Evidence for starbursts in radio galaxies from optical/UV to far-IR

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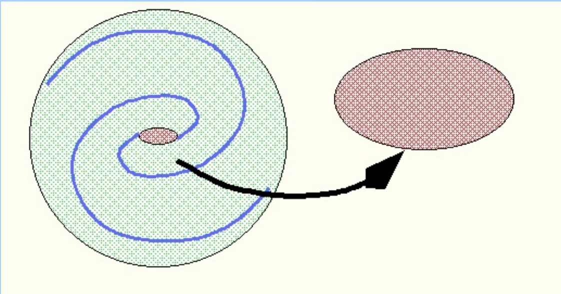
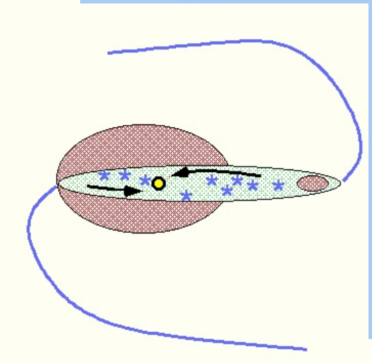
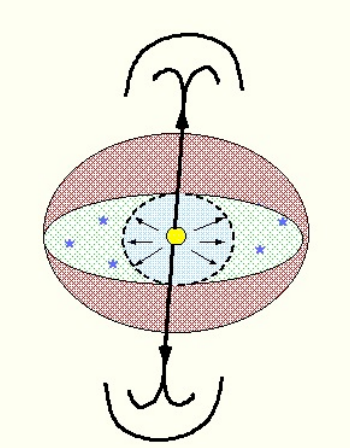
Evolutionary



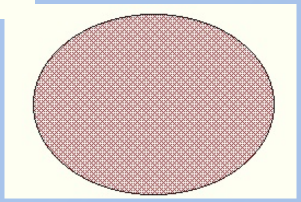
Start of merger



Advanced merger: gas driven towards nucleus; starburst

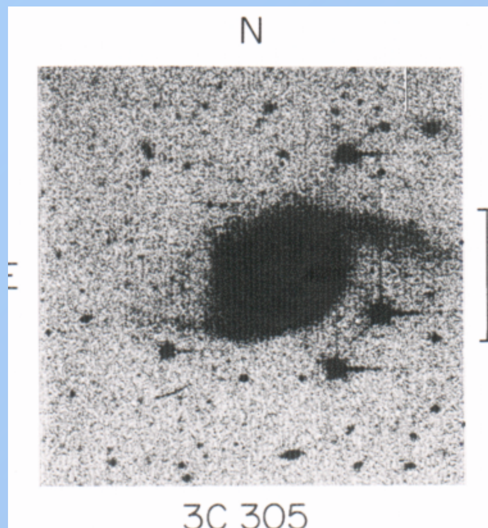


Quasar and jet activity drives gas out of galaxy
Now

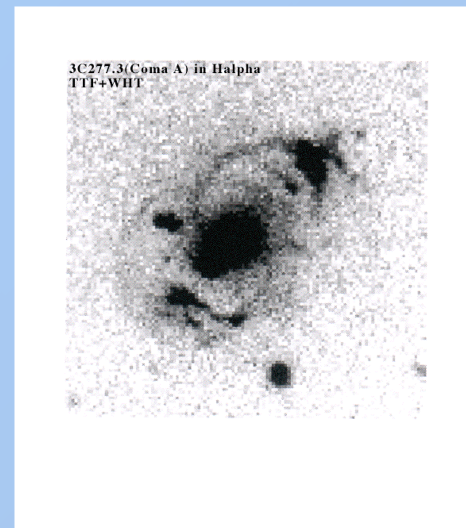


Relaxed
E-galaxy

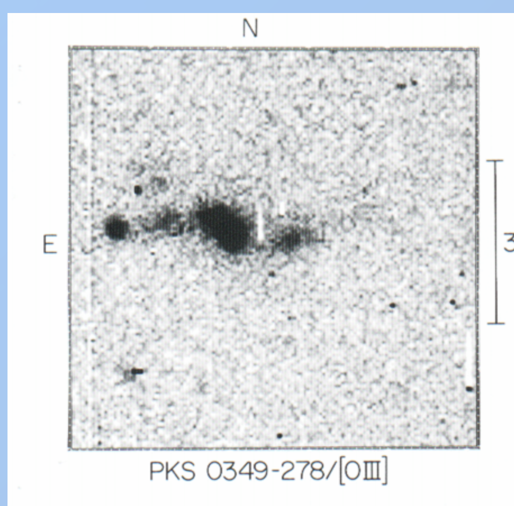
Mergers in radio galaxies



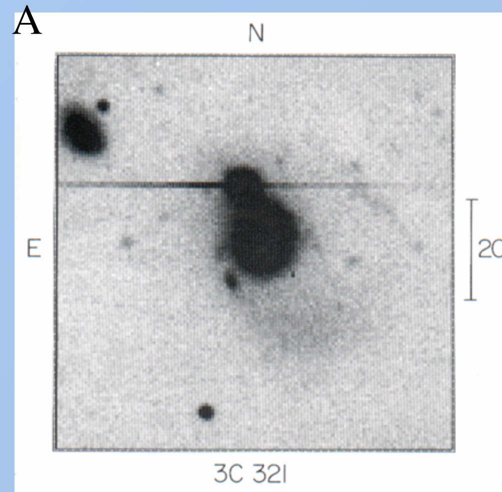
3C305



Coma A



PKS0349-27

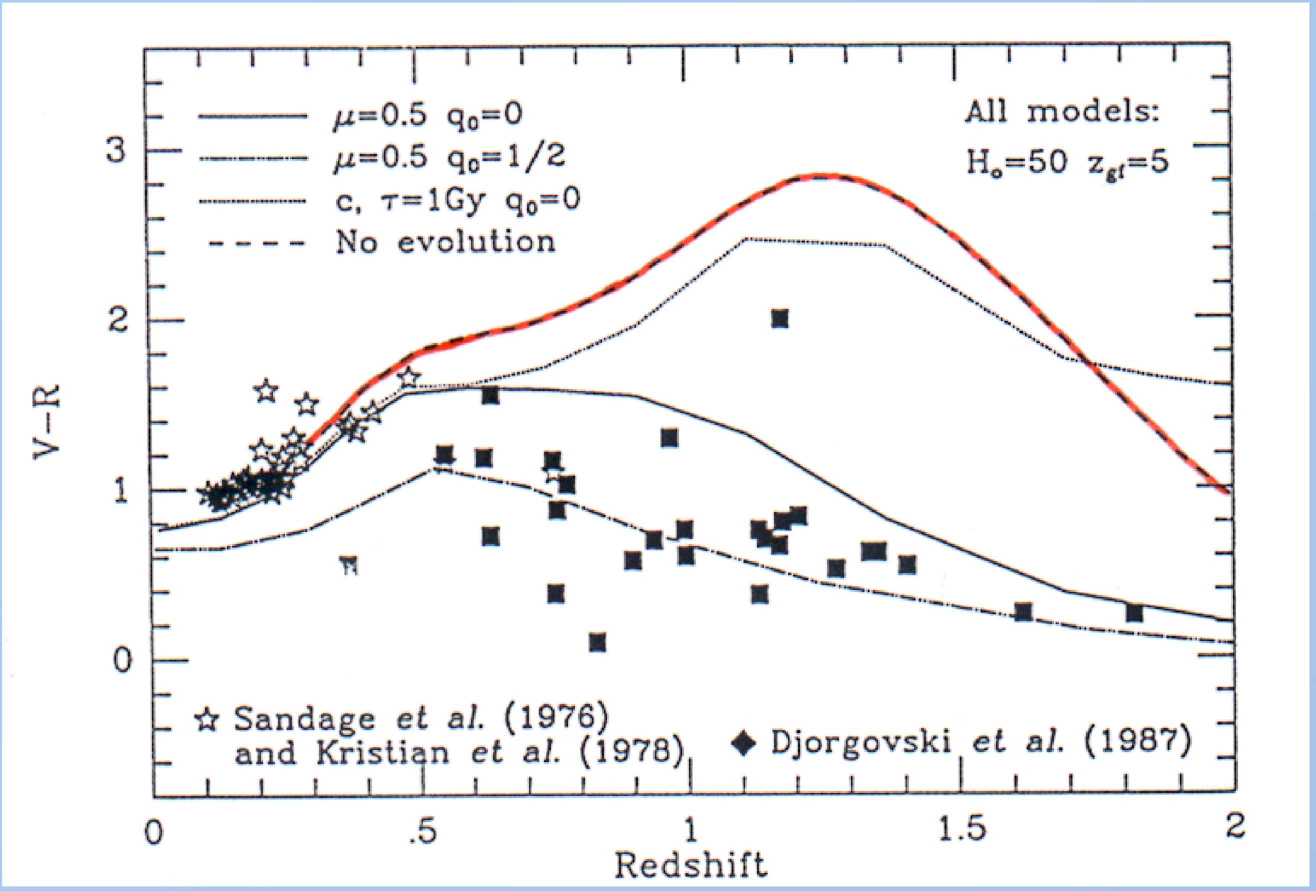


3C321

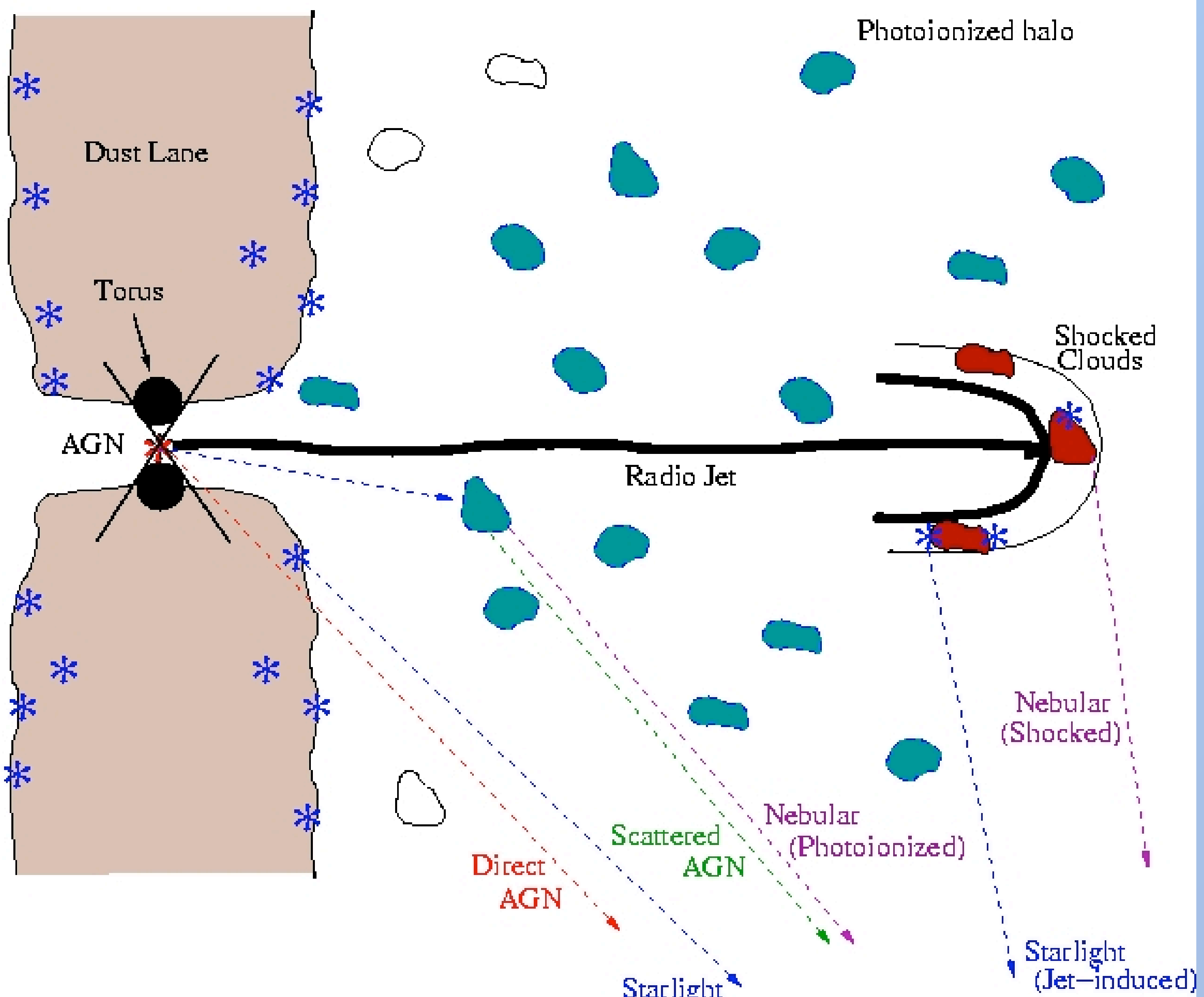
Clear morphological evidence for mergers found in ~50% of powerful radio galaxies with strong emission lines.

Heckman et al. 1986

Distant radio galaxies: colours



Contributions to the UV excess in powerful radio galaxies



Starbursts in radio galaxies: general

- Starburst rate:
  - 2Jy(0.15 < z < 0.7): 20 -- 35% (22 objects)

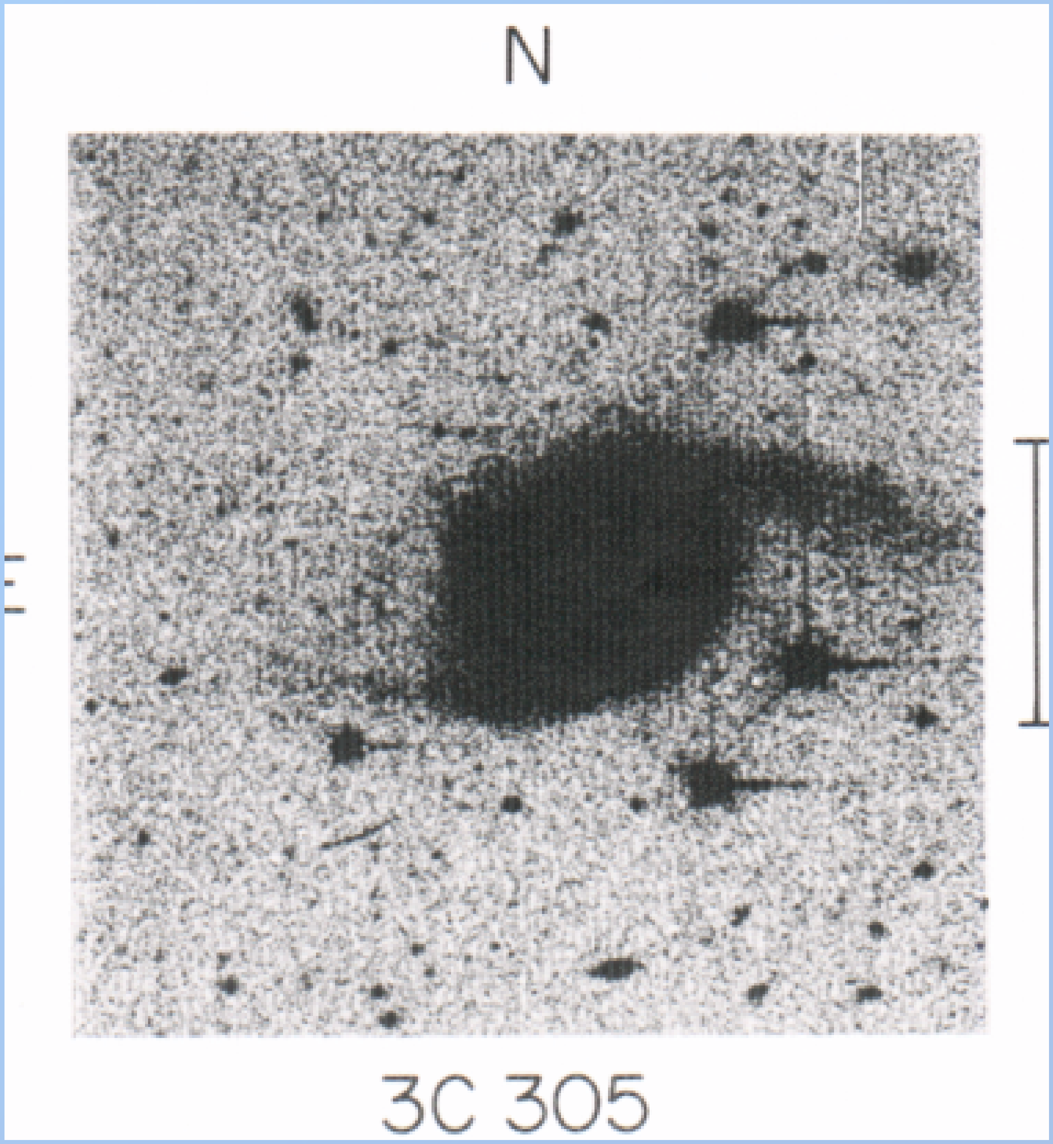
    Tadhunter et al. (2002)
  - 3CR(z<0.2): 33% (14 objects)

    Aretxaga et al. (2001), Wills et al. (2002)
  - 2Jy (z<0.08, FRIs): 25% (12 objects)

    Wills et al. (2004)
- Total sample of 20 PRG with starburst components (z<0.7)
- Observed spectroscopically with WHT, NTT, VLT: wide spectra coverage, intermediate resolution

