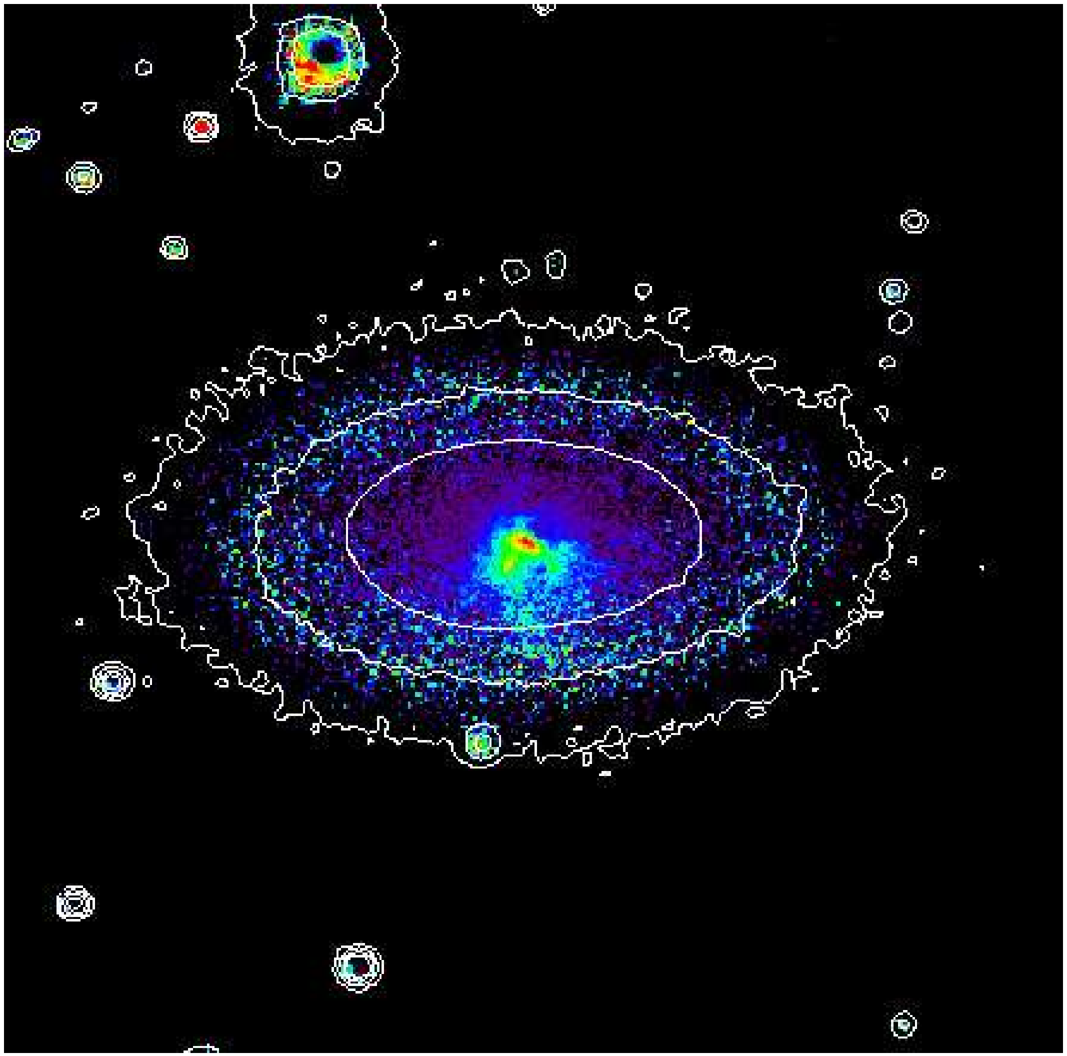
conclusions:

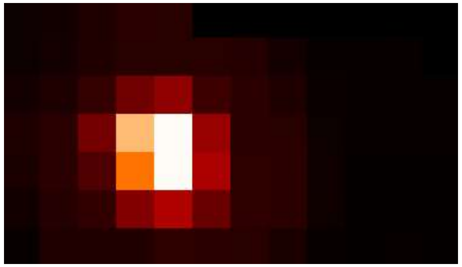
– extinction law highly variable toward clusters of ~ 2–4 Myr
– variations cannot be explained entirely by radiative transfer effects (shell configuration)
– variations correlated with local ISM geometry:
MW and LMC laws → compact HII regions
30 Doradus law → diffuse HII regions
– variations also correlated with column density of transiently-heated dust at 3–5 μm and 8 μm

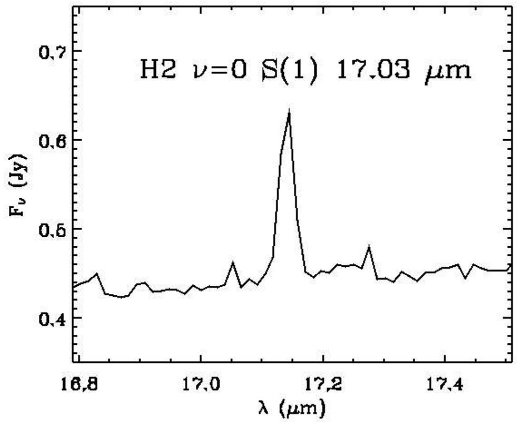
→ points to different photo-processing of dust
in compact regions (grains close to stars)
and in diffuse regions (ISM transformed by past SF)
→ simple extinction correction recipes (monochromatic)
may fail except in specific types of galaxies

– side result: ratio of nebular to stellar extinction $A(H\alpha)/A(R)$ varies between ~ 1.5 and 3.5

