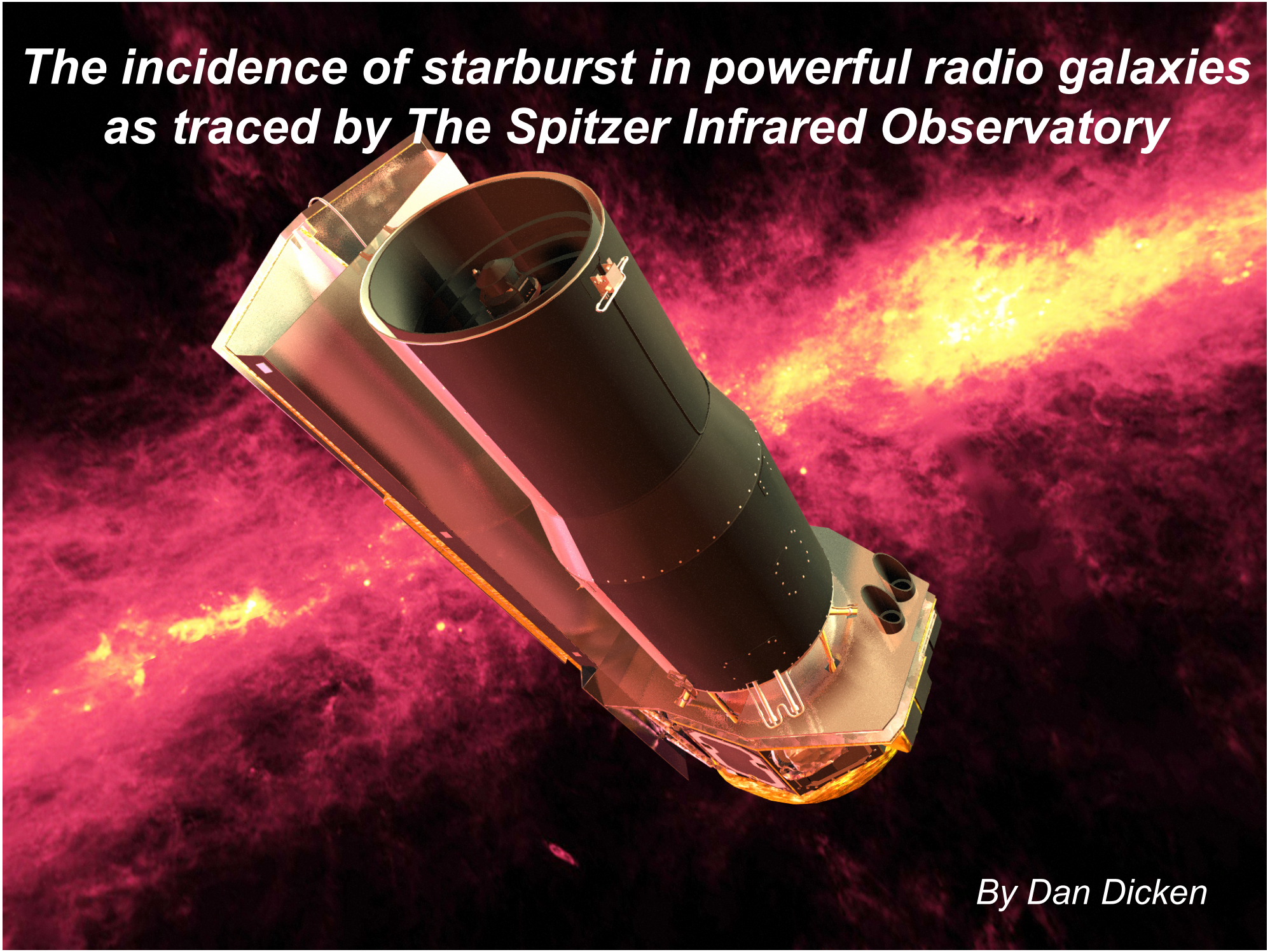
The incidence of starburst in powerful radio galaxies as traced by The Spitzer Infrared Observatory



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The begging: The 2Jy sample?