The reddened nuclear starburst in 3C305

The reddened nuclear starburst in 3C305

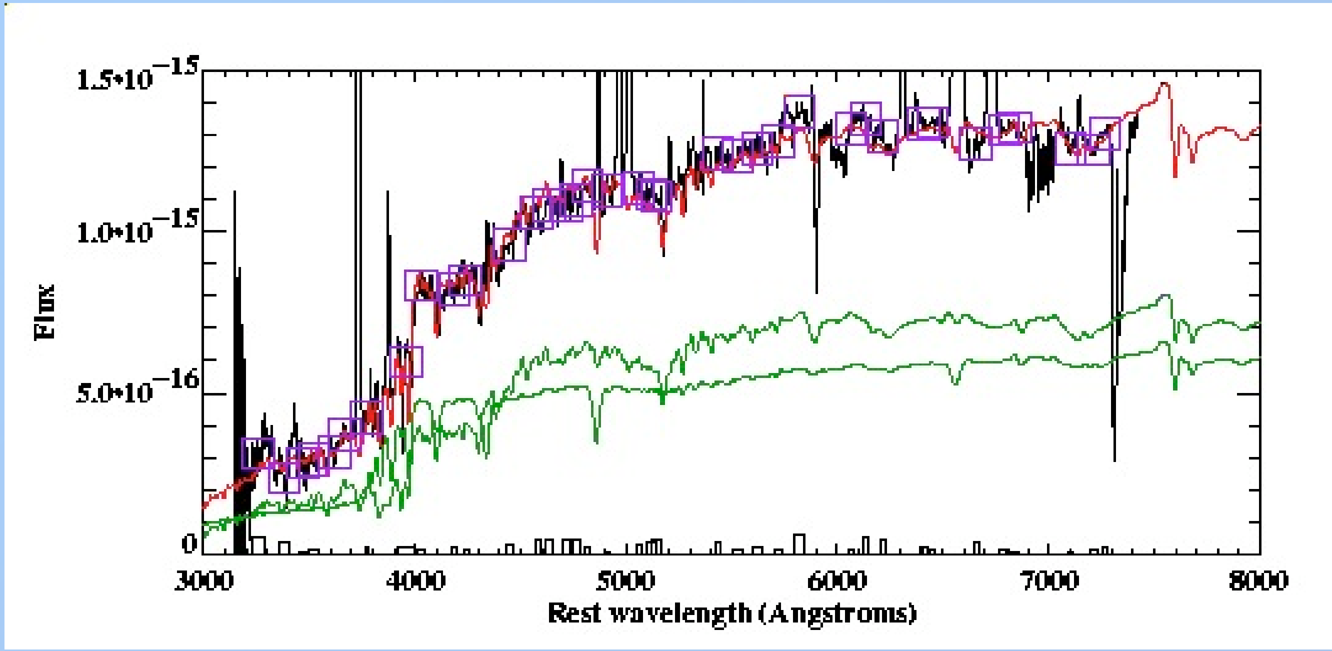


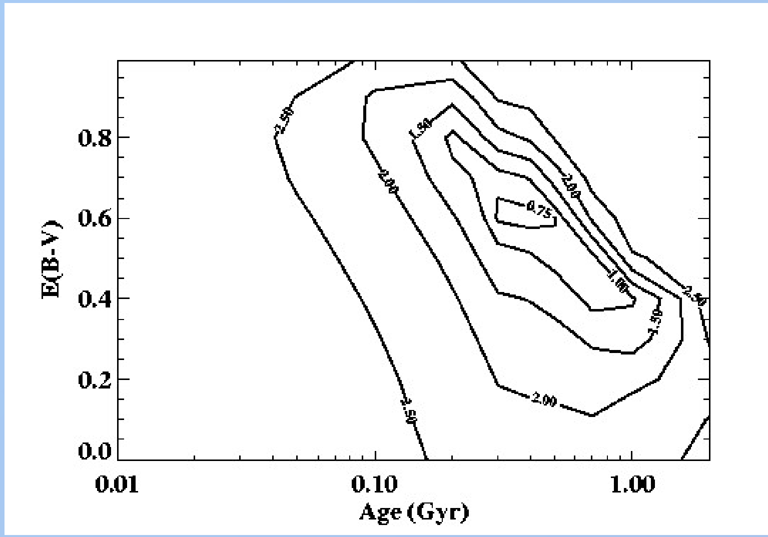
The reddened nuclear starburst in 3C305

3C305 (z=0.042) Heckman et al. 1986

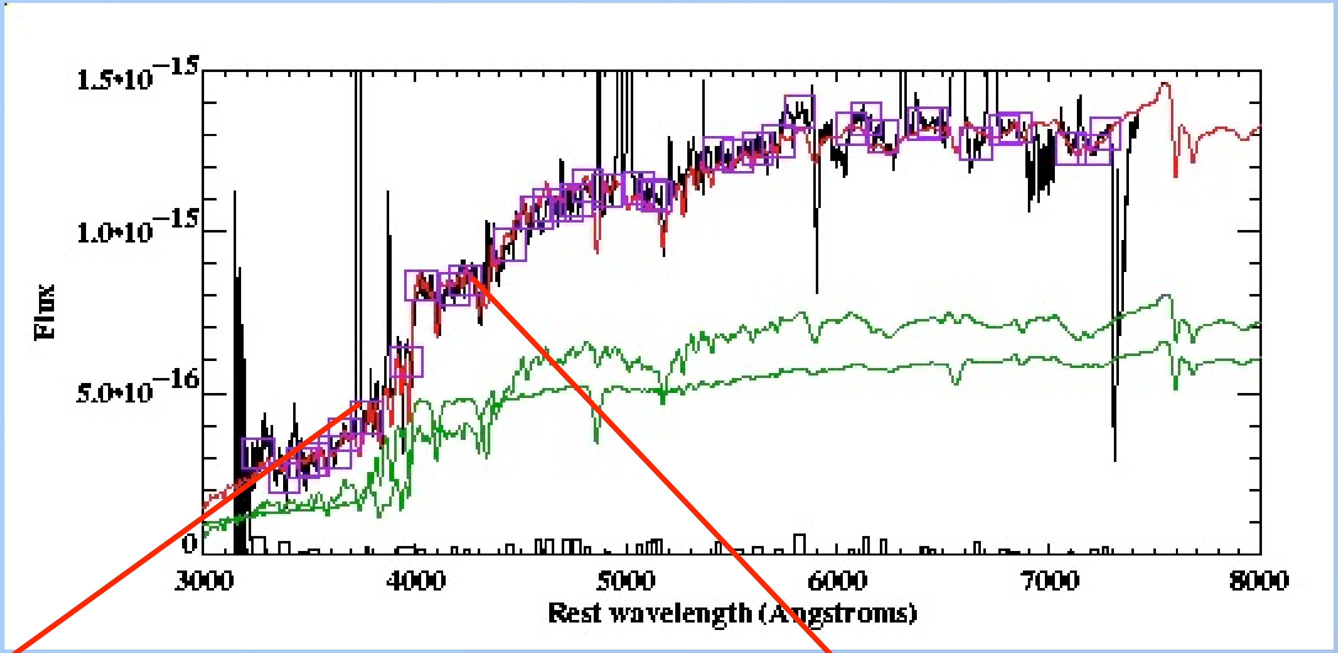
The reddened nuclear starburst in 3C305

The reddened nuclear starburst in 3C305

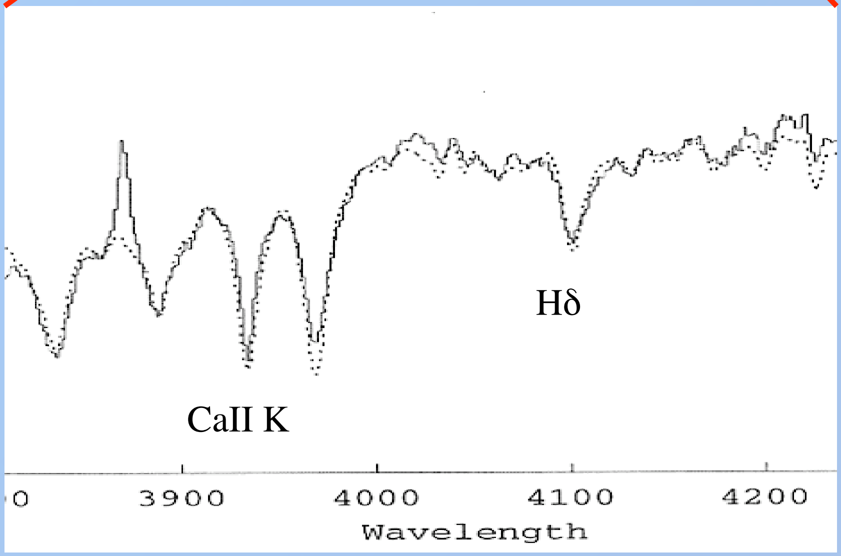




The reddened nuclear starburst in 3C305



WHT/ISIS



Starburst Properties

Age: 0.4 - 0.9 Gyr

E(B-V)=0.4 - 0.8 mag

Mass:1.5+/-0.5x10^{10} M_{sun}

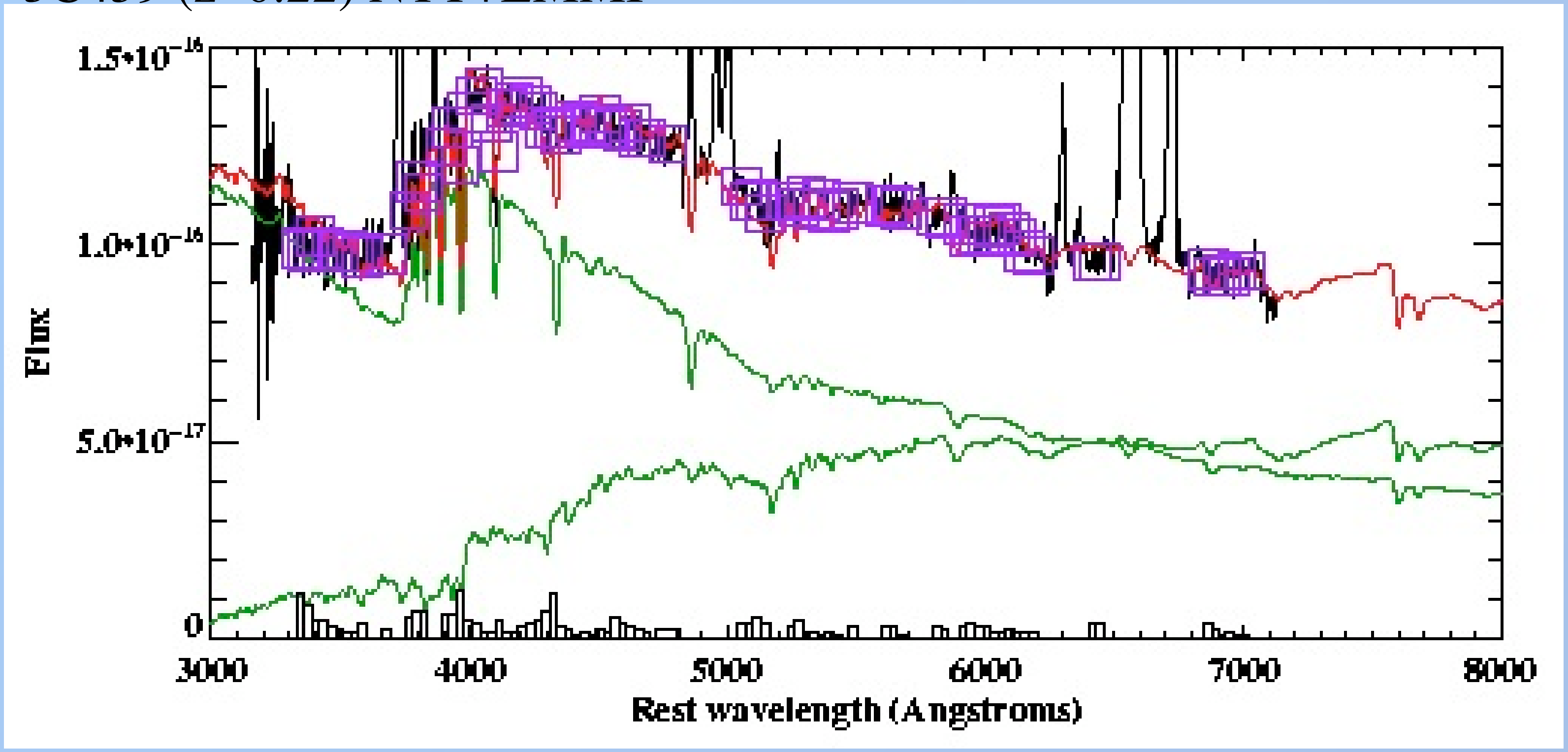
(16 - 40% of total stellar mass)

Bruzual & Charlot(1996) models

Salpeter IMF (0.1-125 M_{sun})

Starburst dominated Objects (z>0.15)

3C459 (z=0.22) NTT+EMMI



YSP Properties

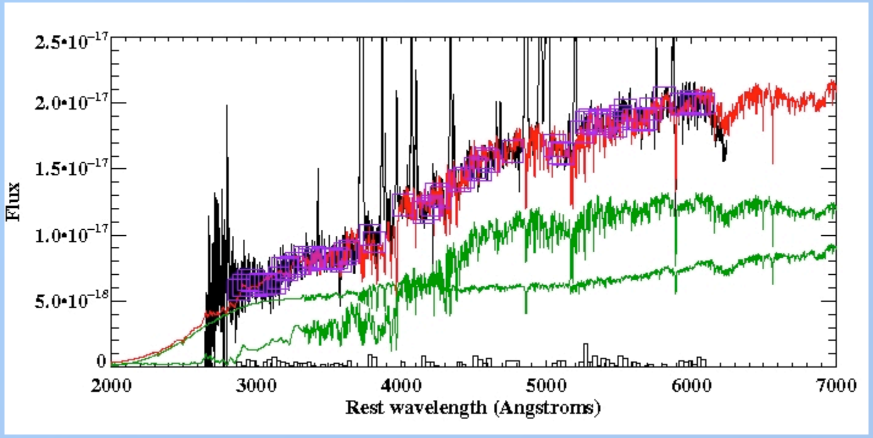
Age: 0.05 Gyr

Mass:4x10^{9} M$_{sun}$

(>5% of total stellar mass in slit)

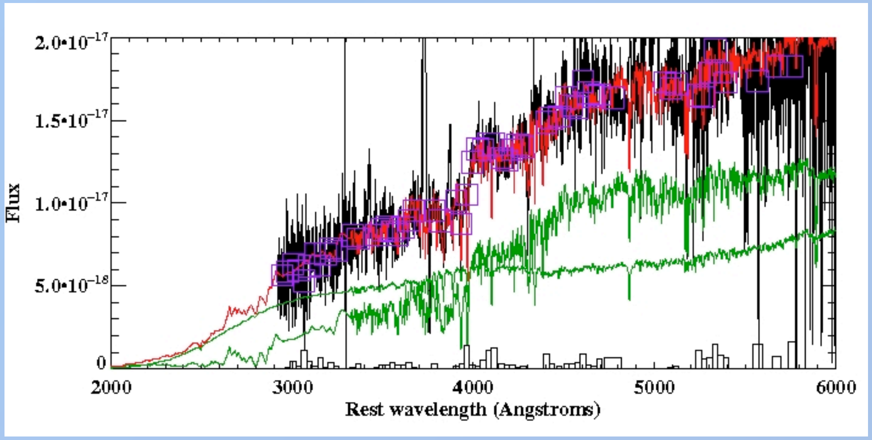
Objects with v.young starburst components

PKS0023-26 (z=0.340) - VLT/FORS2



YSP age: 30Myr
Reddening: E(B-V)=0.8
YSP mass proportion: 9%

PKS0409-75 (z=0.69) - VLT/FORS2

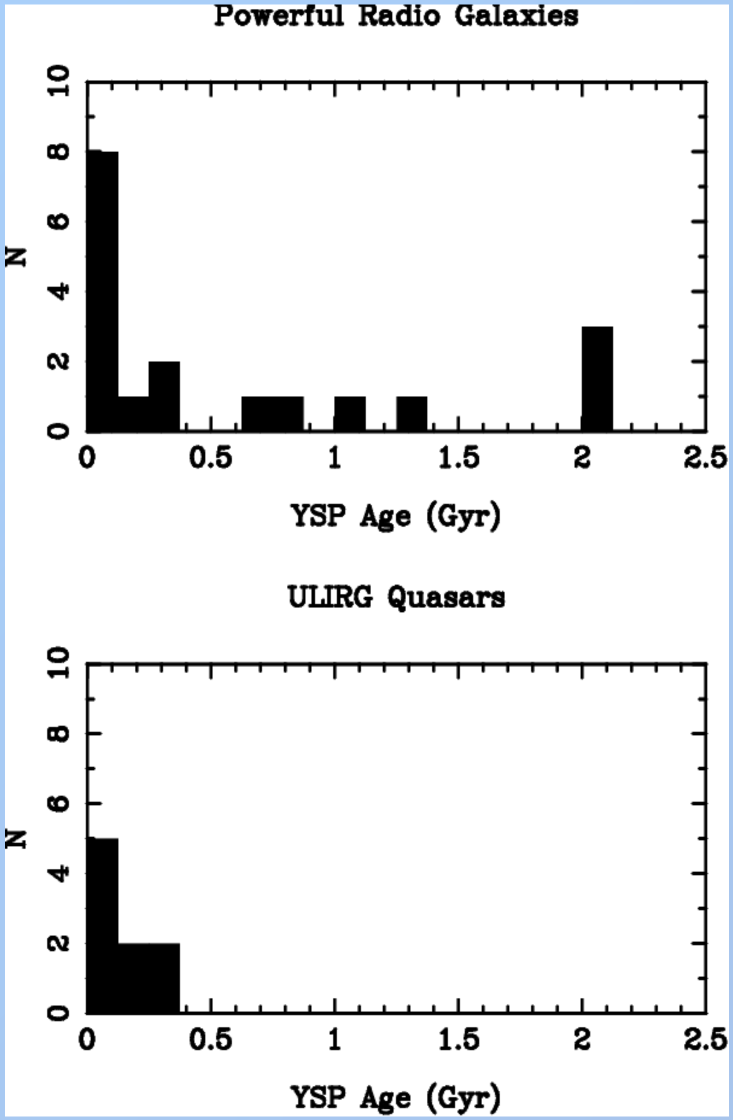


YSP age: 10Myr
Reddening: E(B-V)=0.9
YSP mass proportion: 4%

Holt et al. (2007)

These objects have:
- Low UV polarization
- Relatively weak narrow lines
- No broad lines detected