The extragalactic proto-starburst NGC 1377







Hélène Roussel (Caltech → MPIA)
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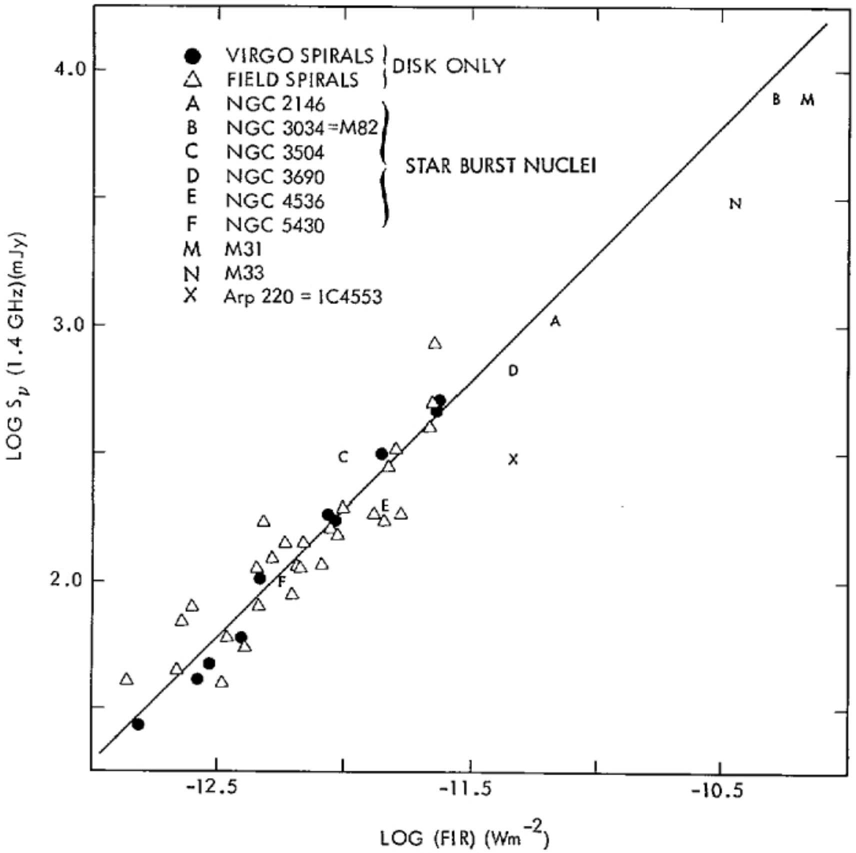
Jim Condon (NRAO)
Rob Kennicutt (Cambridge)
J.D. Smith (U. of Arizona)

infrared-radio correlation:

for star-forming galaxies: $q = \log [\mathrm{FIR}/(3.75\ \mathrm{THz})\ /\ S_{20}] = 2.34 \pm 0.19$

FIR: reprocessing of UV photons by dust

20 cm radio continuum: ~ 95% synchrotron + ~ 5% free-free



Helou et al. 1985

dust heated instantaneously by a starburst

cosmic rays accelerated in SN remnants (end product of stars > 8 $M_\odot$)

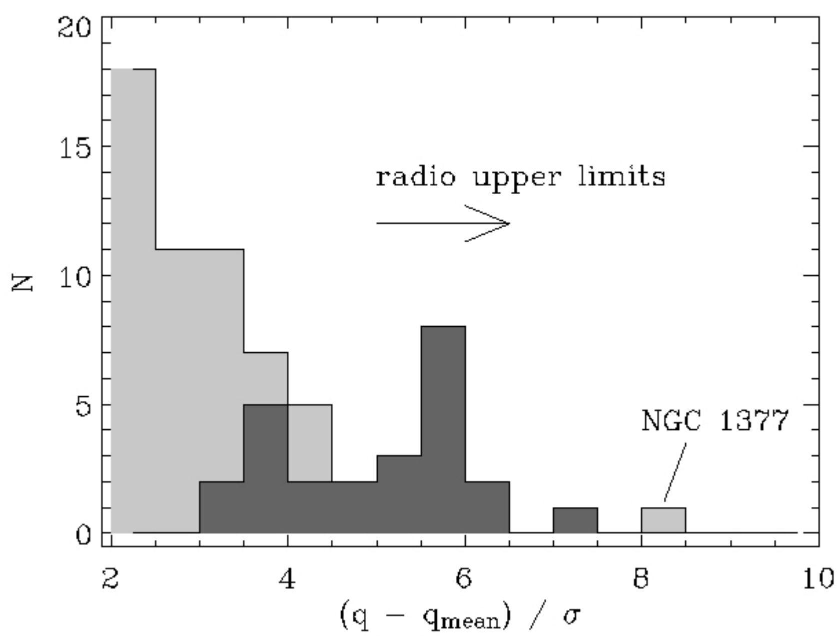
synchrotron decay in ~ 100 Myr

→ different timescales despite the tight correlation

selection of radio-deficient galaxies:

NGC 1377: only galaxy of the IRAS BGS ($F_{60} > 5$ Jy) undetected at 20 cm (1 mJy level) in the VLA survey
$F_{60} / F_{100} = 1.2$ ($T_{BB} = 80$ K, $T_{Gal.\ dust} = 50$ K)

search of other radio-deficient galaxies among IRAS FSC:
– $F_{60} \geq 0.7$ Jy
– $F_{60} / F_{100} \geq 0.7$ → infrared excess not of cirrus origin
– $q > \overline{q} + 3\sigma$



interpretation of the radio weakness:

hot dust → intense radiation field

deficit of synchrotron → CR generated by previous SF episodes have decayed (τ ~ 100 Myr)

↳ CR not yet injected by current burst (delay of ~ 4 Myr)

consistent with rate of occurrence:

< 1% of flux-limited sample, ~ 17% of 60 μm-peakers

characterization of the radio emission mechanisms:

synchrotron: $S_\nu \propto \nu^\alpha$ with α ~ -0.8 ± 0.2

free-free: $\alpha = -0.1$

at high e^- densities: thermal opacity $\tau \propto \nu^{-2.1}$

partial results of a multi-frequency VLA-C survey (3, 6 and 20 cm):

– 8 galaxies with significant opacity → $q_{intrinsic} = \bar{q} + (2–3)\sigma$

– 16 confirmed at 20 cm, followed up at 3 and 6 cm

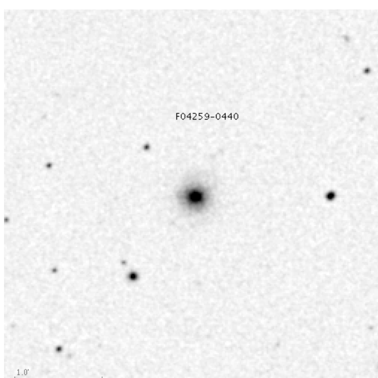
– 23 new intrinsically radio-deficient galaxies:

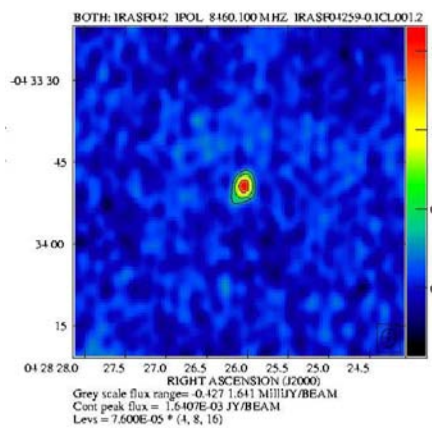
6 undetected (0.2–0.3 mJy level)

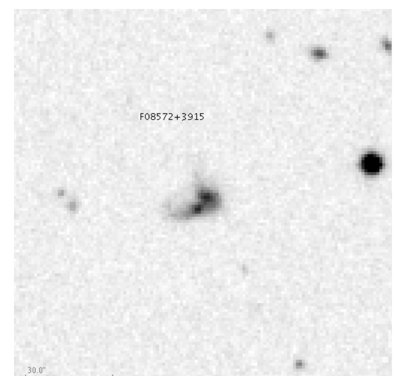
11 with steep spectrum: α(3–6cm) < -0.4 → synchrotron residue

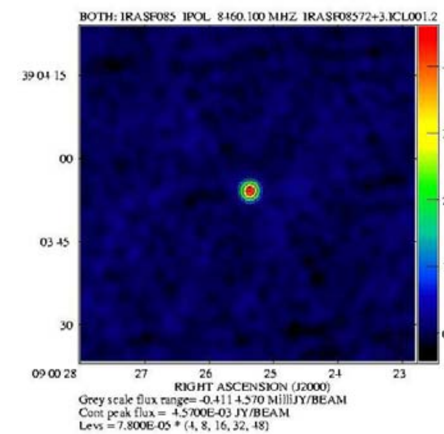
6 with flat spectrum: α(3–6cm) > -0.4

at least 2 IR-luminous galaxies dominated by free-free:









D ~ 60 Mpc

$L_{FIR} = 2.2 \times 10^{10}\ L_{\odot bol}$

E-S0, LINER, shells

S(3 cm) = 1.65 mJy, α(3-6 cm) = -0.21

D ~ 230 Mpc

$L_{FIR} = 5.1 \times 10^{11}\ L_{\odot bol}$

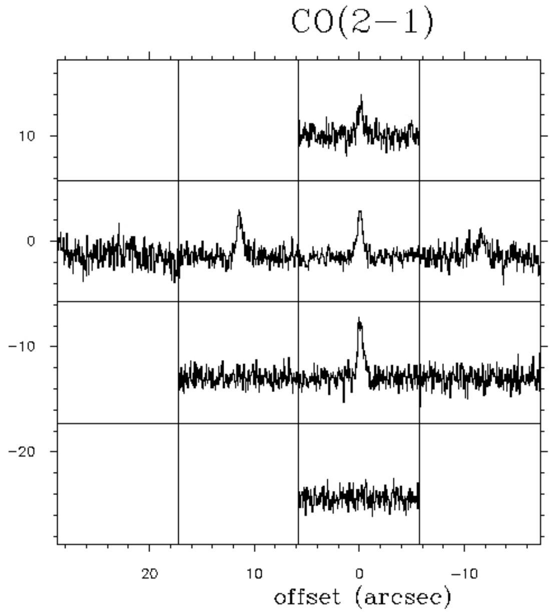
merger, LINER

S(3 cm) = 4.61 mJy, α(3-6 cm) = -0.08

NGC 1377: cold molecular gas:

$M(H_2) \geq 2 \times 10^8\ M_\odot$

$T_b(2\text{-}1)\ /\ T_b(1\text{-}0) = 0.53 \pm 0.14$



mass needed to fuel the starburst: $\leq 3 \times 10^7\ M_\odot$

($M_{dust} = 4 \times 10^4\ M_\odot$ to $3 \times 10^5\ M_\odot$)

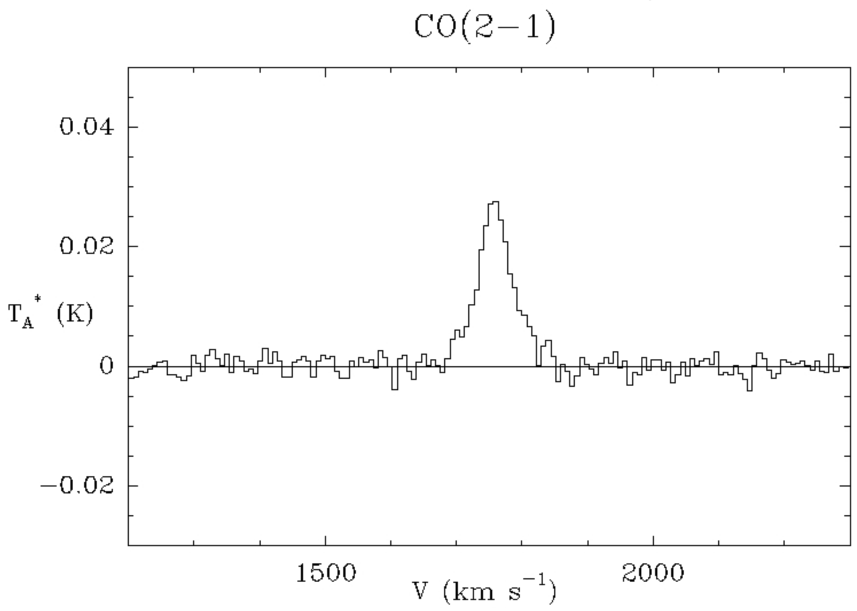
FWHM = 66 km/s

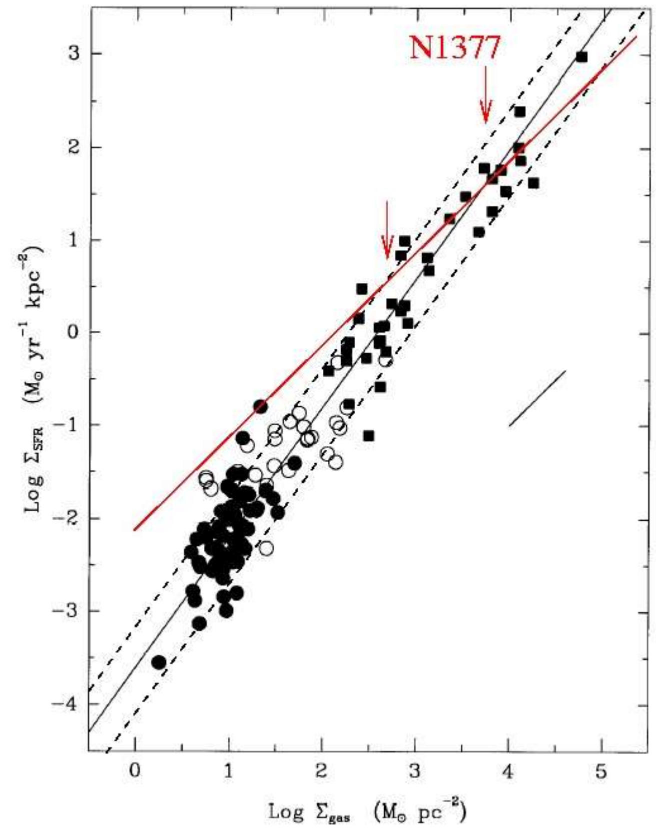
Schmidt law:

$D_{gas} = (200 \pm 250)$ pc

Toomre criterion:

$Q_{gas} < 0.33$ (for $D_{gas} = 500$ pc)



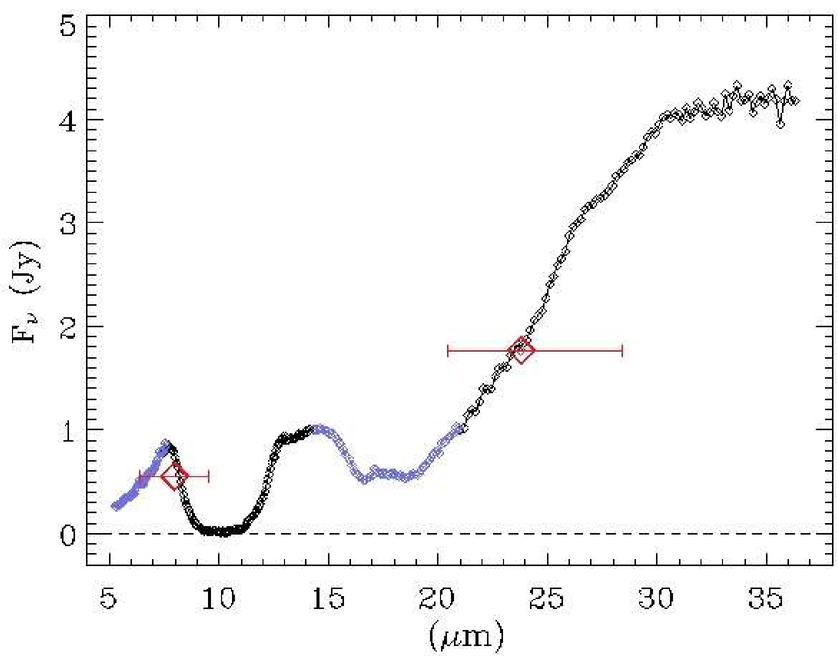


Kennicutt 1998

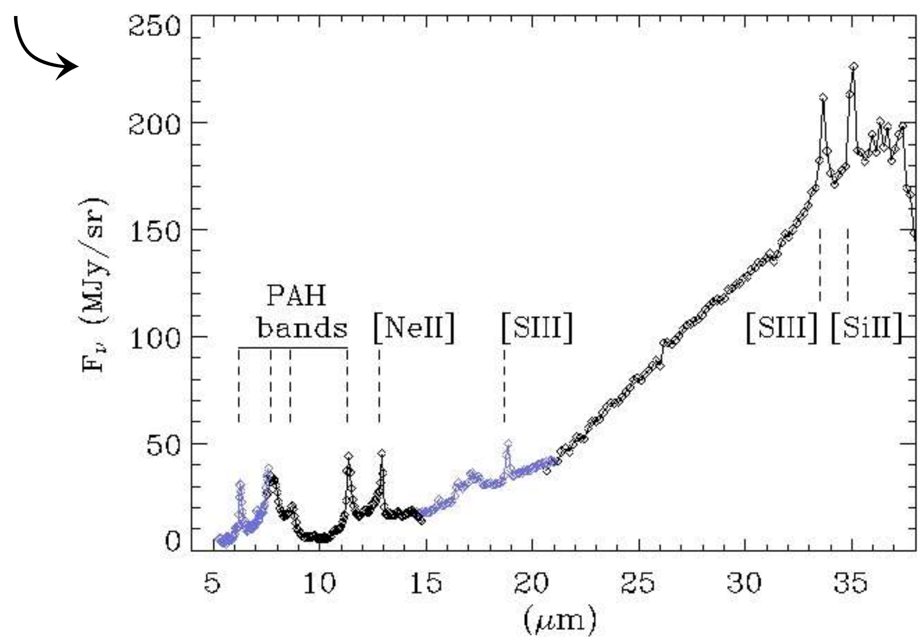
Spitzer SINGS observations of NGC 1377:

broadband imaging at 3.6 / 4.5 / 5.7 / 8 / 24 / 71 / 156 μm
spectral mapping 5–40 μm at low and high resolution

dust emission unresolved (≤ 100 pc)
evidence for very high optical depth (amorphous silicates 10 & 18 μm)



compare with a typical starburst:
nucleus of NGC 2798 (also in SINGS)

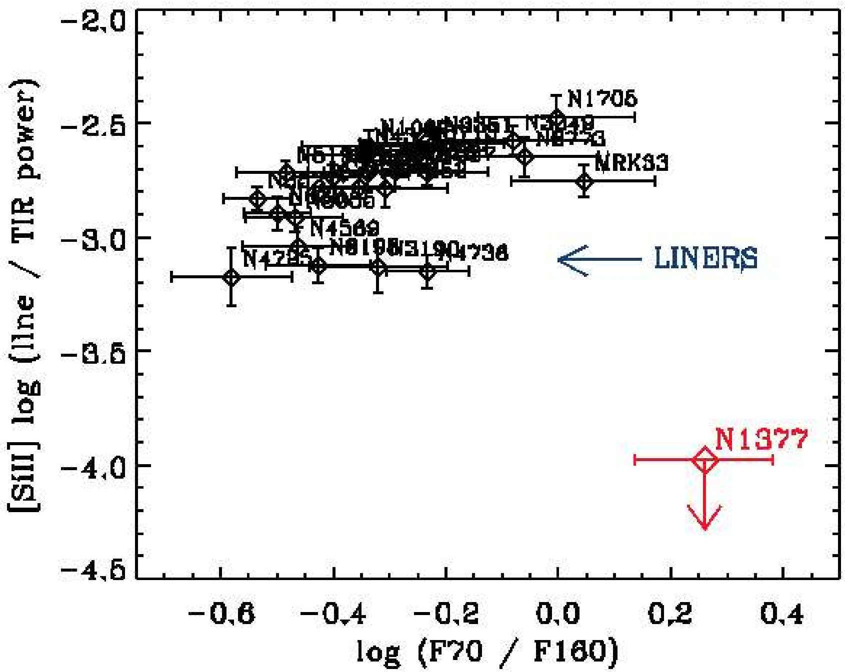


spectral features:

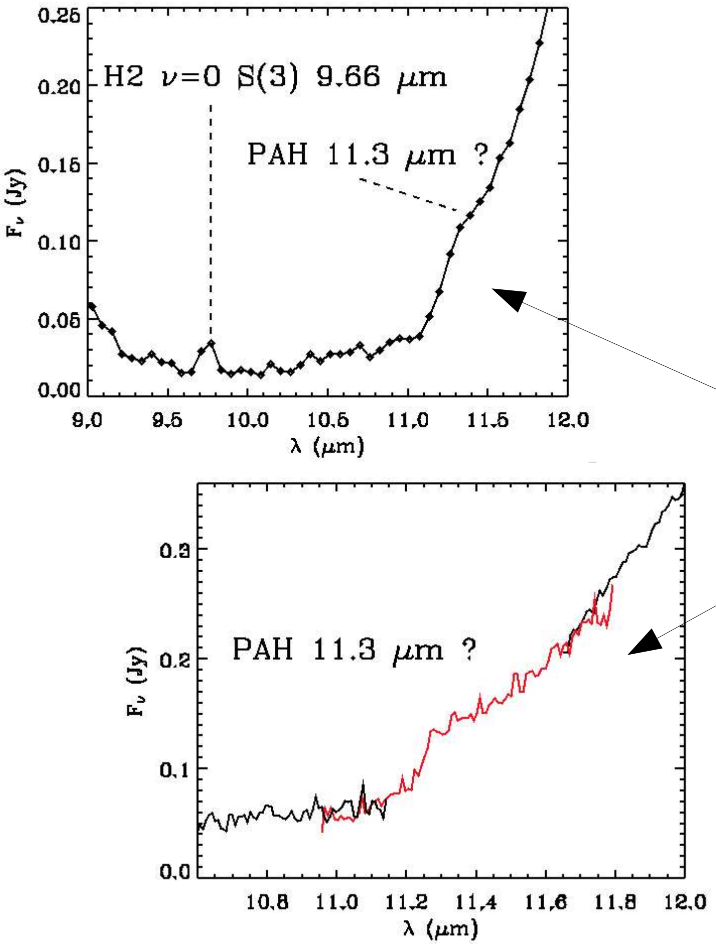
no forbidden lines detected (high and low excitation)
→ confirmation of the absence of HII regions and PDRs

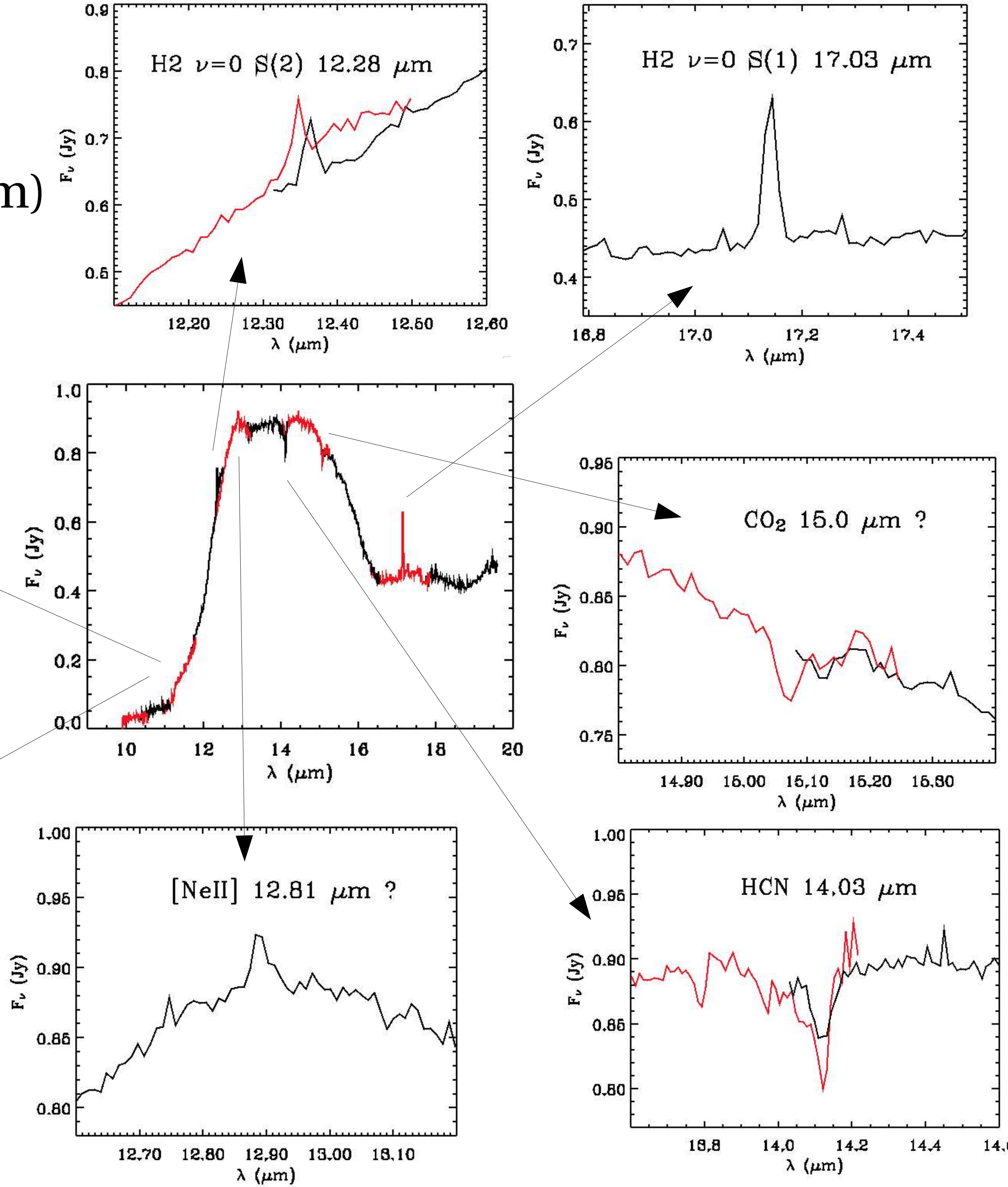
(radio limits on free-free → > 70% of N_{Lyc} absorbed by dust ;
near-IR spectroscopy → stringent limits on Paβ and Brγ ;
far-IR spectroscopy → stringent limits on $[CII]_{158\ \mu m}$ and $[OI]_{63\ \mu m}$)