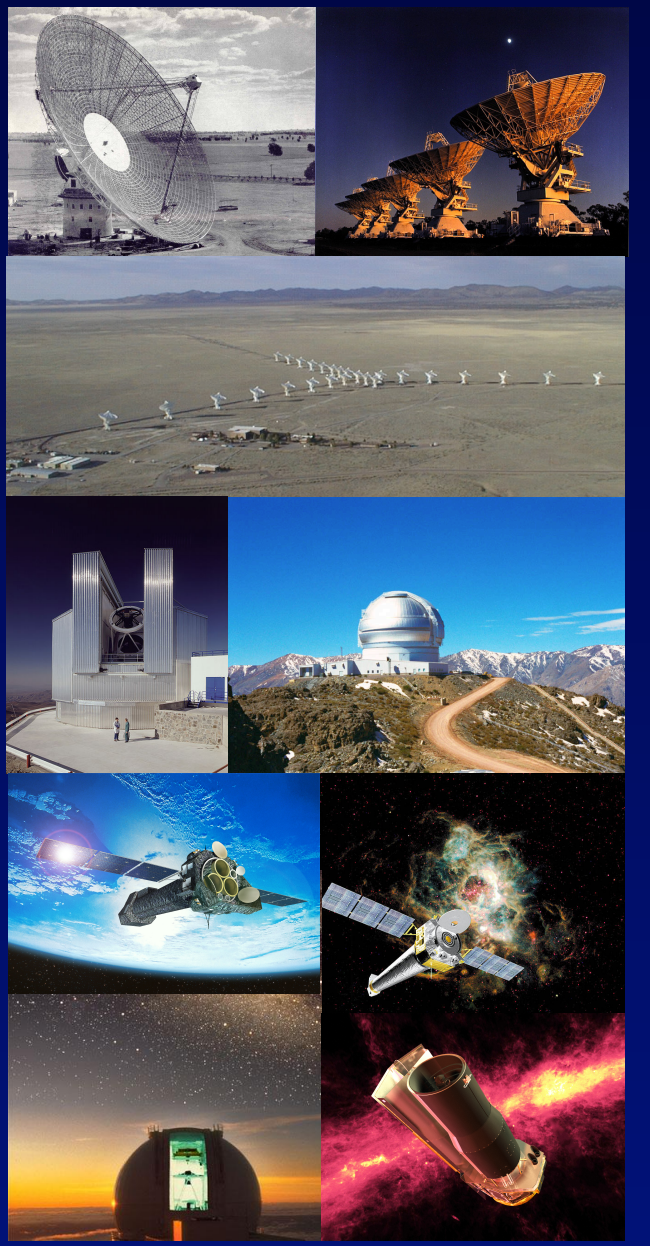
2 decades ago Clive and Raffealla et al. were keen to investigate the properties of Radio-loud AGN

The motivation: data for the famous 3C catalogue had remained unpublished/incomplete/did not exist

The aim: To study in detail the relationship between the multi-wavelength properties of a complete sample

Original publications: Tadhunter et al. (1993) and Morganti et al. (1993) and di Serego-Alighieri (1994)

Observational campaigns: VLA, ATCA, WHT, Gemini, Chandra, XMM, UKIRT, SOFI/NTT, Spitzer



The 2Jy Sample

- Taken from the sample of Wall and Peacock (1985)
  Flux limited to $S_{2.7Ghz}$>2Jy
- Sub-sample of (delta<+10 degrees)
- This sample consists of 88 objects:
  - 68 galaxies
  - 18 quasars
  - 2 BL Lac objects

Why study samples of radio galaxies

Why Samples?

- We cannot directly image AGN
- An alternative: Statistical studies of complete samples
- As observations improve the basic model of orientation based unification is increasingly challenged

Why Radio Galaxies?

- Radio galaxies make up 10% of AGN galaxies as a class and AGN make up 2% of field galaxy population (Peterson 1997)
- Can be selected, without orientation bias, on their isotropic radio emission

Why observe radio galaxies in the infrared?

Its not just about seeing through the dust!