The Ages of the YSP in ULIRG and PRG



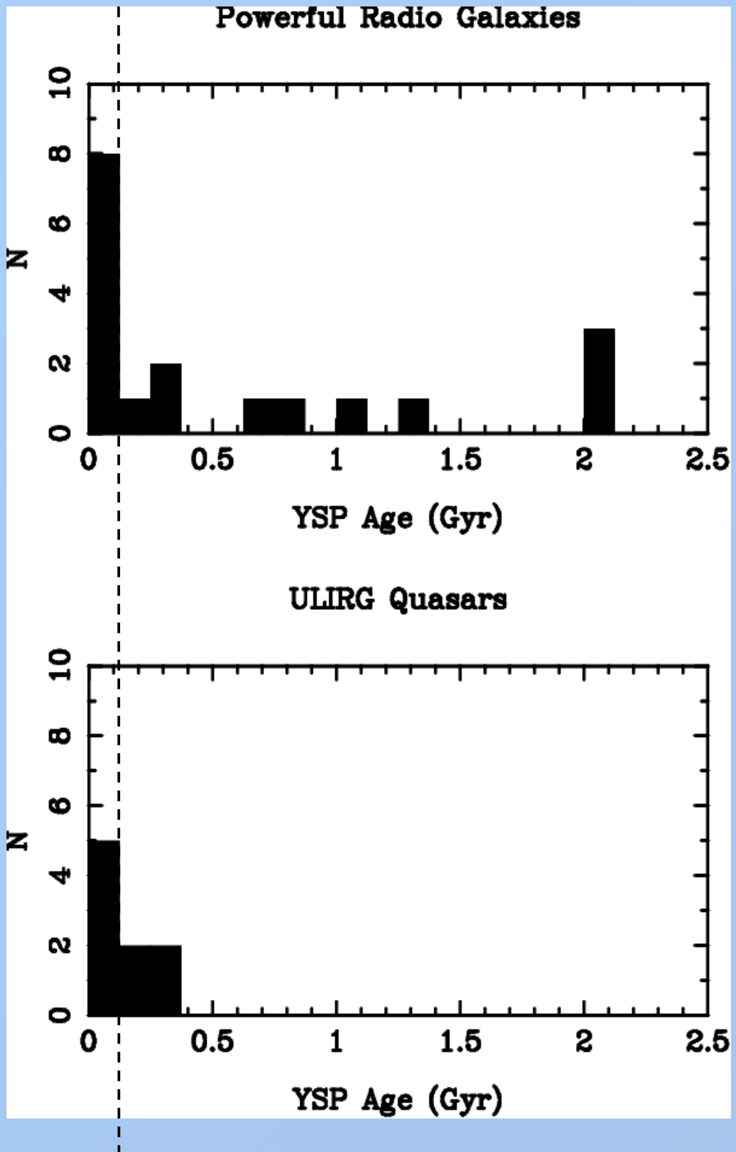
Powerful Radio Galaxies:

Tadhunter et al. (2002,2005)
Robinson et al. (2003)
Wills et al. (2003, 2007)
Aretxaga et al. (2001)
Holt et al. (2006,2007)

ULIRG quasars:

Canalizo & Stockton (2001)

The Ages of the YSP in ULIRG and PRG



Typical maximum age of radio source

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ULIRG quasars:

Canalizo & Stockton (2001)

Star formation in Fornax A

HST+ACS Goudfrooij et al. 2005

Evidence for young stellar populations:

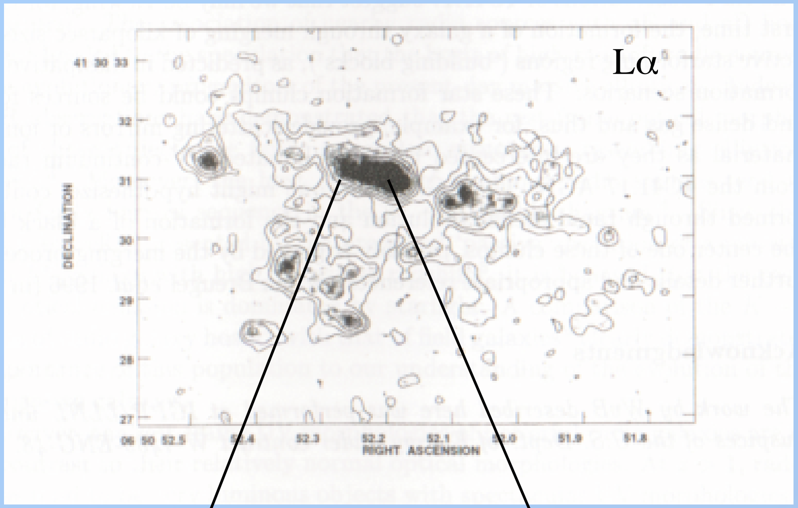
- Diffuse stellar light has luminosity weighted age 2-3 Gyr (Kuntschner 2002)

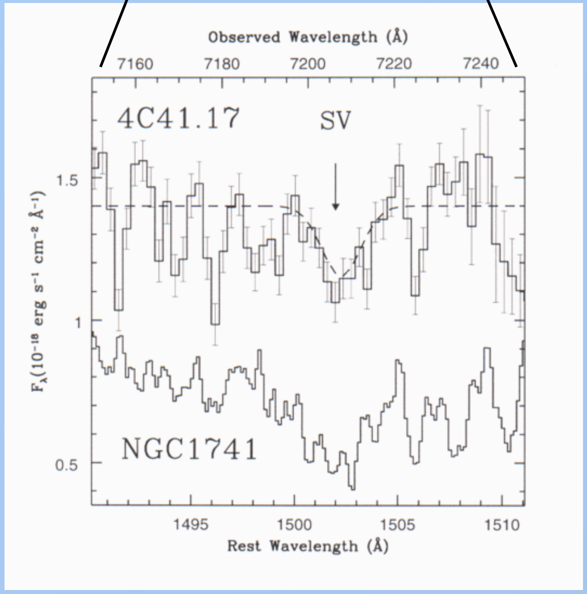
- Globular clusters have ages 3+/-0.5 Gyr (Goudfrooij et al. 2003)

----> current galaxy formed from a major merger of gas-rich galaxies 2-3 Gyr ago

Star Formation in 4C41.17 at z=3.8?

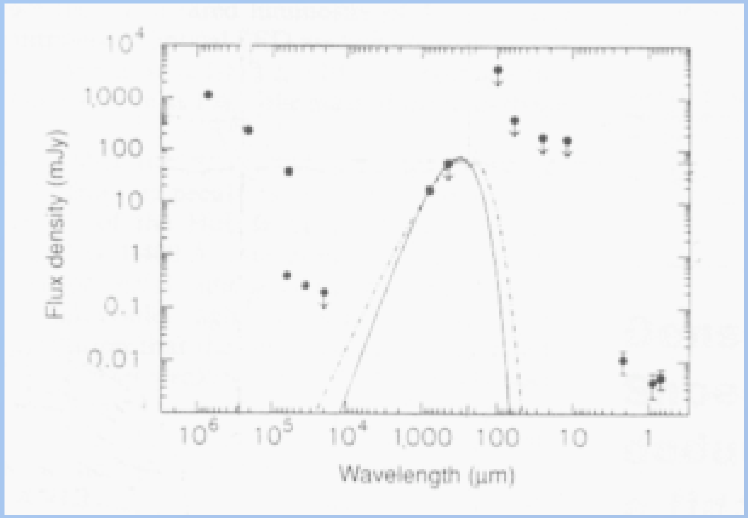
UV/optical





Dey et al. 1997

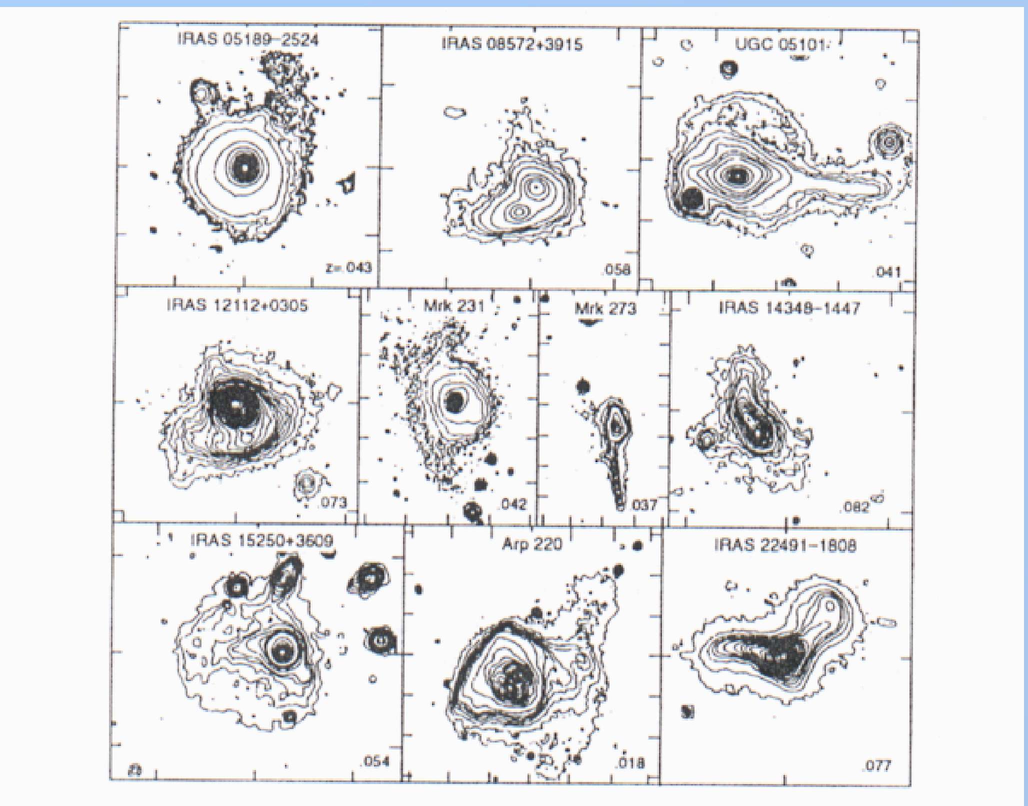
Far-IR/sub-mm



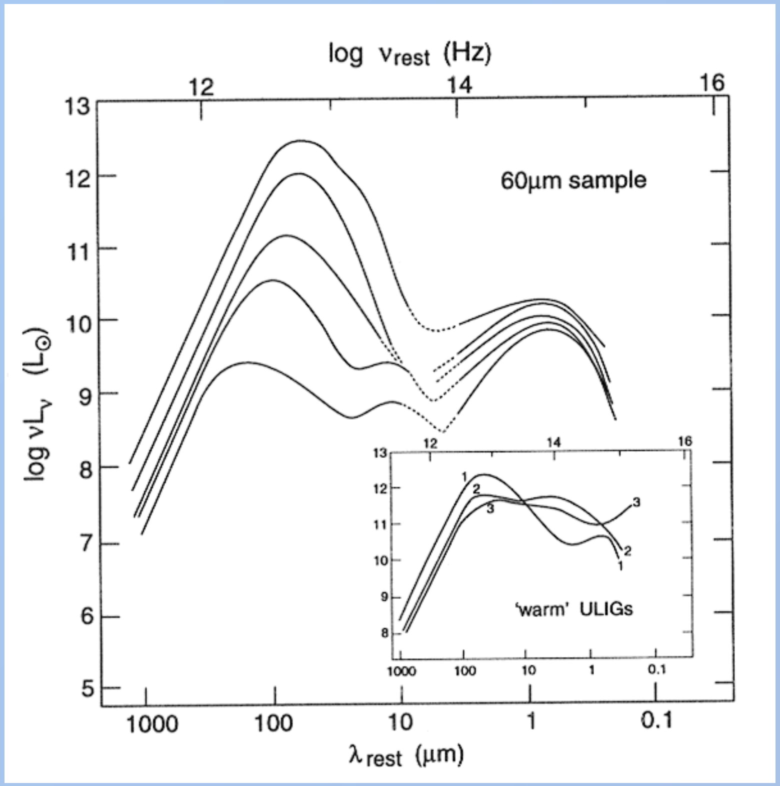
Dunlop et al. 1994

Star formation rate from sub-mm:
2,000 - 10,000 M⊙/yr

Ultra-Luminous Infrared Galaxies (ULIRG)



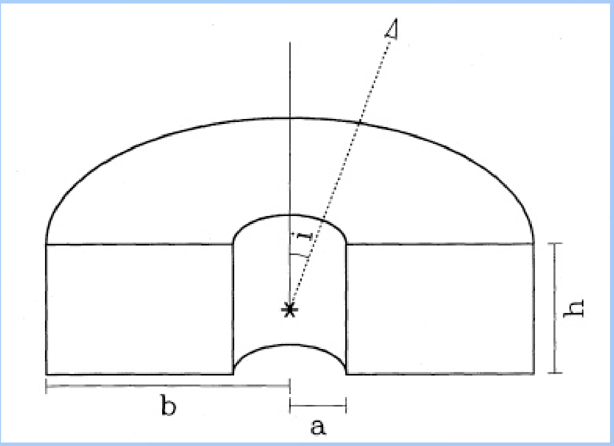
Morphologies



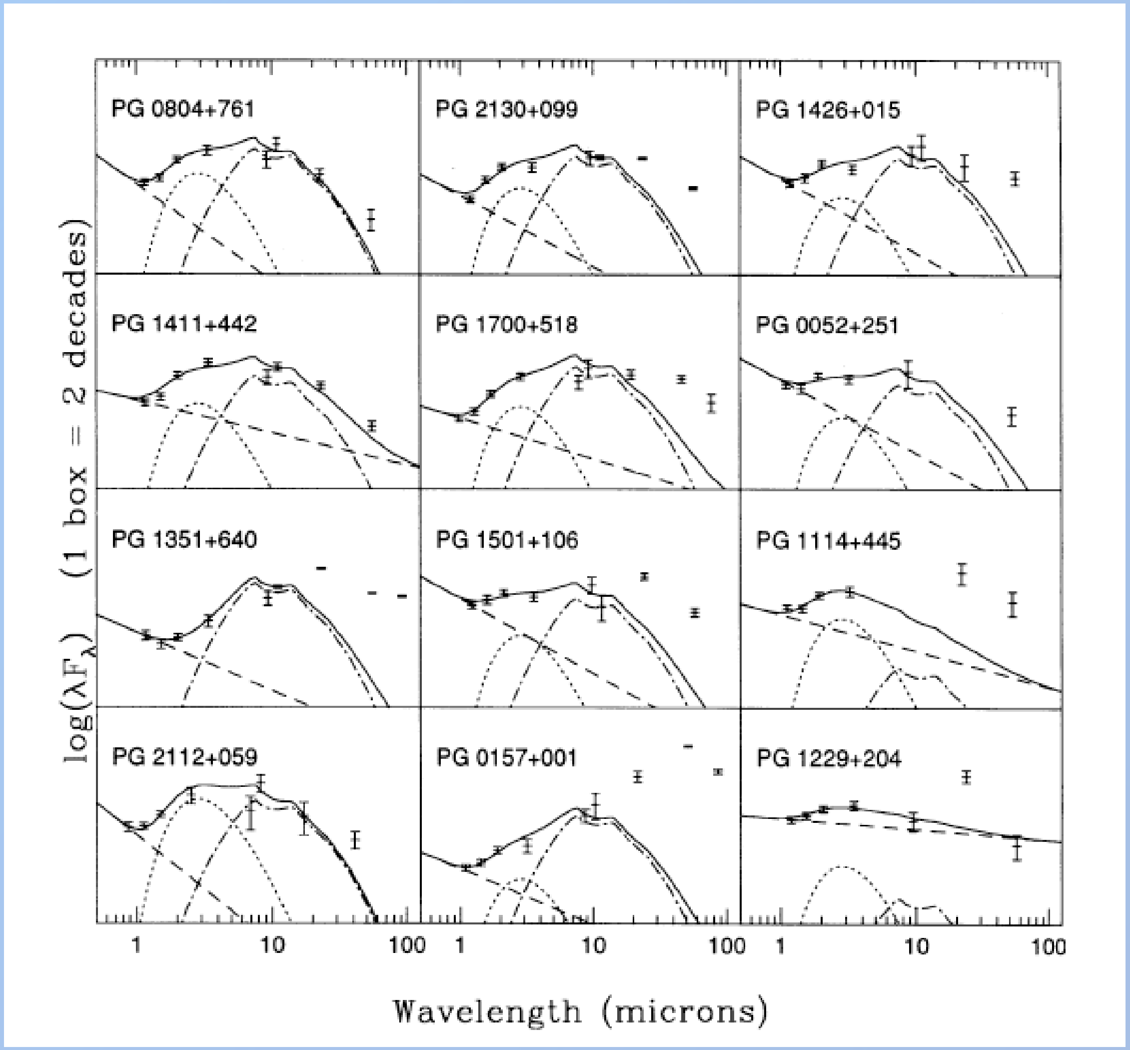
SEDs

Sanders & Mirabel 1996

Compact, dense torus model for mid/far-IR continuum



Pier & Krolik (1992,1993)