$[SiII]_{34.8\ \mu m}$:



warm H_2 lines:
likely shock-excited
(also hot H_2 line at 2.2 μm)





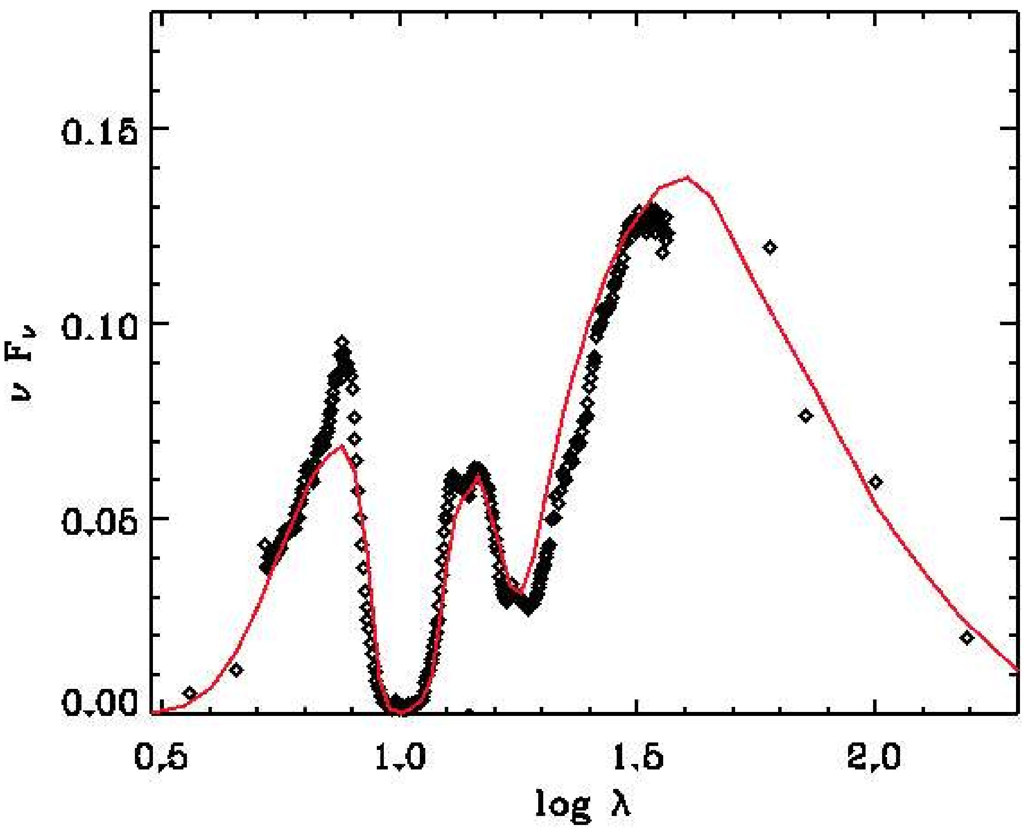
faint 11.3 μm PAH:
also 17 μm complex ?

radiative transfer model:

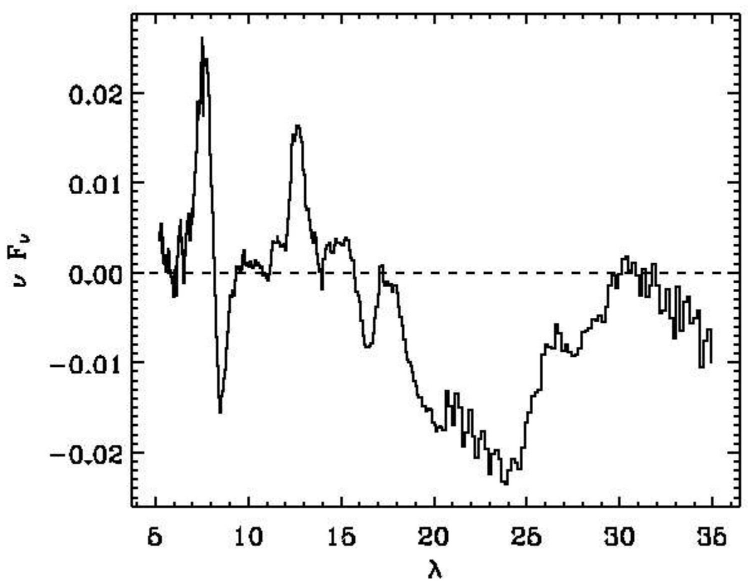
use of the DUSTY model (Ivezić et al. 99)
limitations: hypothesis of a single spherically symmetric source
no out-of-equilibrium treatment for small grains

acceptable fit (not unique !) obtained for:
τ_V ~ 80, T_{max} ~ 2000 K, steep density profile
70% silicates (Ossenkopff et al. 92), 30% graphite

overabundance of small grains ?
→ shocks ?