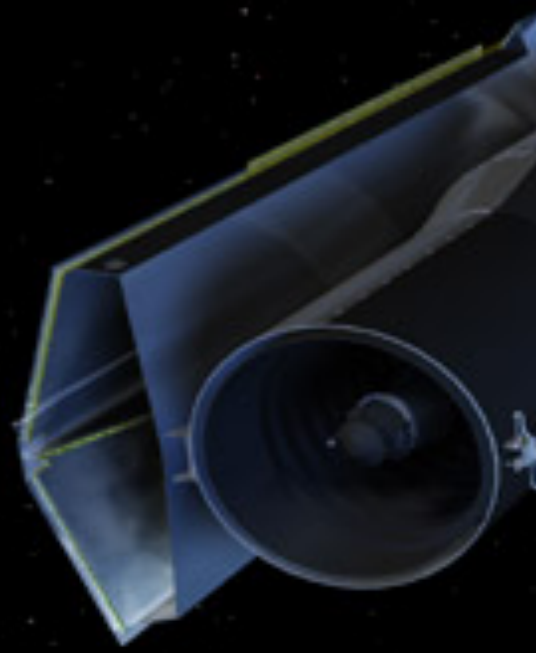
Huge amounts of energy from AGN is emitted at these wavelengths, up to $L_{FIR} > 10^{12} L_{sun}$

Mid-infrared spectral features: PAH, silicate absorption, emission lines

Interpreting the red-shifted sub-mm emission of distant galaxies

The Spitzer Space Telescope

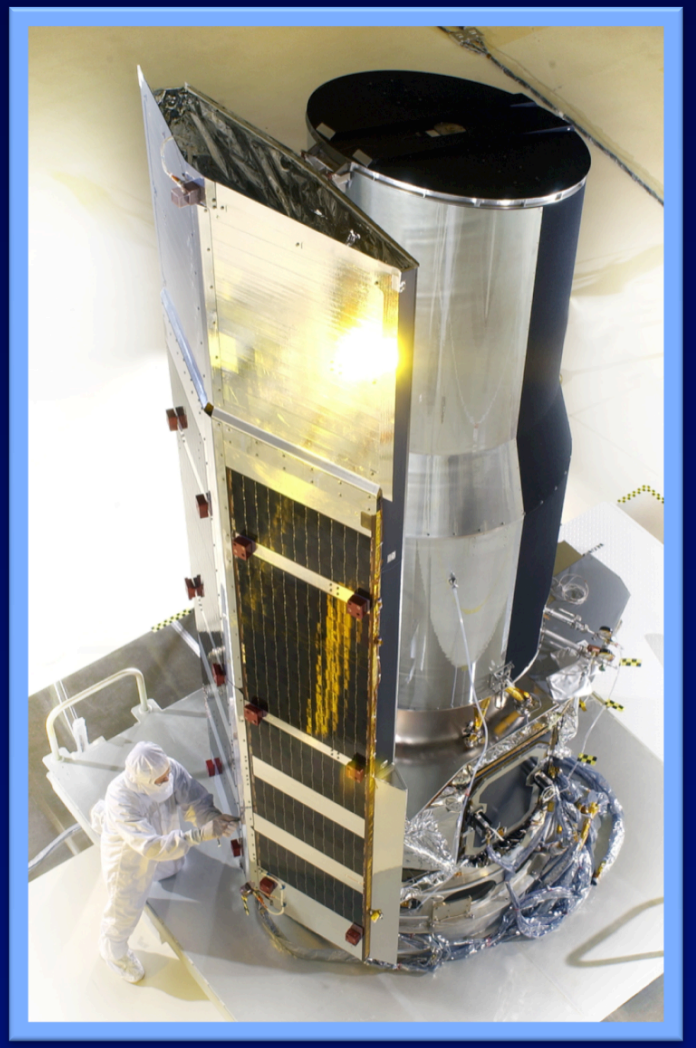
- Launched August 2003, cold mission lasted almost 6 years (IRAS 10 months, ISO less than 3 years)
- 85cm mirror cooled which was cooled to less than 5.5K
- Unlike previous observatories, it lies in thermally stable earth trailing orbit