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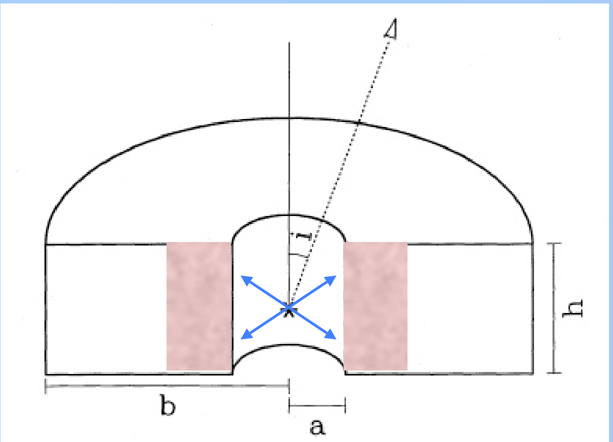
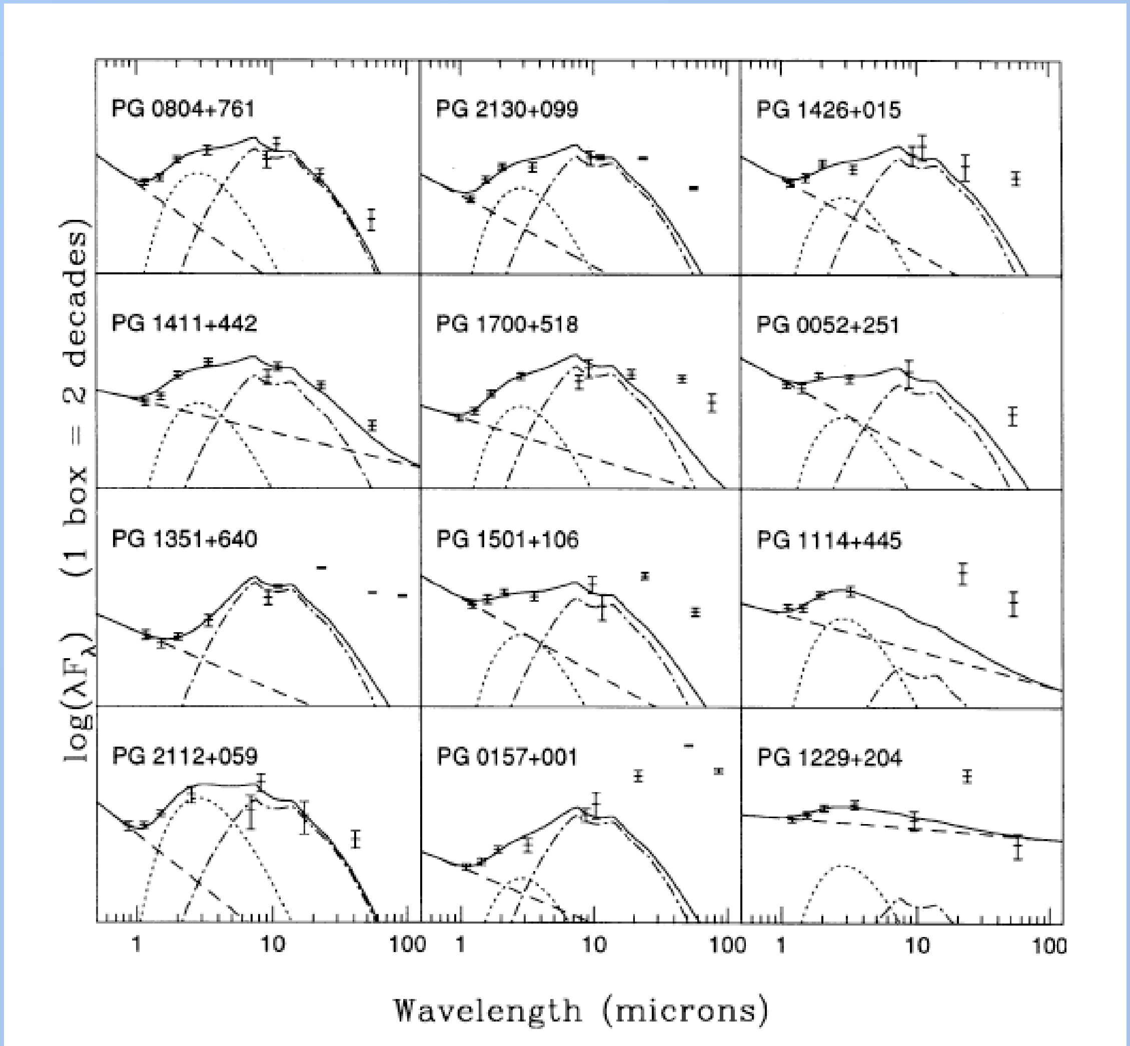
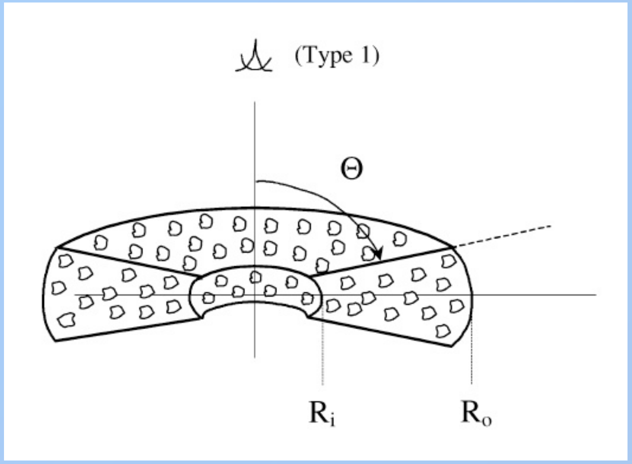


Pier & Krolik (1992,1993)

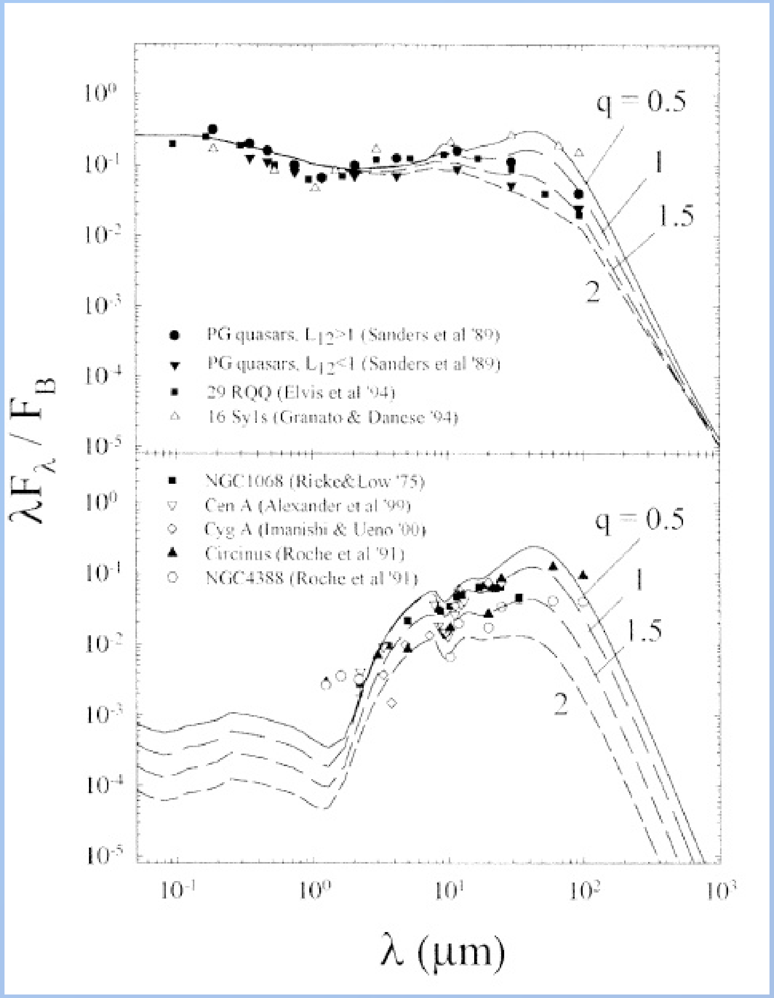
- Compact torus model often fails to reproduce the far-IR continuum of AGN



Clumpy torus model



Nenkova et al. (2002)



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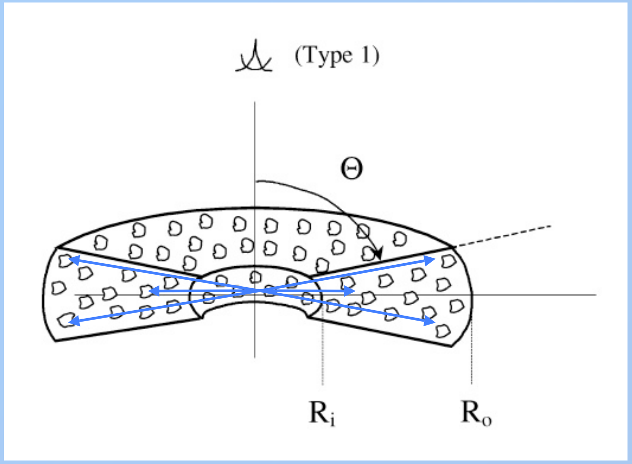

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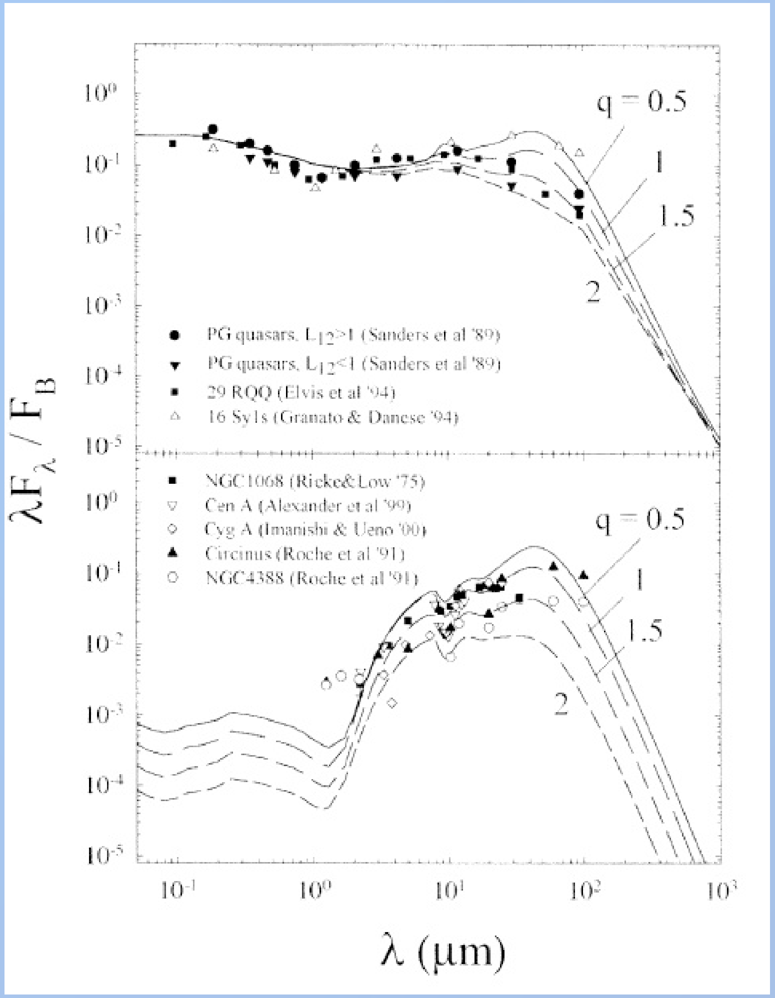
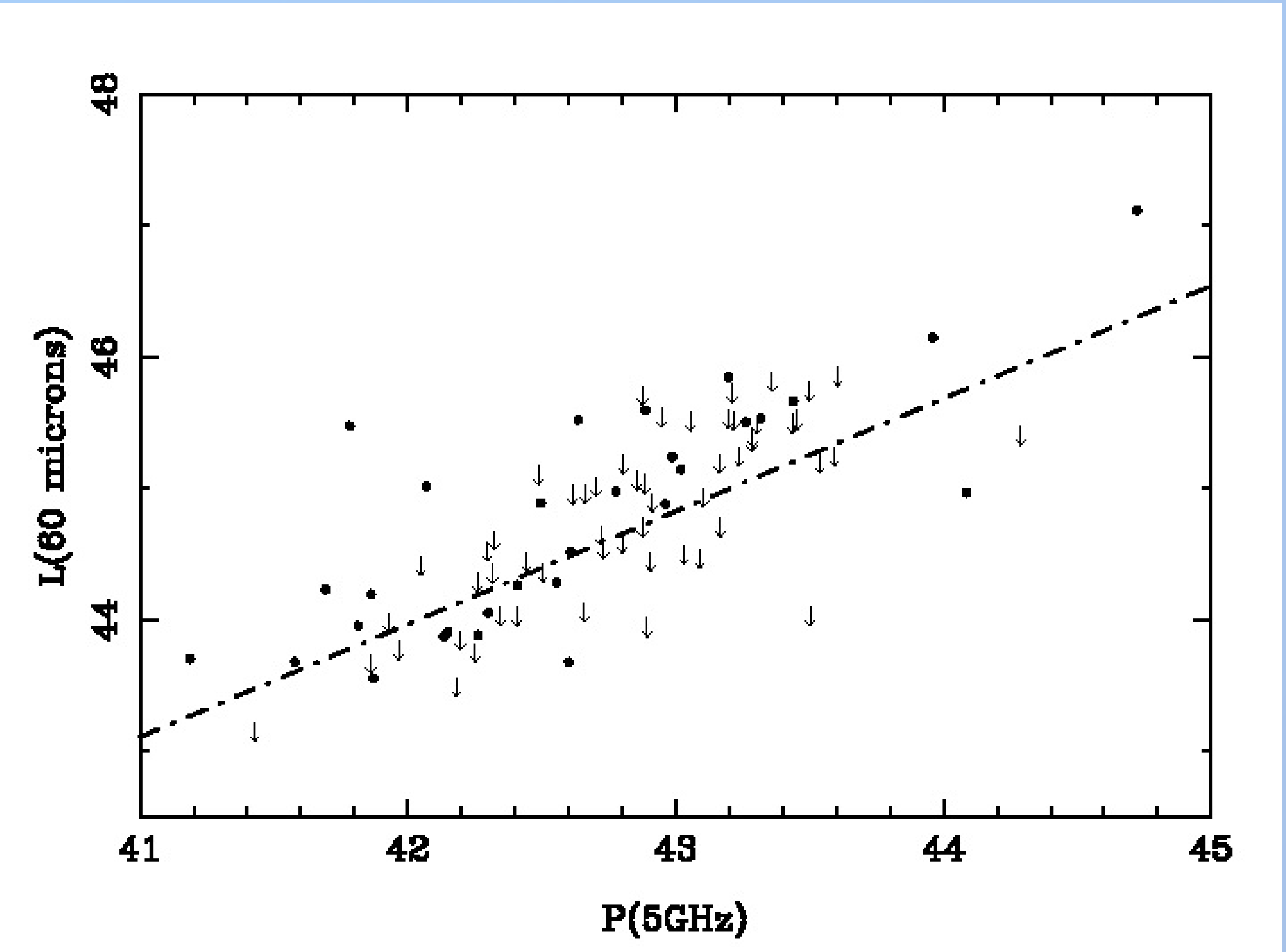


* Clumpy torus model, or any model in which the AGN illuminates a substantial amount of dust on a >0.1kpc scale, can produce the far-IR continuum (but this does not rule out a starburst contribution!)

3C Radio Galaxies at 60μm with IRAS

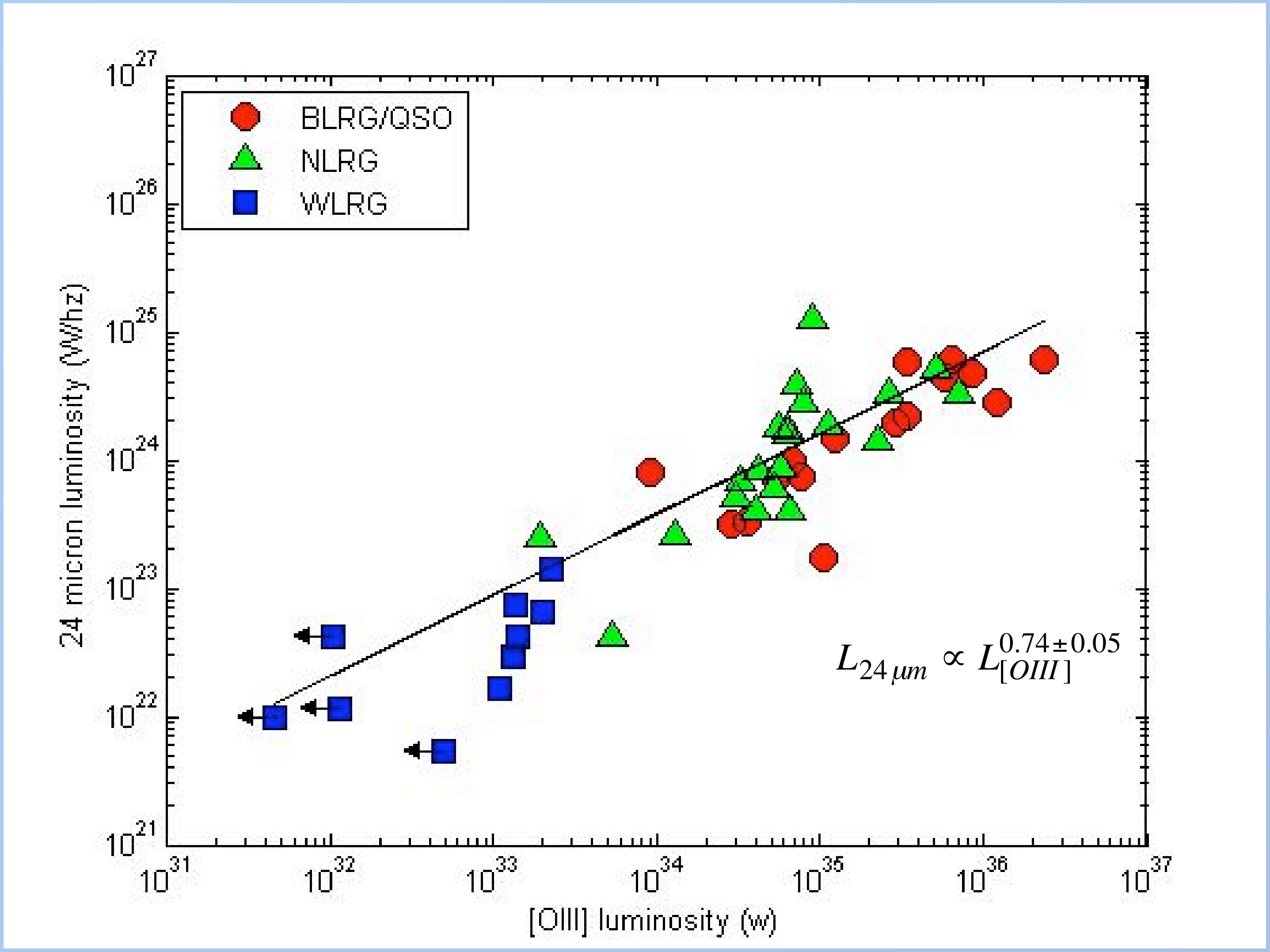


Only ~30% of 3CR radio galaxies at z<0.5 were detected by IRAS at 60μm

Deep Spitzer observations of a complete sample of southern 2Jy radio sources

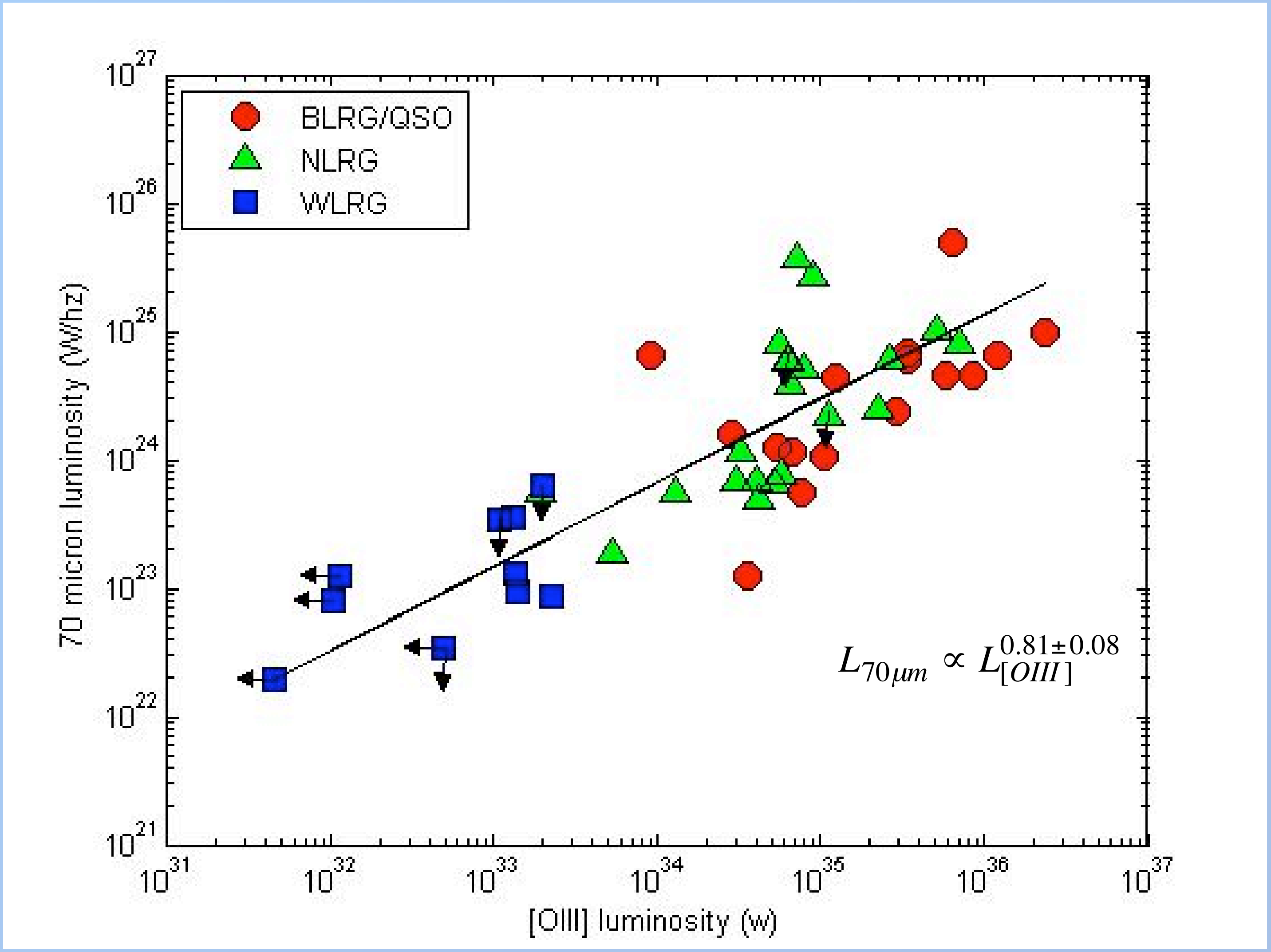
- Complete southern 2Jy sample, comprising all 47 radio galaxies and steep spectrum radio quasars with:
  - $S_{2.7GHz} > 2Jy$
  - $\delta < +10^o$
  - $0.05 < z < 0.7$
- Complete emission line information available
- For most objects (excluding luminous quasars/BLRG) we also have information about the stellar populations
- Deep Spitzer/MIPS observations of all objects:
  -- 100% complete at 24μm
  -- 89% complete at 70μm