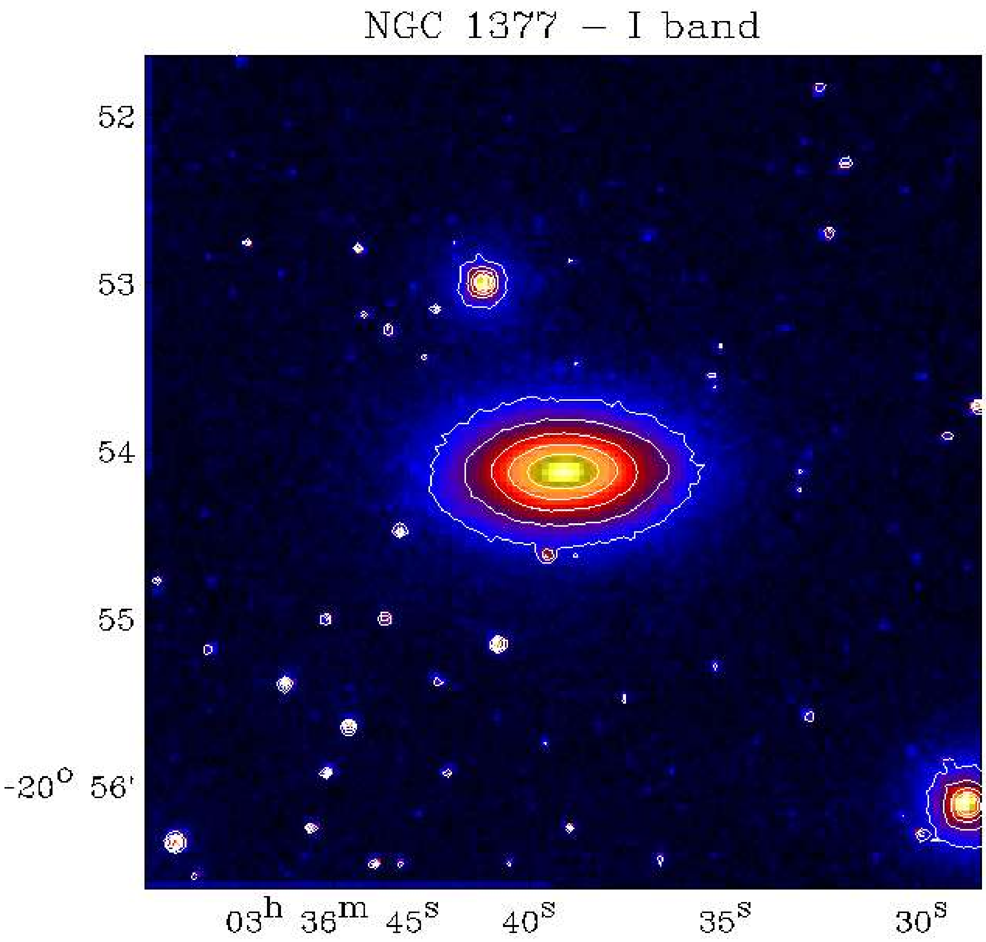


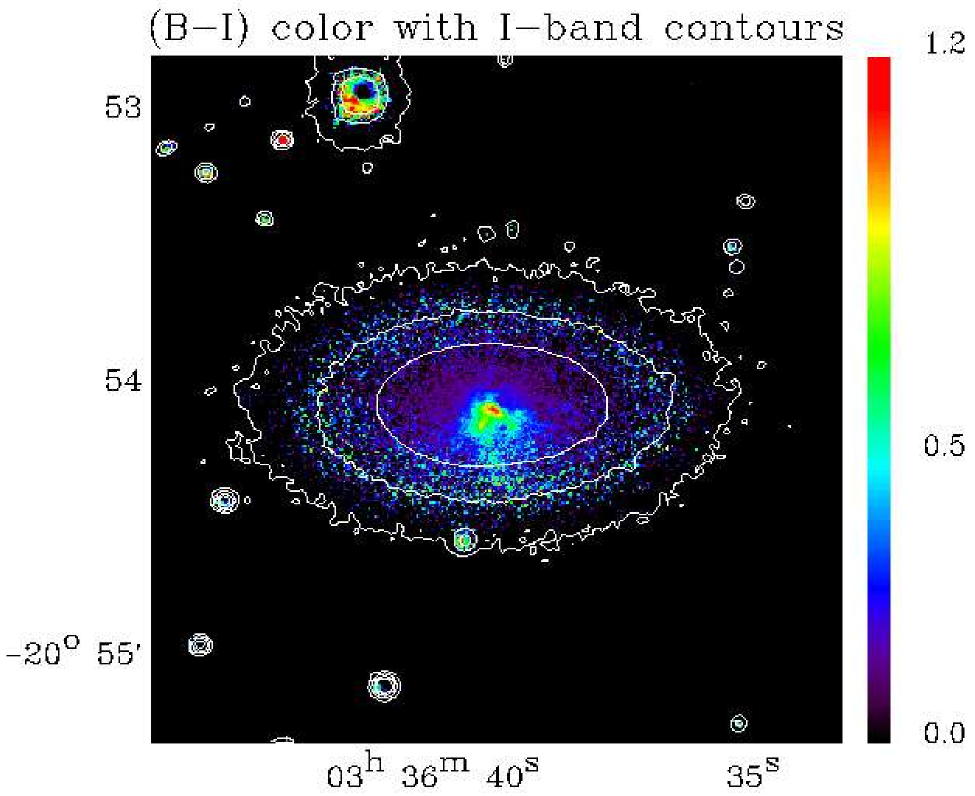
residues: PAHs, crystalline silicates



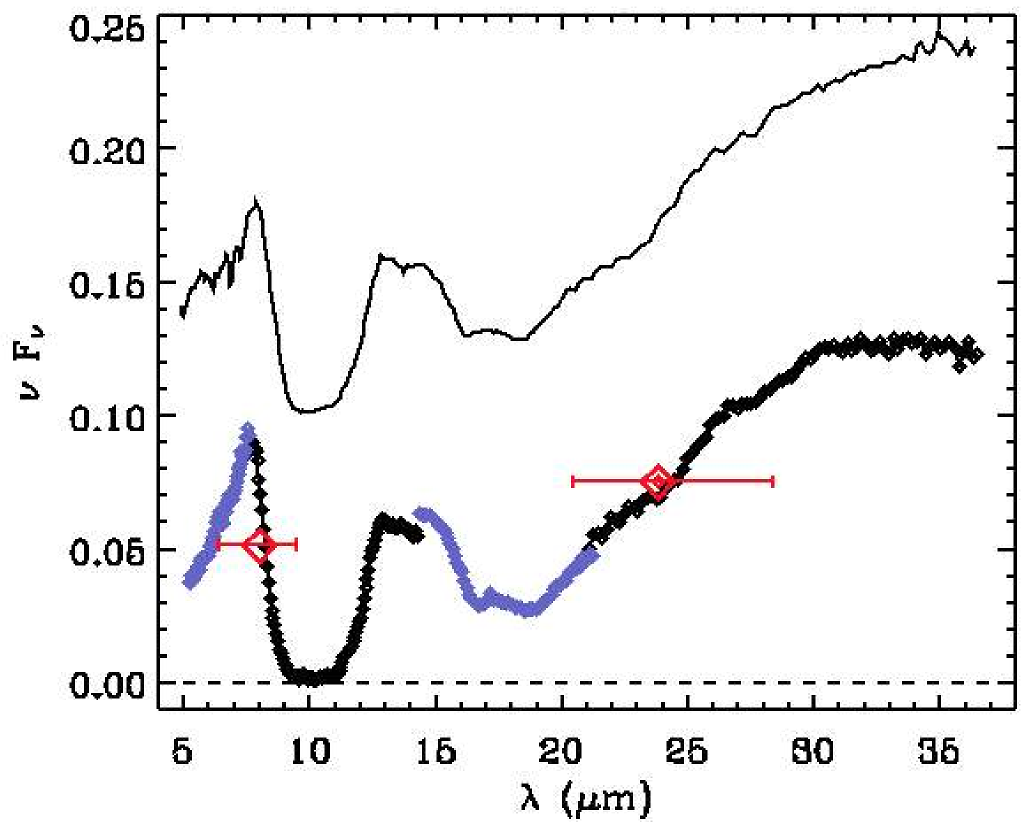
optical morphology:

optical/near-IR: lenticular galaxy
optical color map → disturbance in center and south
3 extinction peaks + diffuse structure (total extent: 2 kpc)
minor merger ?





comparison with deeply obscured LIRGs-ULIRGs:

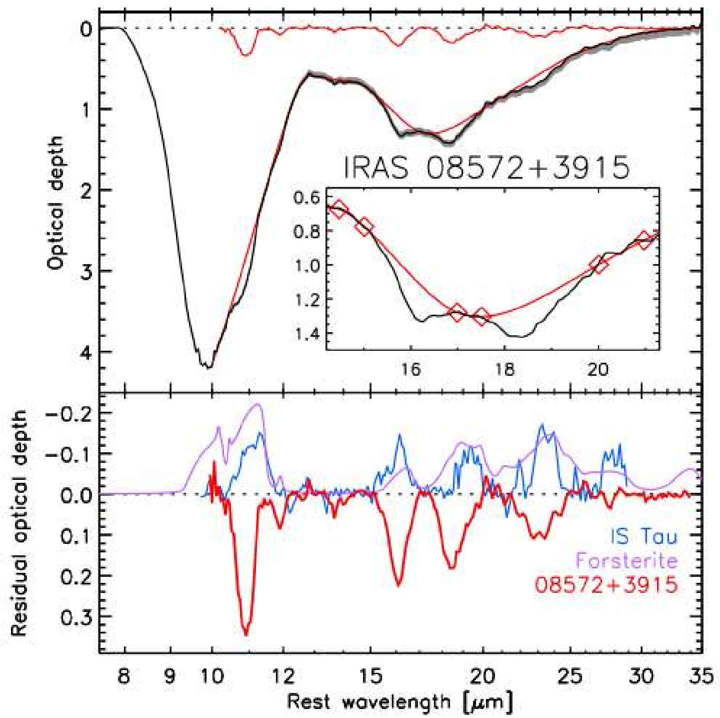


radio-deficient LIRG (dominated by free-free)

$L_{FIR} = 5.1 \times 10^{11} L_{\odot bol}$

NGC1377

$L_{FIR} = 4.3 \times 10^{9} L_{\odot bol}$



Spoon et al. 05:

signatures of crystalline silicates

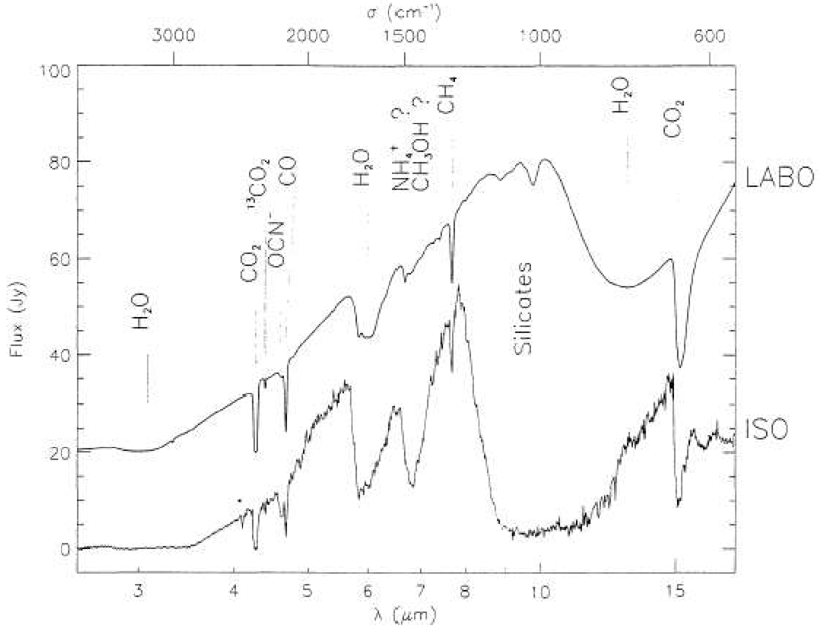
balance: injection by massive stars

amorphization by CR

a scaled-up version of BN objects ?

BN objects: intermediate stage between
- protostar (accretion phase)
- and ultra-compact HII region (Henning & Gürtler 86)
in dense molecular clouds, compact optically-thick dust shells
H_2 lines formed in shocks between outflows and molecular cloud

important difference between massive protostars
and opaque starbursts: temperature of dense gas



d'Hendecourt et al. 99

protostars: ices
starbursts: gas-phase features
of a few 100 K

conclusions:

class of nascent starbursts defined by:
– infrared/radio continuum in strong excess
– hot dust → intense activity

interpretation: “pure” starburst observed before bulk of SN explosions (τ ~ 4 Myr), and after long quiescence (τ ~ 100 Myr)
NGC 1377: most extreme case, HII region growth inhibited

characteristics:
– compact, hot and highly obscured dust reservoir
– subthermal and possibly overcritical gas reservoir
– shocked molecular gas

same phenomenon observed over wide range of luminosities
→ NGC 1377 analogs promising to understand
initial conditions and early evolution of starbursts in ULIRGs

perspectives: Spitzer GO2 program of ~ 20 nascent starbursts
wide range of q ratios and luminosities