Studies	Observatory	Far-IR detection rate	Sample notes
Neugebauer et al. (1986)	IRAS	74/179 (41)%	Heterogeneous sample of IRAS pointed observations, mainly radio-quiet AGN.
Golombek et al. (1988)	IRAS	58/131 (44)%	Heterogeneous sample based on all objects with pointed observations from IRAS.
Heckman et al. (1994)	IRAS	26 of over 200 objects	Low detection rate, hence utilized combined images matched in redshift.
Impey & Gregorini (1993)	IRAS	19/140 (13)%	Drawn from 3 separate magnitude limited samples.
Hes et al. (1995)	IRAS	10/68 (15)%	Statistically sound sample based on all objects with redshift 0.3<z<0.8 from the 3CR catalogue.
Meisenheimer et al. (2001)	ISO	13/20 (65)%	10 pairs of quasars and NLRG matched in radio luminosity and redshift from the 3CR catalogue.
Haas et al. (2004)	ISO	35/75 (47)%	Heterogeneous sample based on objects available in ISO archive.
Shi et al. (2005)	Spitzer	47/47 (100)%	Heterogeneous sample based on objects with previous HST observations.
Cleary et al. (2007)	Spitzer	20/33 (60)%	Statistically sound sample based on the 3CRR sample of Barthel (1989) with redshifts 0.5<z<1.0 and further reduced by ecliptic latitude.
Dicken et al. (2008), Chapter 4	Spitzer	41/46 (90)%	Statistically sound sample from Tadhunter et al. (1993) with redshifts 0.05<z<0.7, and steep spectrum selection.

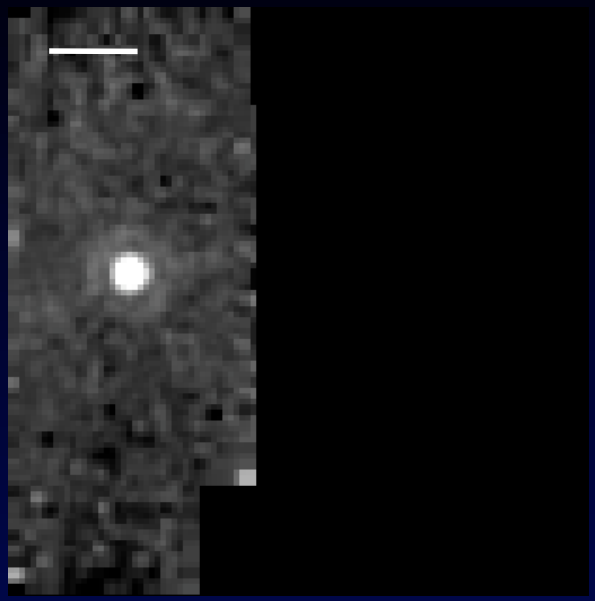
Our Spitzer 2Jy sample

- Flux limited $S_{2.7Ghz}$>2Jy
- Sub-sample of 46 steep spectrum selected radio galaxies and quasars taken from Tadhunter et al. (1993) and Morganti et al. (1993)
- Intermediate redshifts: 0.05<z<0.7
- Optical Classifications
  - Broad-line radio galaxies/Quasar 35%
  - Narrow-line radio galaxies 43%
  - Weak-line radio galaxies 22%
- Radio Classifications
  - FRII 72%
  - FRI 13%
  - Compact Steep Spectrum 15%