Evidence for AGN heating of the mid-IR continuum in AGN



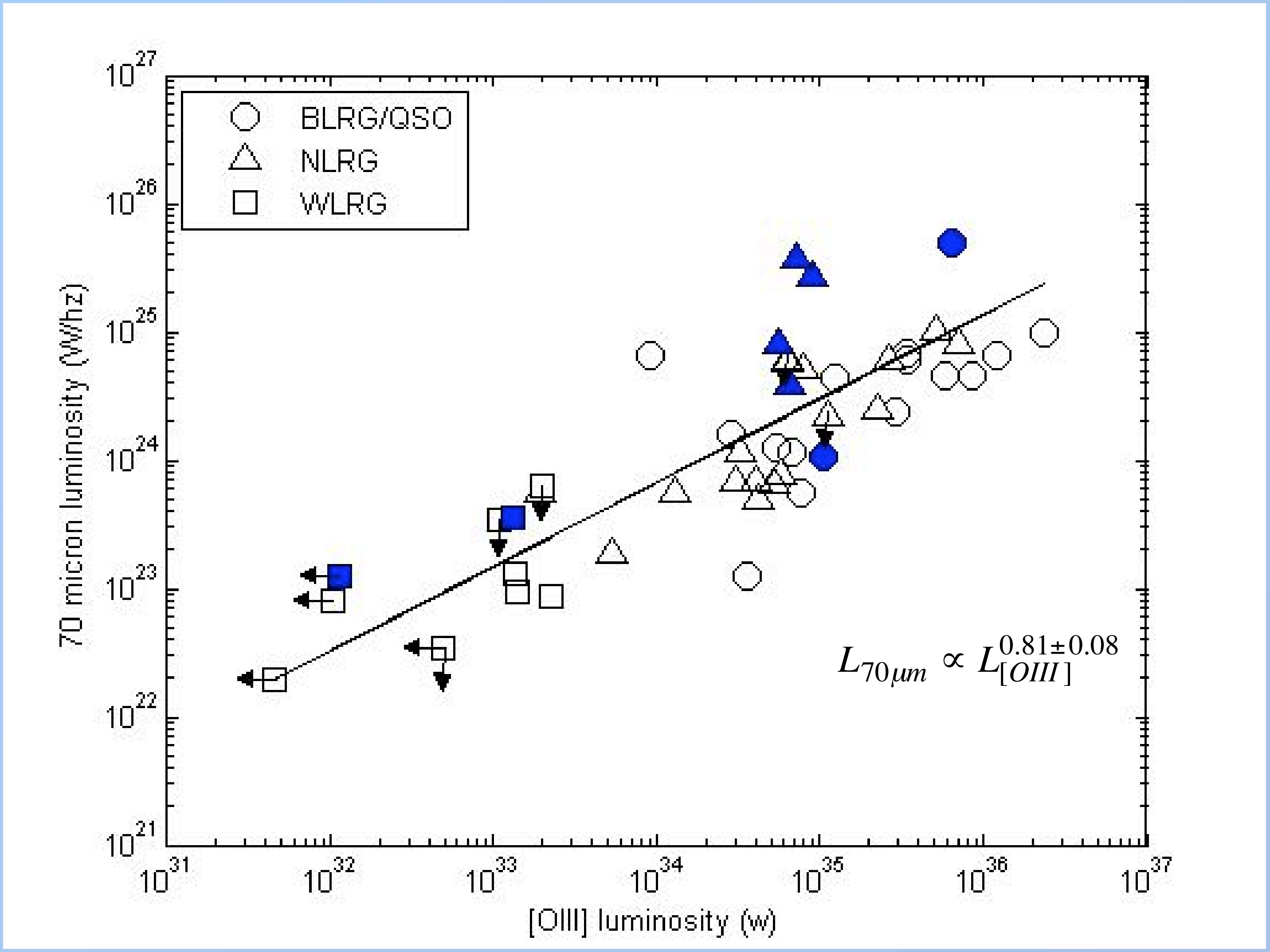
Tadhunter et al. (2007)

Starburst or AGN heating of the cool, far-IR emitting dust?



Tadhunter et al. (2007)

Starburst or AGN heating of the cool, far-IR emitting dust?



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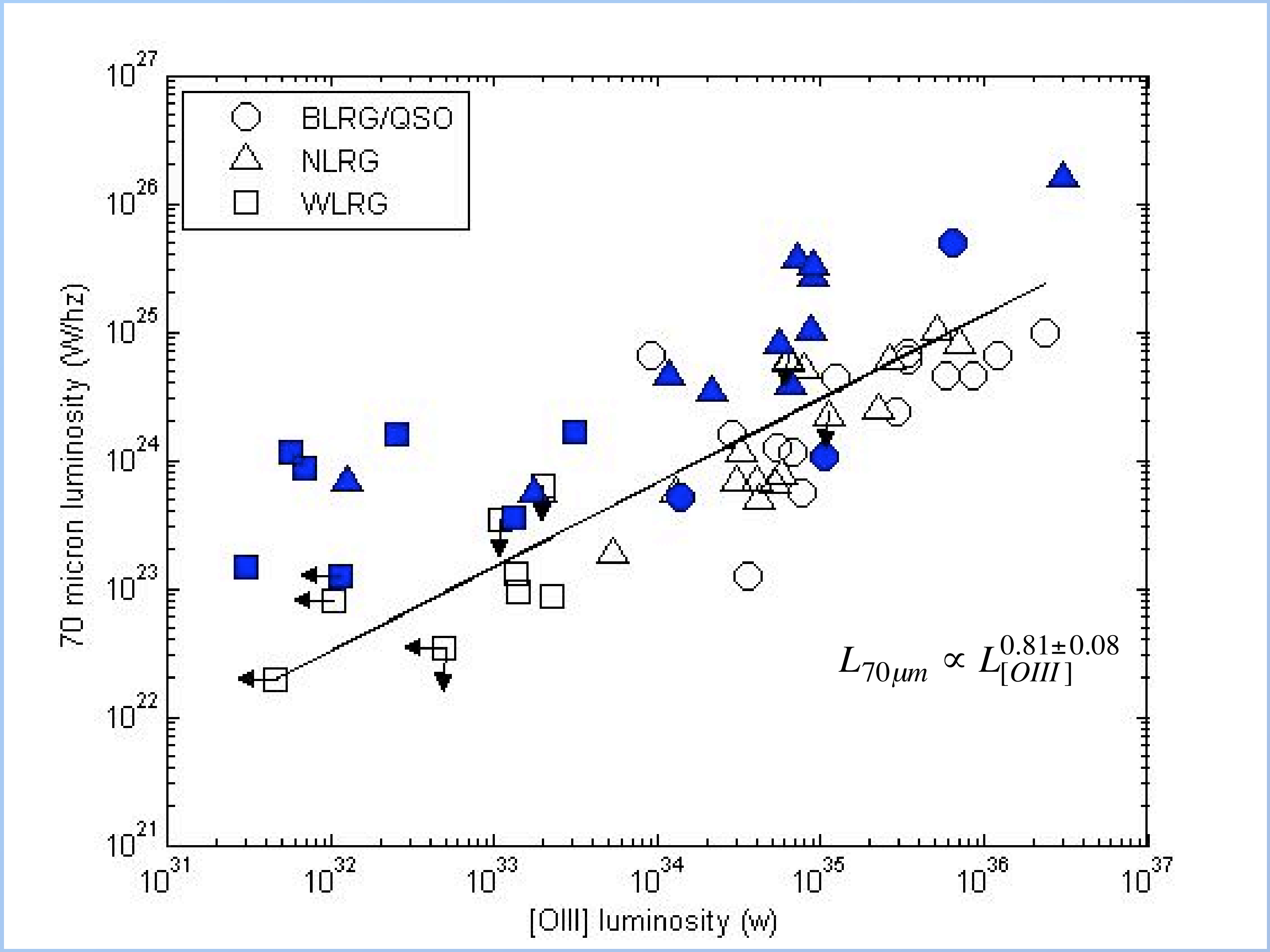

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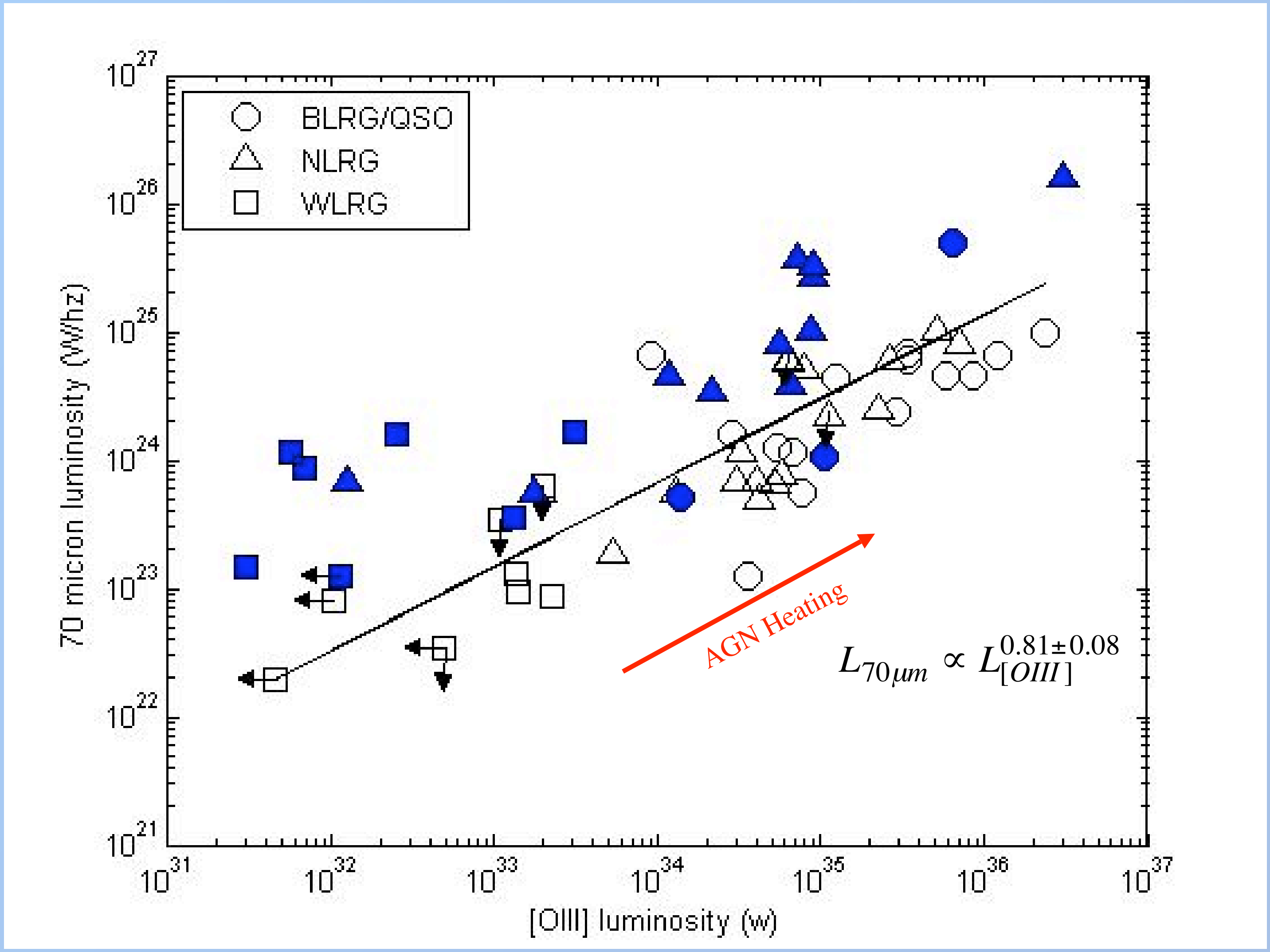

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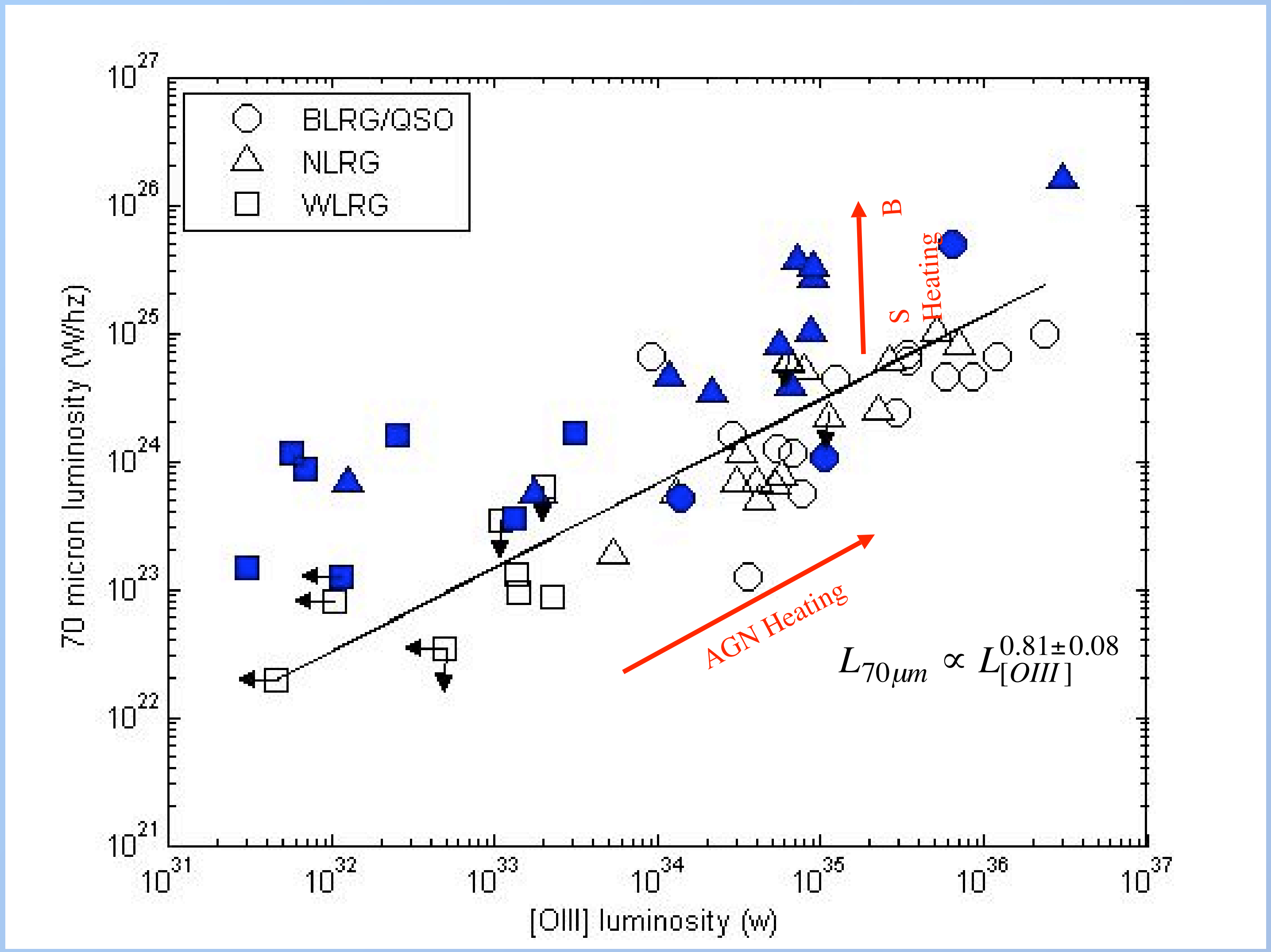

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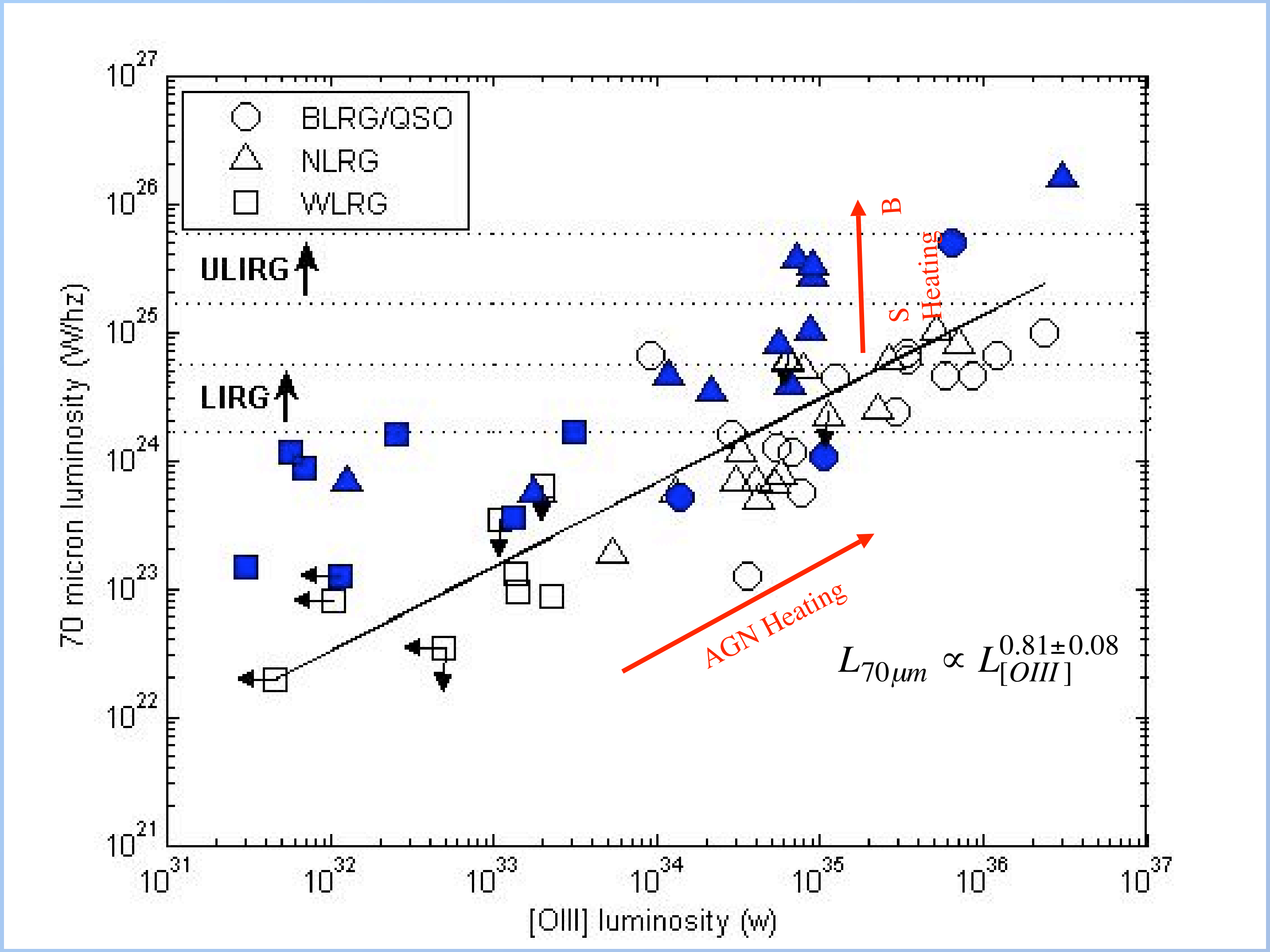

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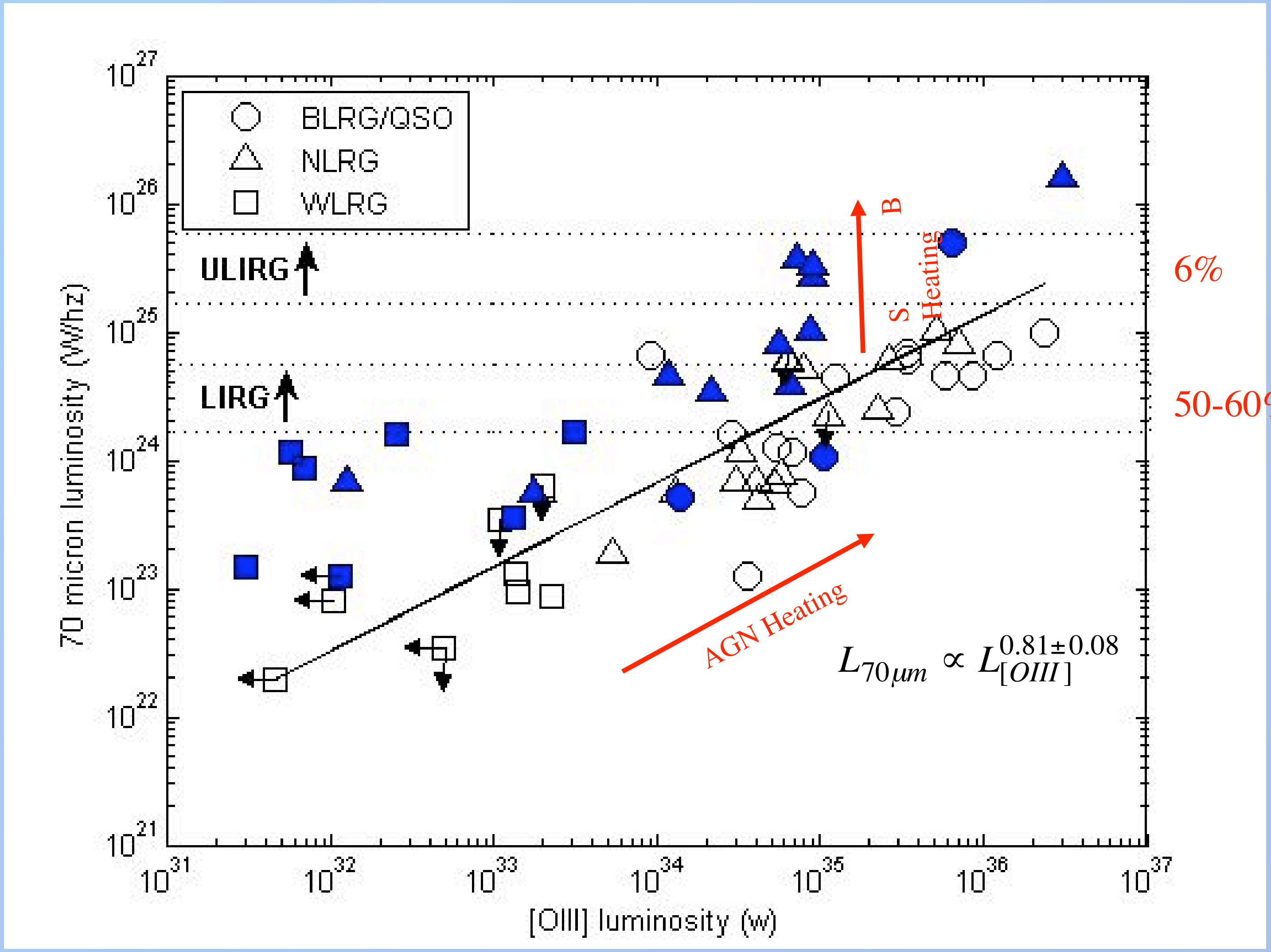


Tadhunter et al. (2007)

Is AGN heating energetically feasible?

- Assuming optically thick NLR clouds with covering factor f_{NLR}, mid-IR emitting dust structures with covering factor f_{MIR}, and far-IR emitting dust structures with covering factor f_{FIR} we find:

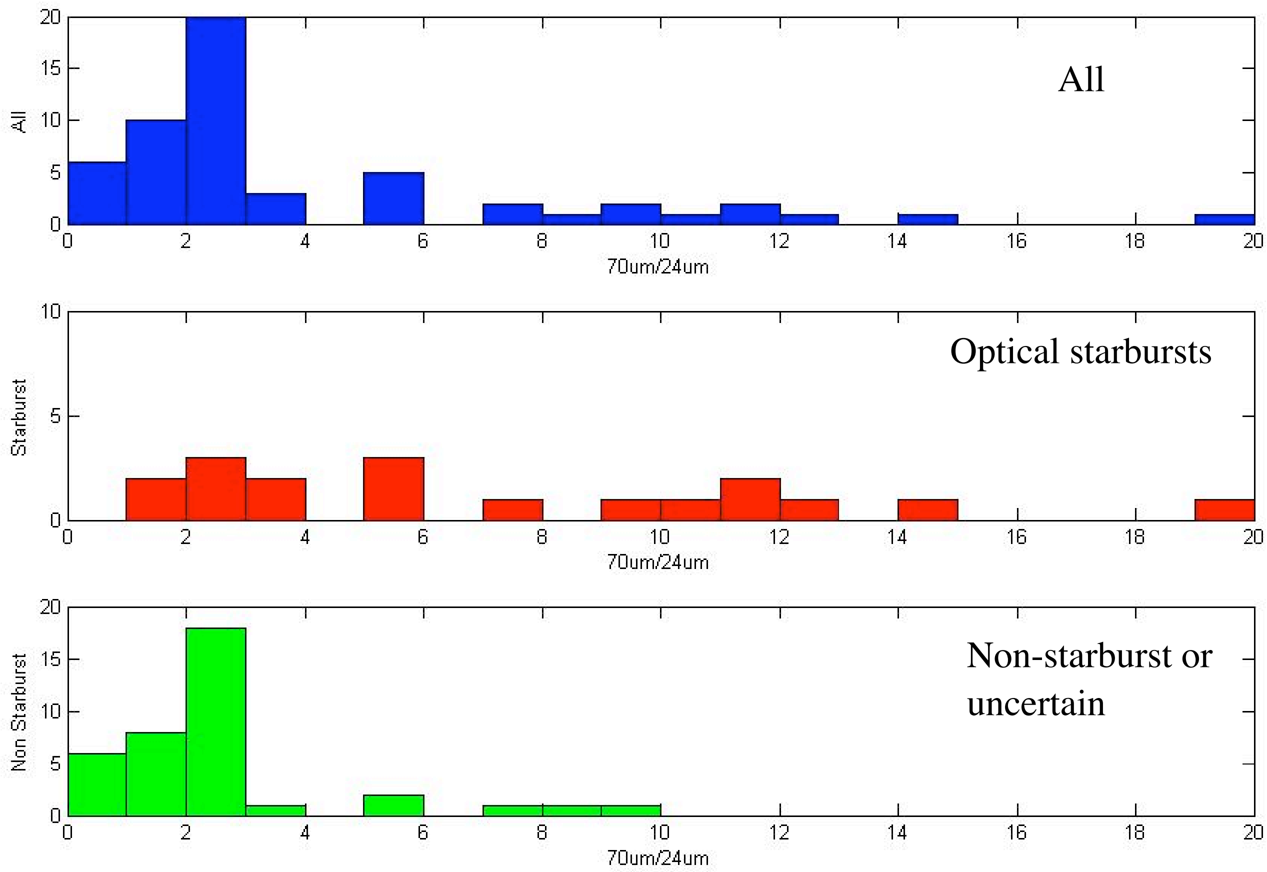
$$\frac{f_{MIR}}{f_{NLR}} \sim 12 \qquad \frac{f_{FIR}}{f_{NLR}} \sim 6$$

(to explain normalisations of best fitting regression lines)

$$f_{NLR} \sim 0.01 - 0.05 \Rightarrow f_{MIR} \sim 0.1 - 0.6$$

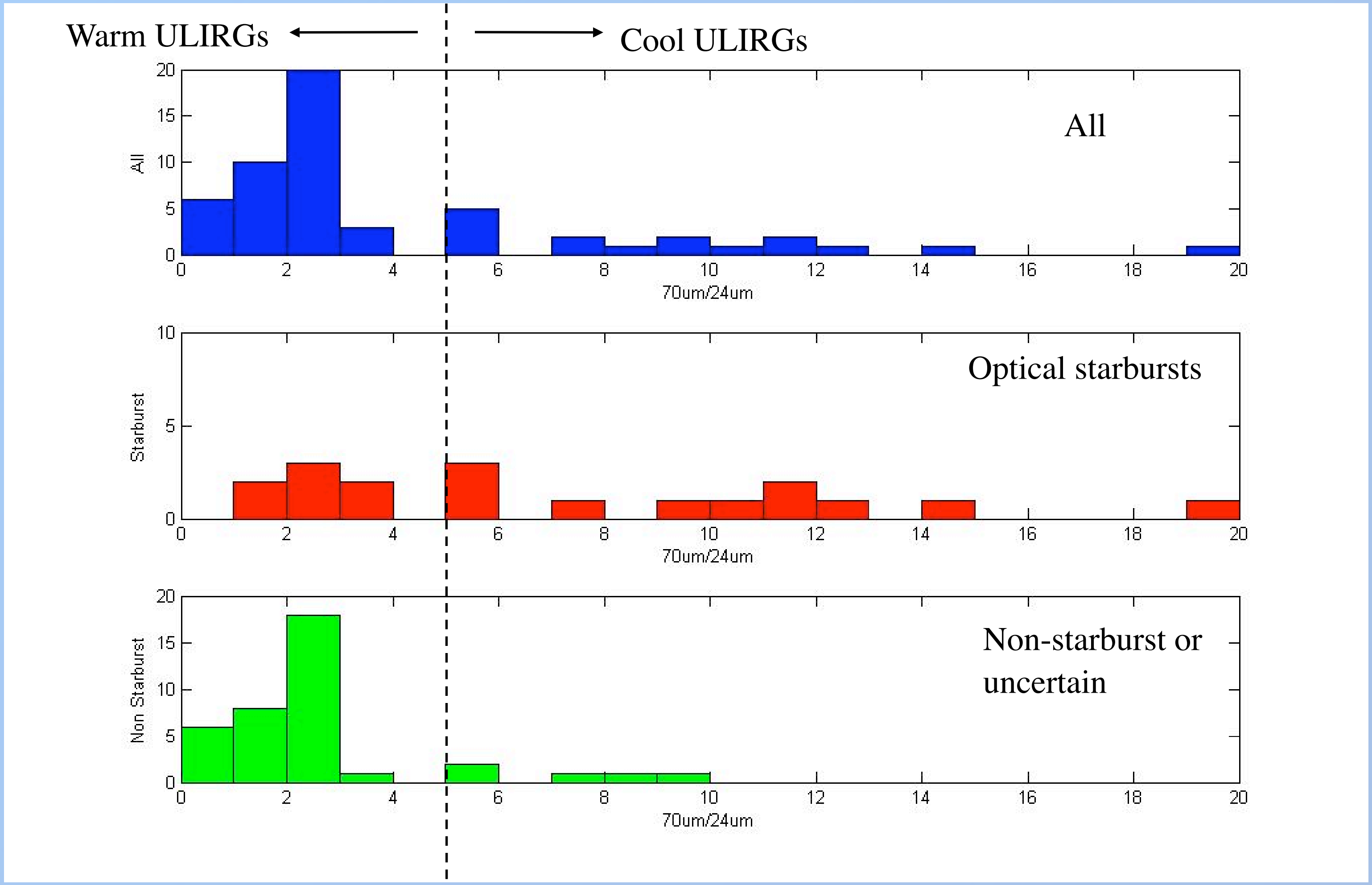
--- consistent with the typical torus covering factors required by the unified schemes.

Mid- to far-IR colours and starbursts



Spitzer observations of a complete sample of 47 2Jy radio sources at 70 and 24μm

Mid- to far-IR colours and starbursts



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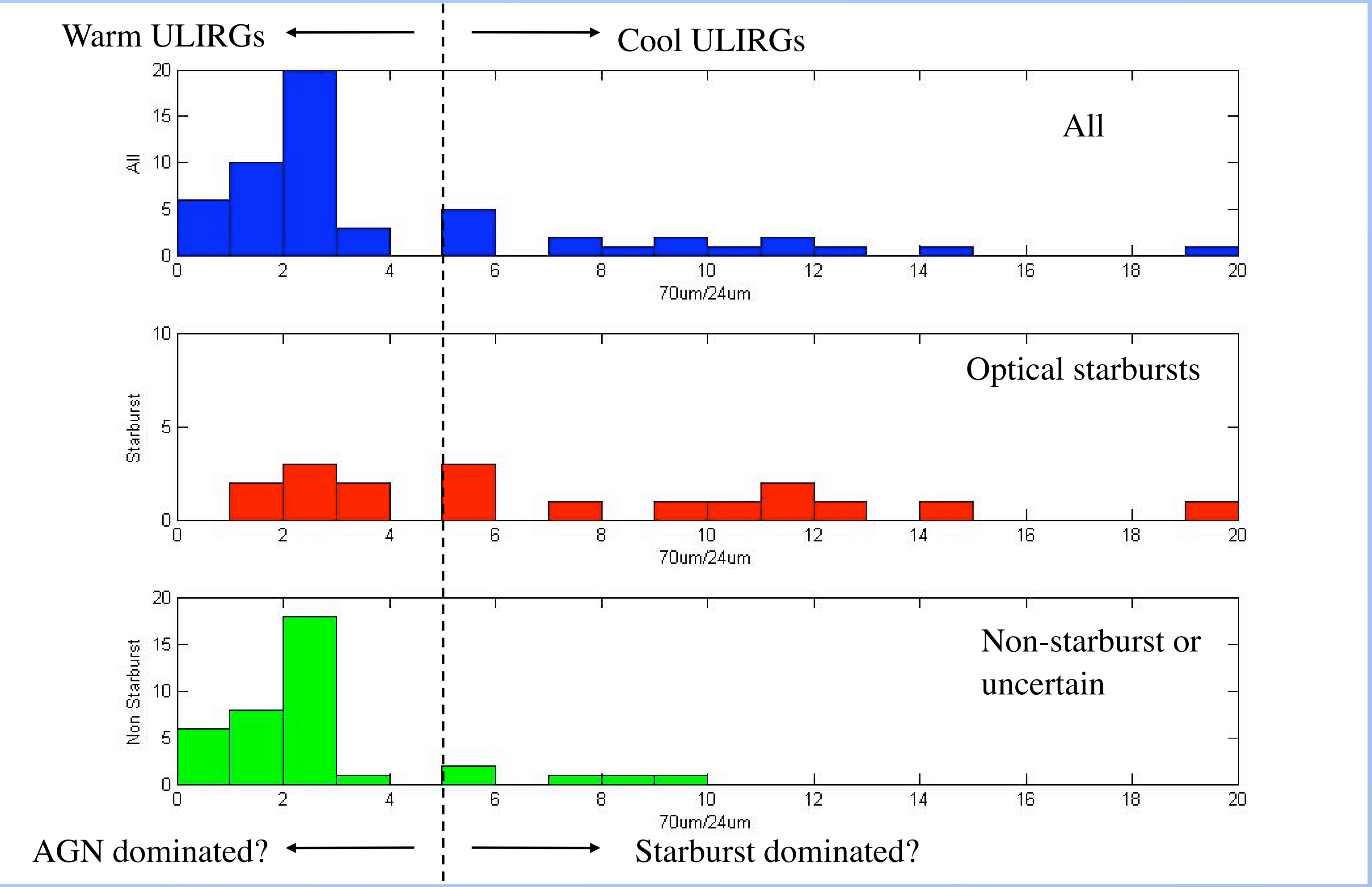