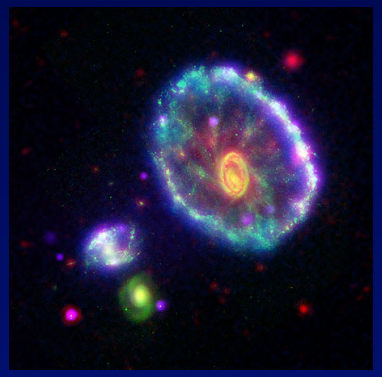
Spitzer MIPS images

Spitzer MIPS 24 micron image WARM dust 120K

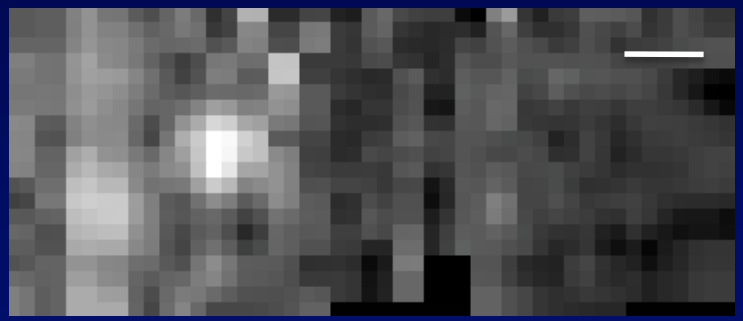


Spitzer MIPS 70 micron image COOL dust 40K

Spitzer MIPS Detection rates: 24μm - 100%, 70μm - 90%

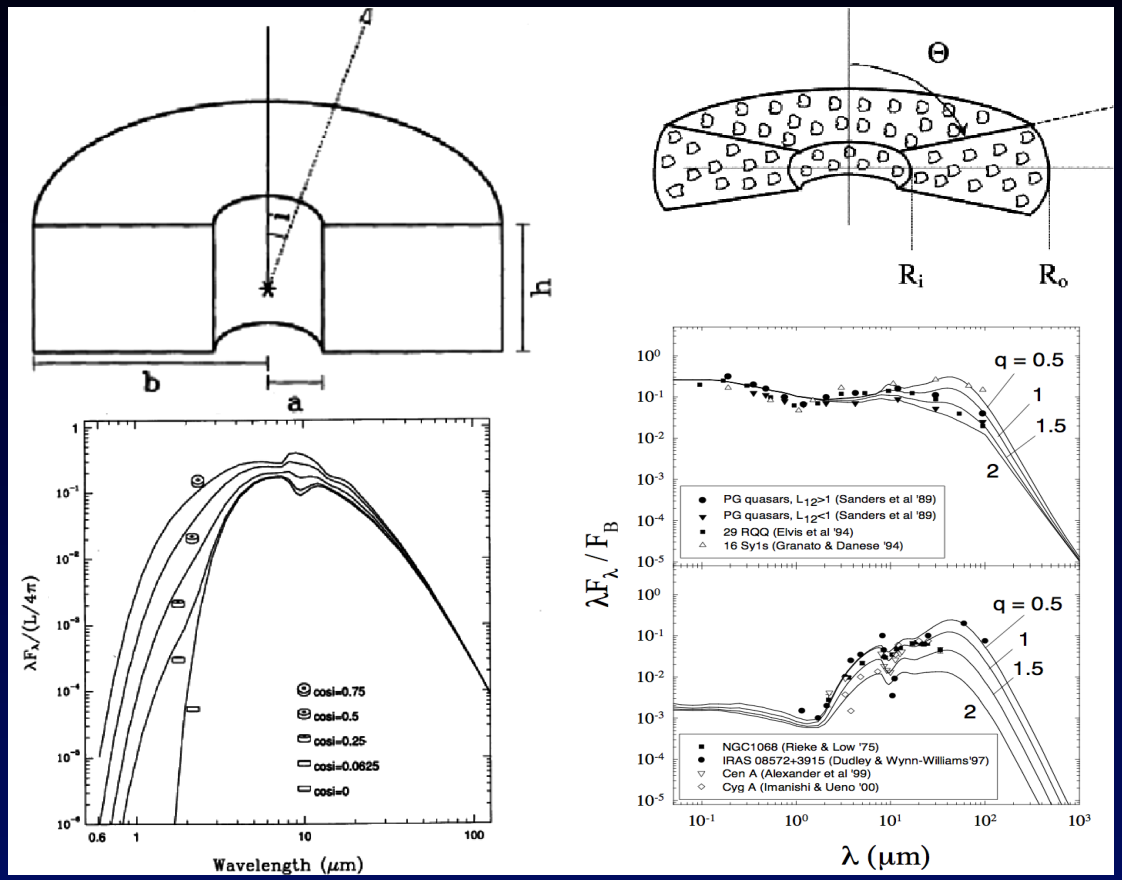


Spitzer IRAC composite image of the cartwheel galaxy and NGC2841.