Spitzer observations of a complete sample of 47 2Jy radio sources at 70 and 24μm

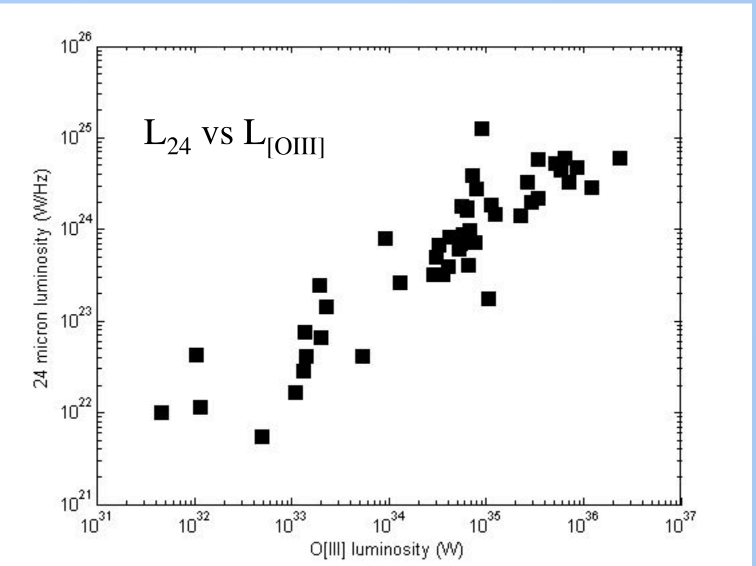
Spitzer observations of 2Jy sample: results

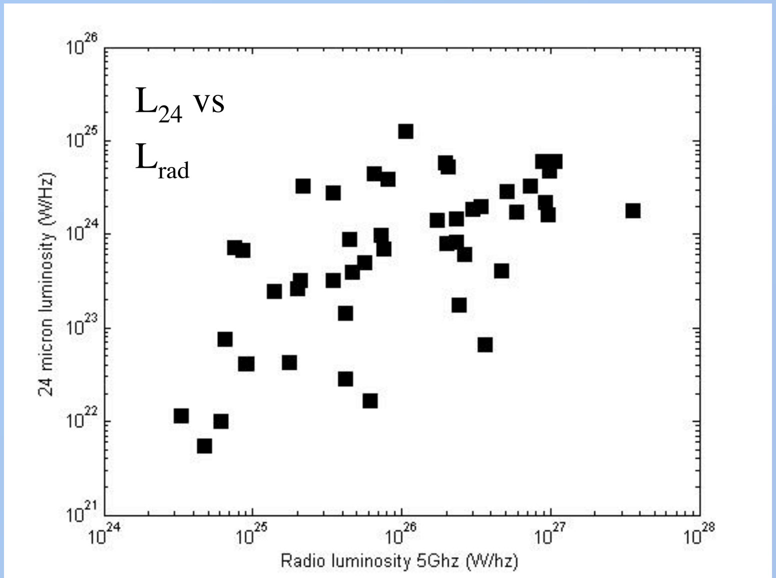
- Mid-IR dust heating mechanism (warm dust): predominantly AGN heating (from 24μm vs. $L_{[OIII]}$)
- Weak line radio galaxies: no evidence that they have heavily obscured, luminous AGN
- Far-IR dust heating mechanism (cool dust): predominantly AGN heating (from 70μm vs. $L_{[OIII]}$) but starbursts boost the far-IR luminosities by up to an order of magnitude in objects with optical evidence for starbursts
- Importance of starburst contribution in Far-IR: based on their mid- to far-IR colours, starbursts dominate the heating of the cool dust in only ~20% of radio galaxies
- Triggering the activity: based on optical/UV and far-IR results, only ~20 - 30% of PRG are undergoing major, merger-induced starbursts

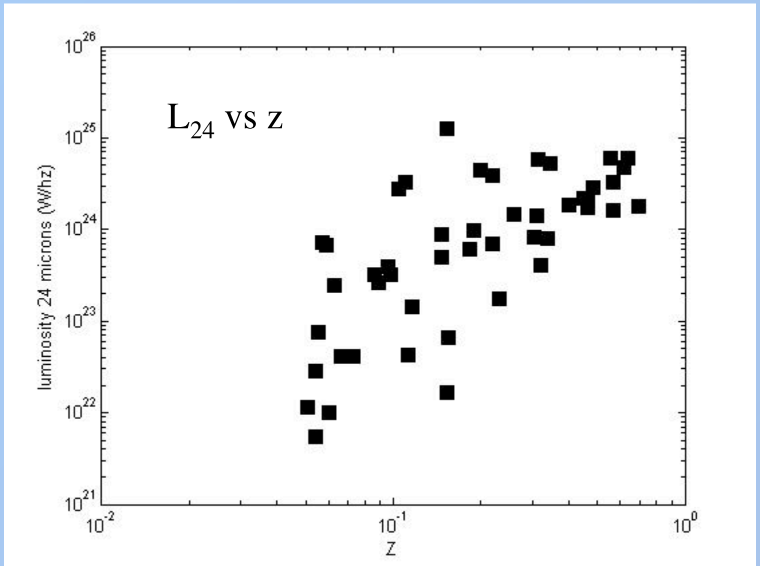
Conclusions

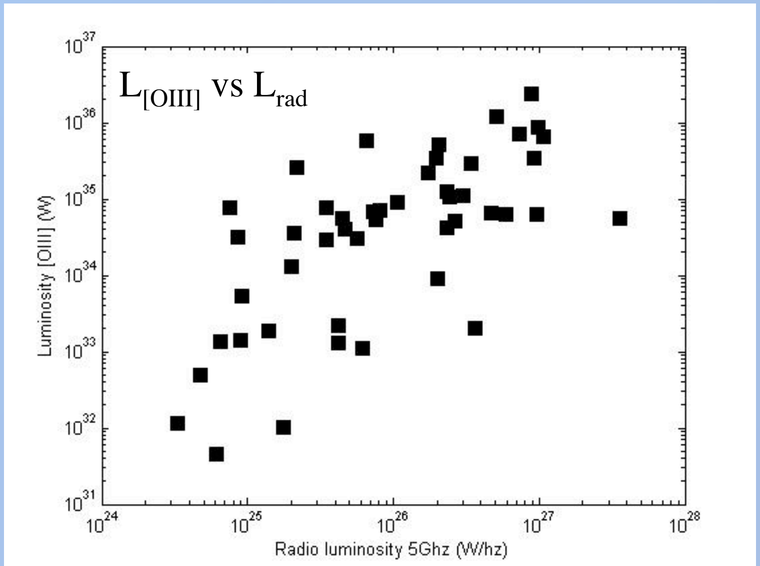
- AGN-related continuum: caution required when interpreting the colours and SEDs of radio galaxies and quasars because of activity-related continuum
- Timing of AGN activity: the AGN/jet activity is not always coeval with the major merger-induced starburst associated with the triggering events
- Far-IR: cool dust heated by a combination of AGN and starburst illumination, with AGN heating dominating in most cases
- Triggering mechanism: only ~20-30% of radio galaxies triggered at the peak of major gas-rich mergers, the remainder may be triggered later in merger sequence, by minor mergers/interactions, or by cooling flows.

Correlation analysis -- 2Jy sample



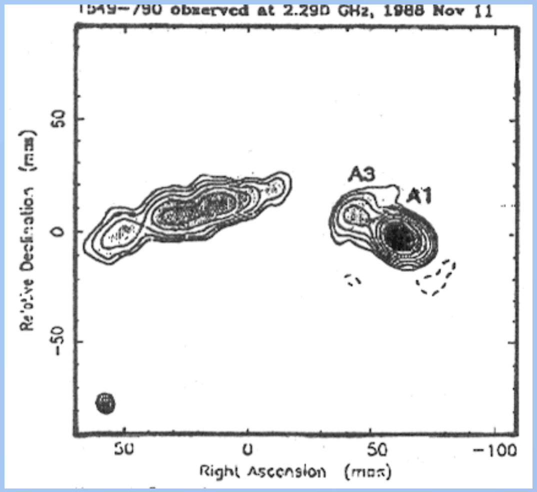




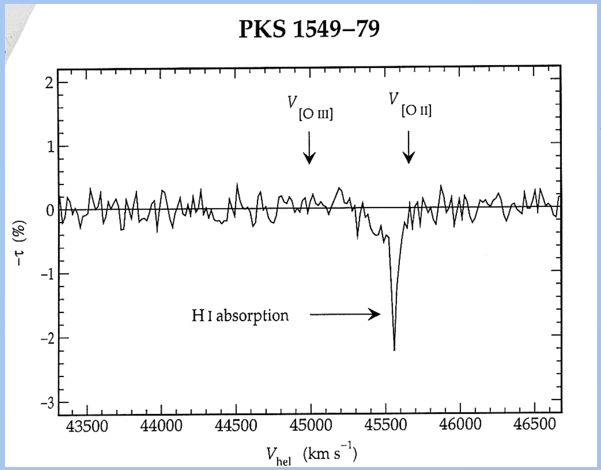


PKS1549-79 (z=0.15): a proto-quasar in the local Universe

- Flat radio spectrum
- One-sided VLBI jet (radius ~420pc)
- Variability
- ULIRG -- as luminous as 3C273 in mid-IR
- Significant HI 21cm absorption

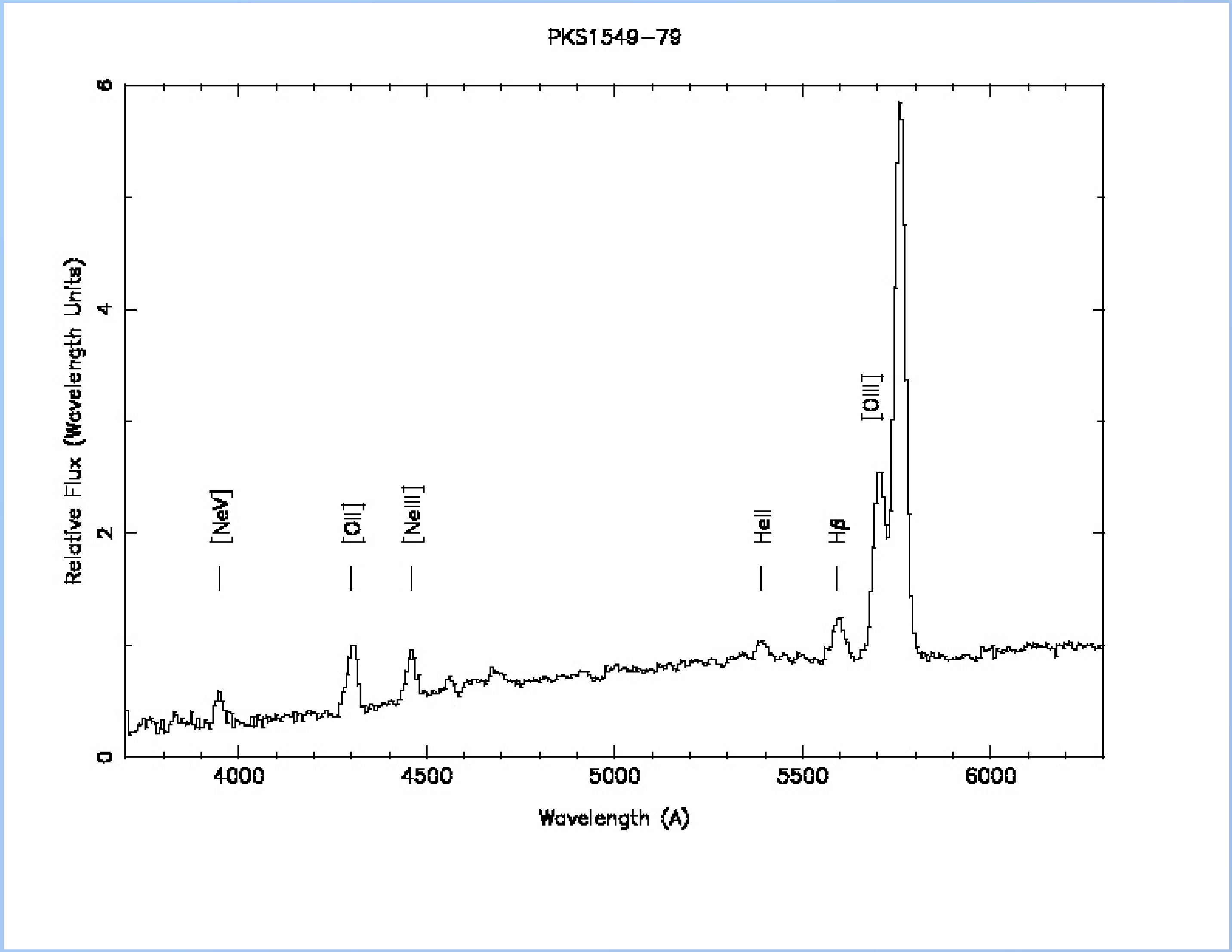


King (1996)



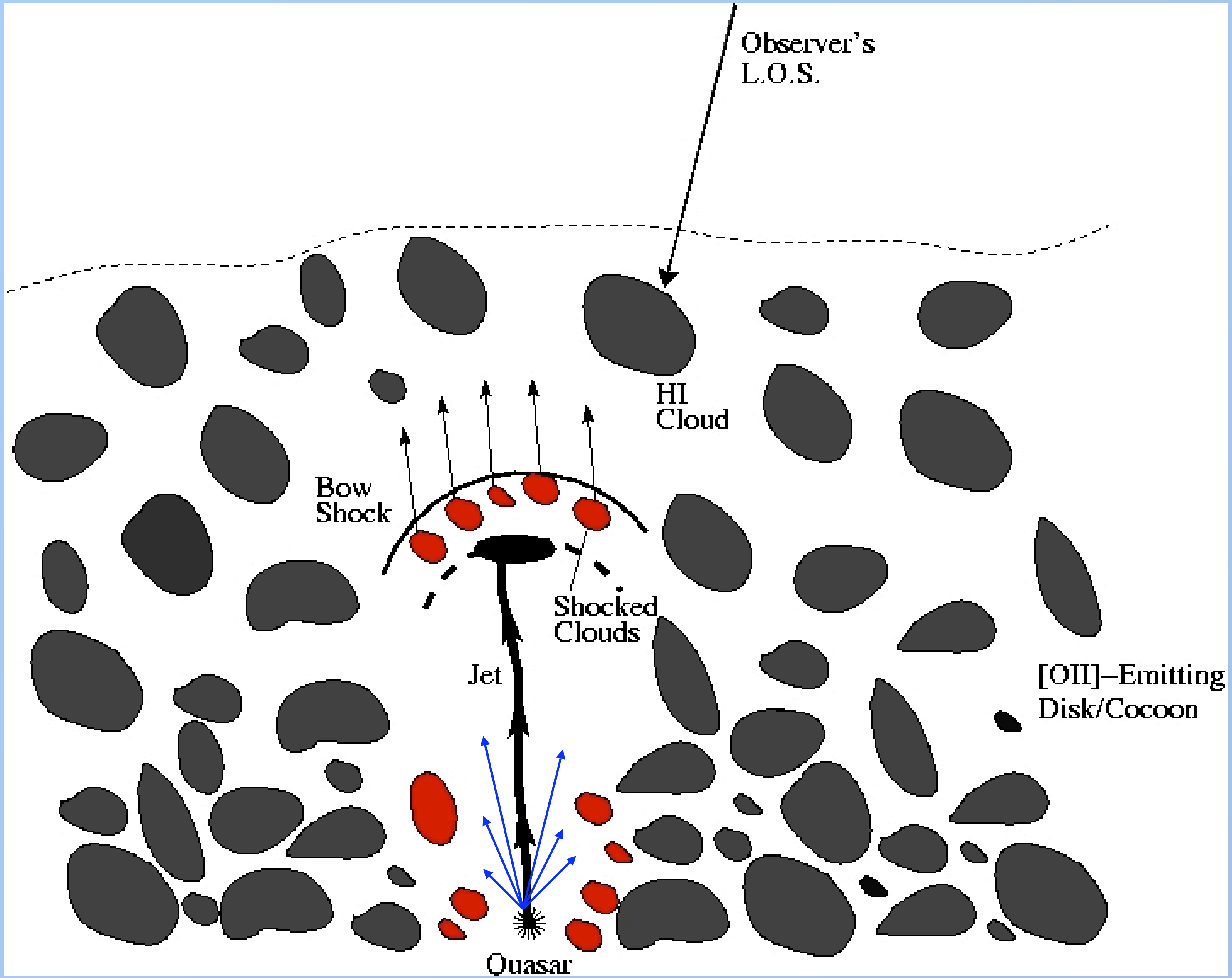
Morganti etal. (2001)

PKS1549-79: Optical Spectrum

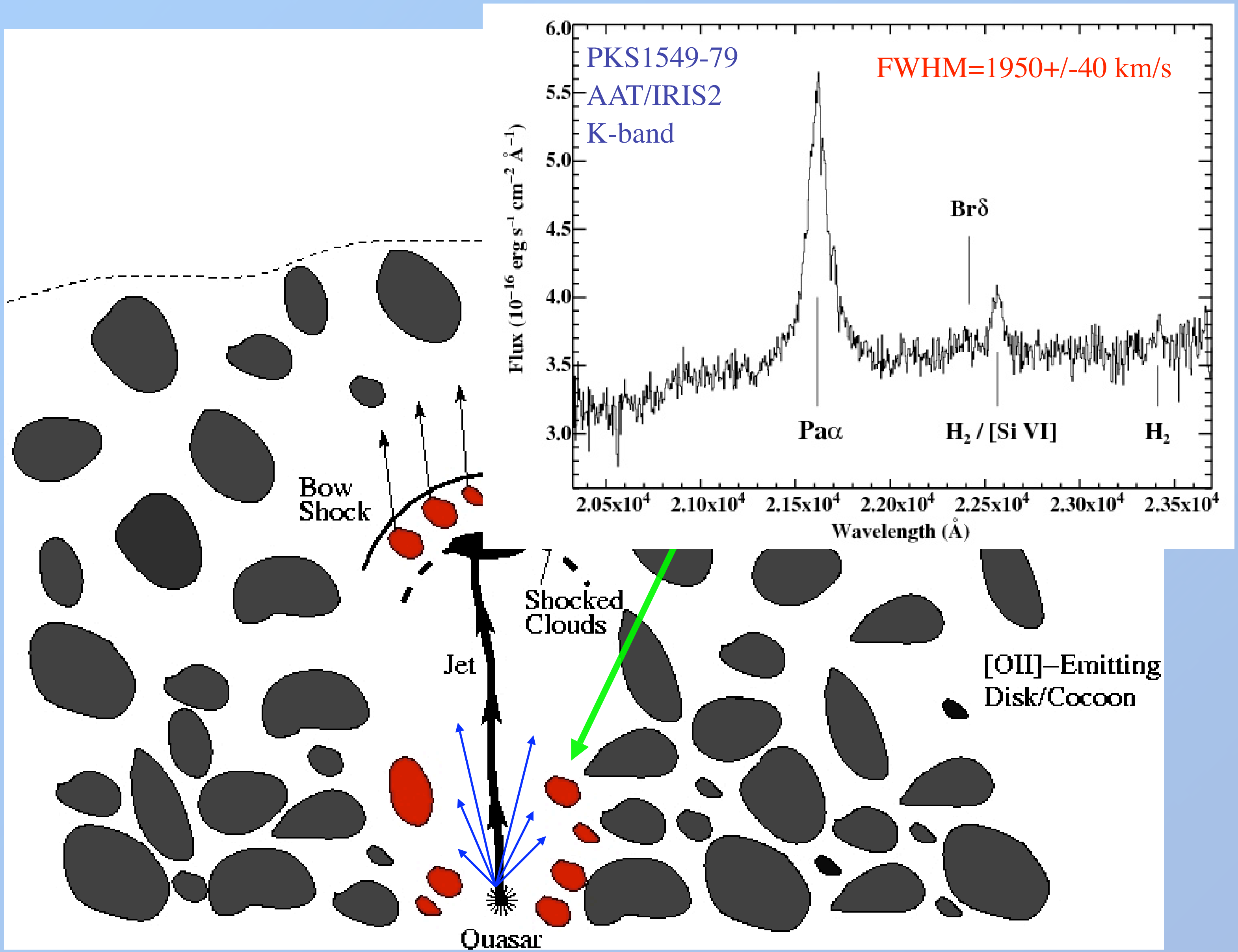


Tadhunter et al. (2001)

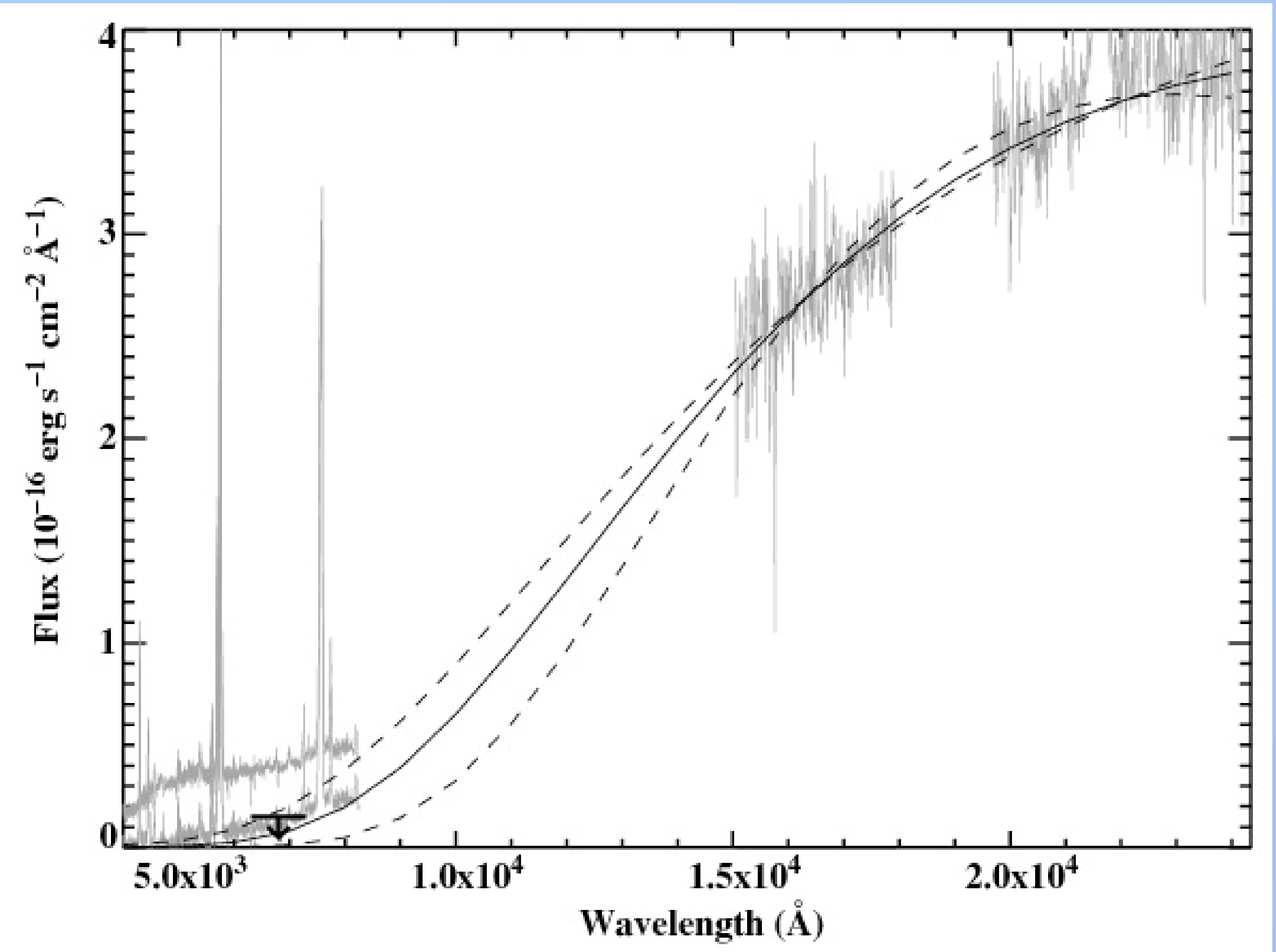
The early stages of radio source evolution



The early stages of radio source evolution



Optical/near-IR continuum SED



NTT+
SOFI

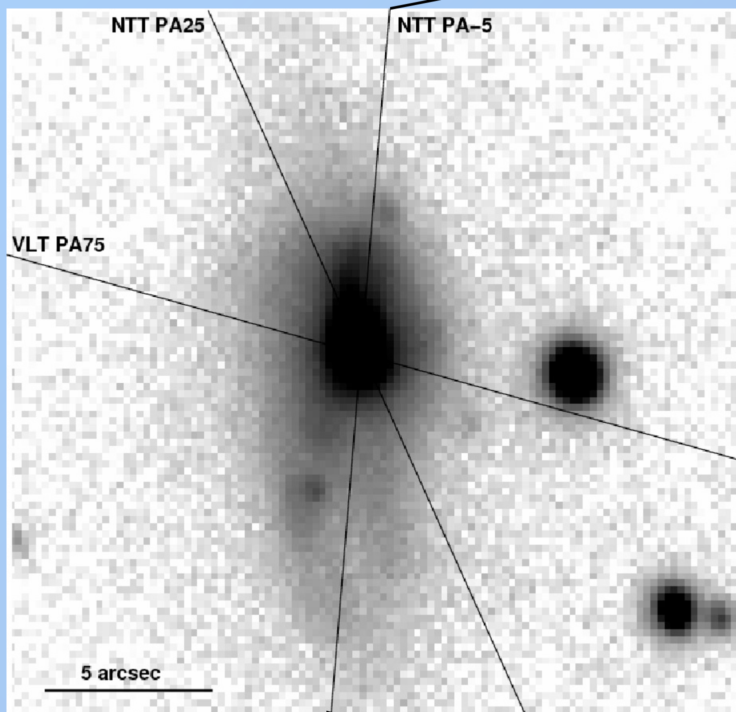
VLT+
FORS2

Quasar properties: $-27.56 < M_v < -23.5$

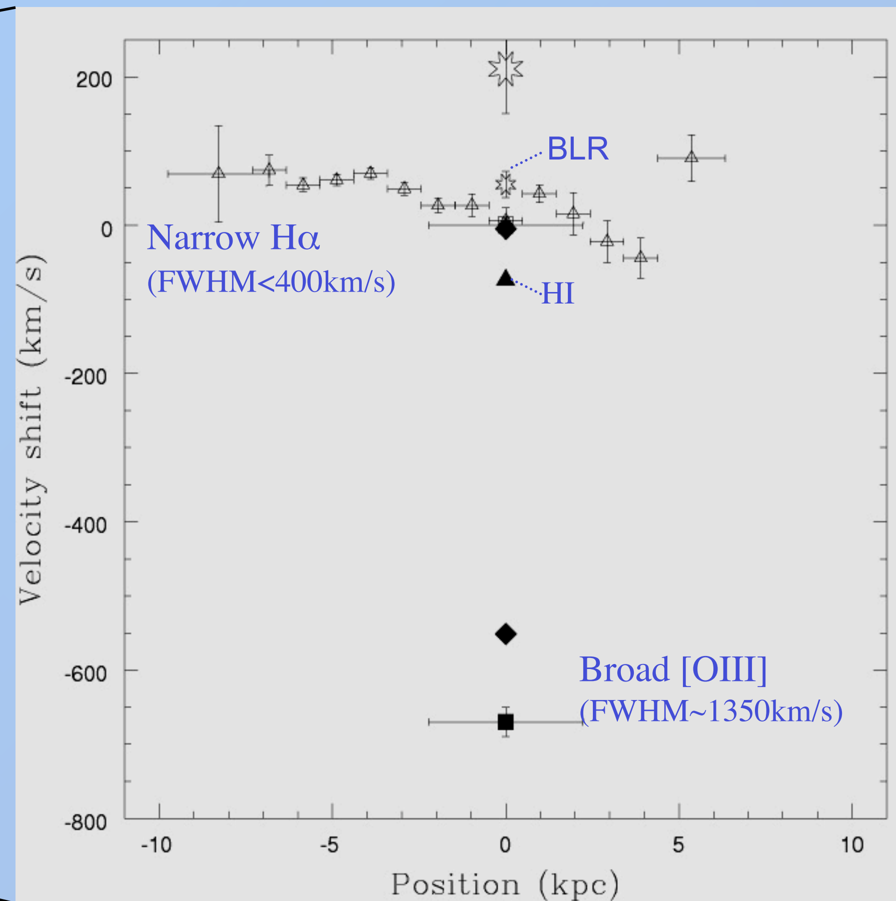
$6.4 < A_v < 13.2$

Holt et al. (2006)

Emission line kinematics in PKS1549-79



VLT+FORS1
Gunn r



VLT+FORS2

Holt et al. (2006)

Nature of the AGN in PKS1549-79

- Narrow line Seyfert 1 (FWHM Paα < 2000 km/s)
- Black hole mass: 3.6×10^7 -- 2.4×10^8 M_{sun}

  (virial) (from M_r)
- High Eddington ratio: $0.3 < L_{bol}/L_{edd} < 35$, typical of NLSy1 (but larger than most quasars which have $L_{bol}/L_{edd} < 0.1$)
- Relatively modest warm gas outflow:

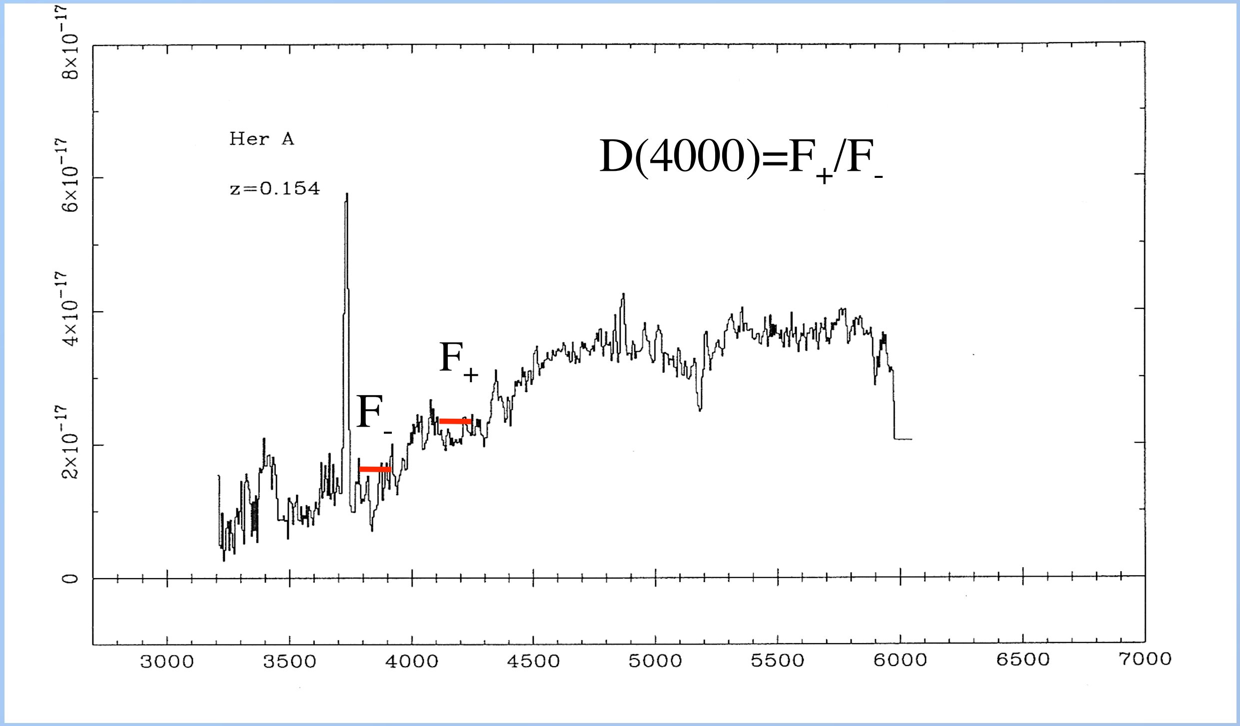
$$0.12 < \dot{M} < 12\ M_{sun}\ yr^{-1}$$

$$5.1\times10^{40} < \dot{E} < 5.1\times10^{42}\ erg\ s^{-1}$$

$$1.5\times10^{-6} < \dot{E}/L_{edd} < 1.5\times10^{-4}$$

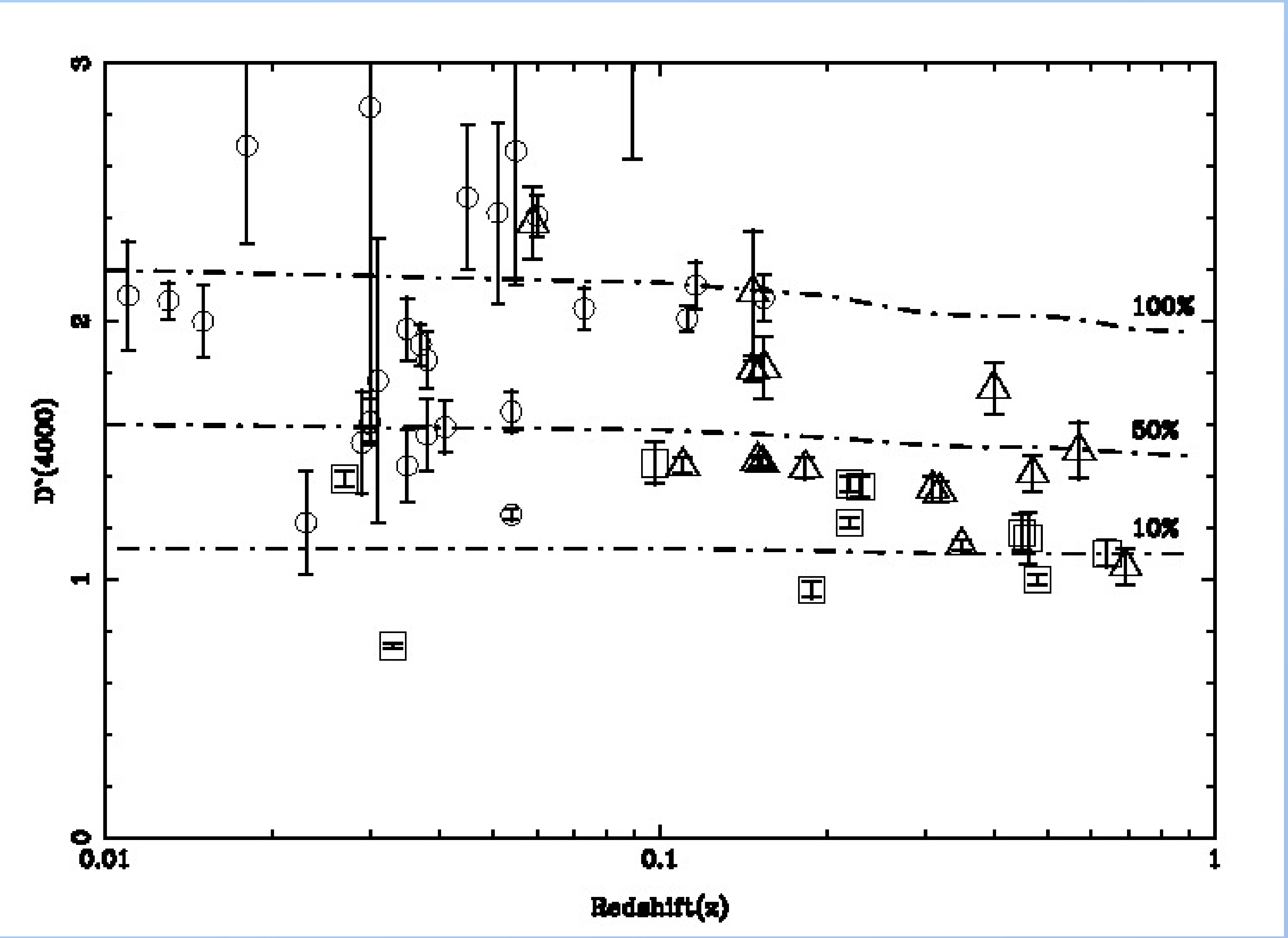
Holt et al. (2006)

Evidence for a UV excess



D4000 Break Measurements for Southern 2Jy Sources (Tadhunter et al. 2002)

Evidence for a UV excess



D4000 Break Measurements for Southern 2Jy Sources (Tadhunter et al. 2002)