Spitzer MIPS 160 micron image

The origin of mid- and far-infrared emission

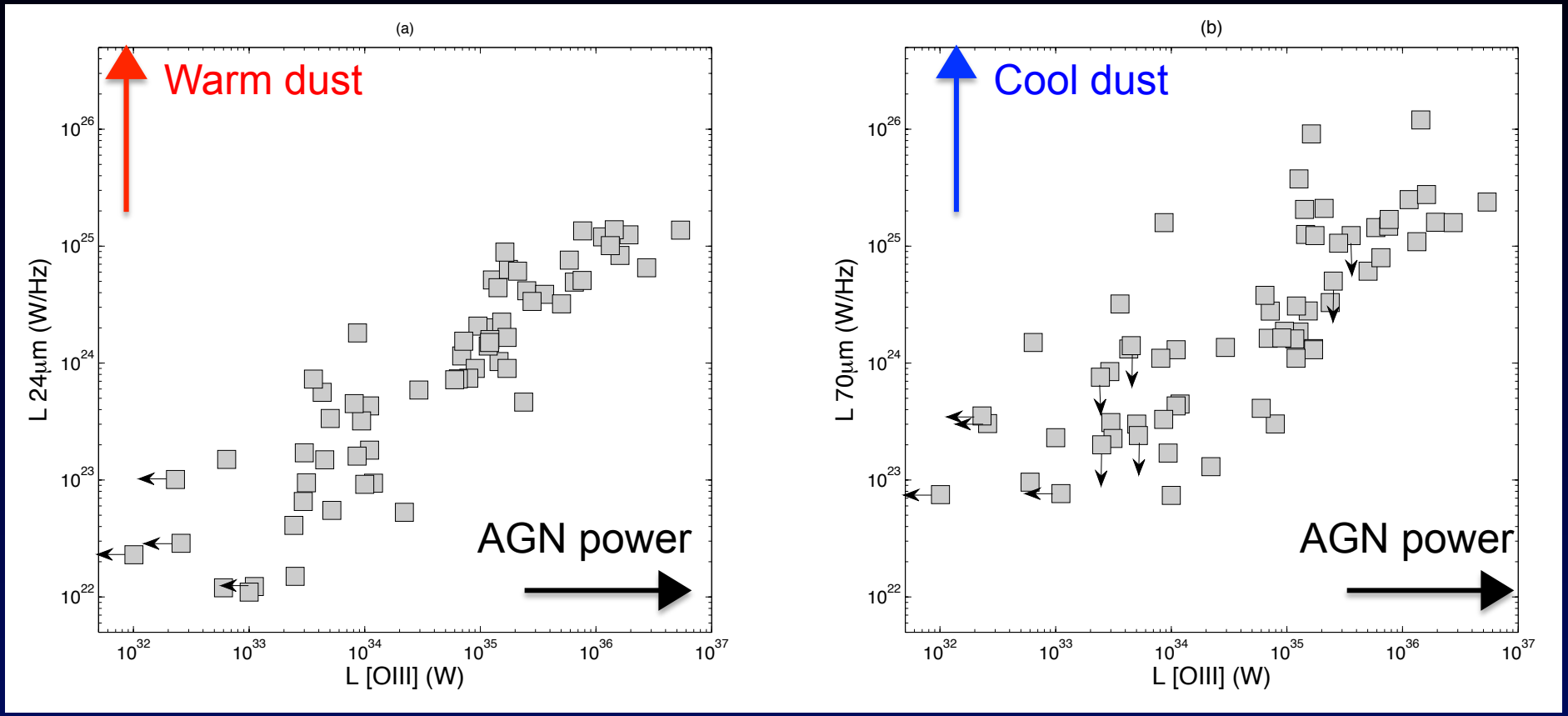


Compact torus
Pier & Krolik (1994)

Clumpy torus
Nenkova et al. (2002)

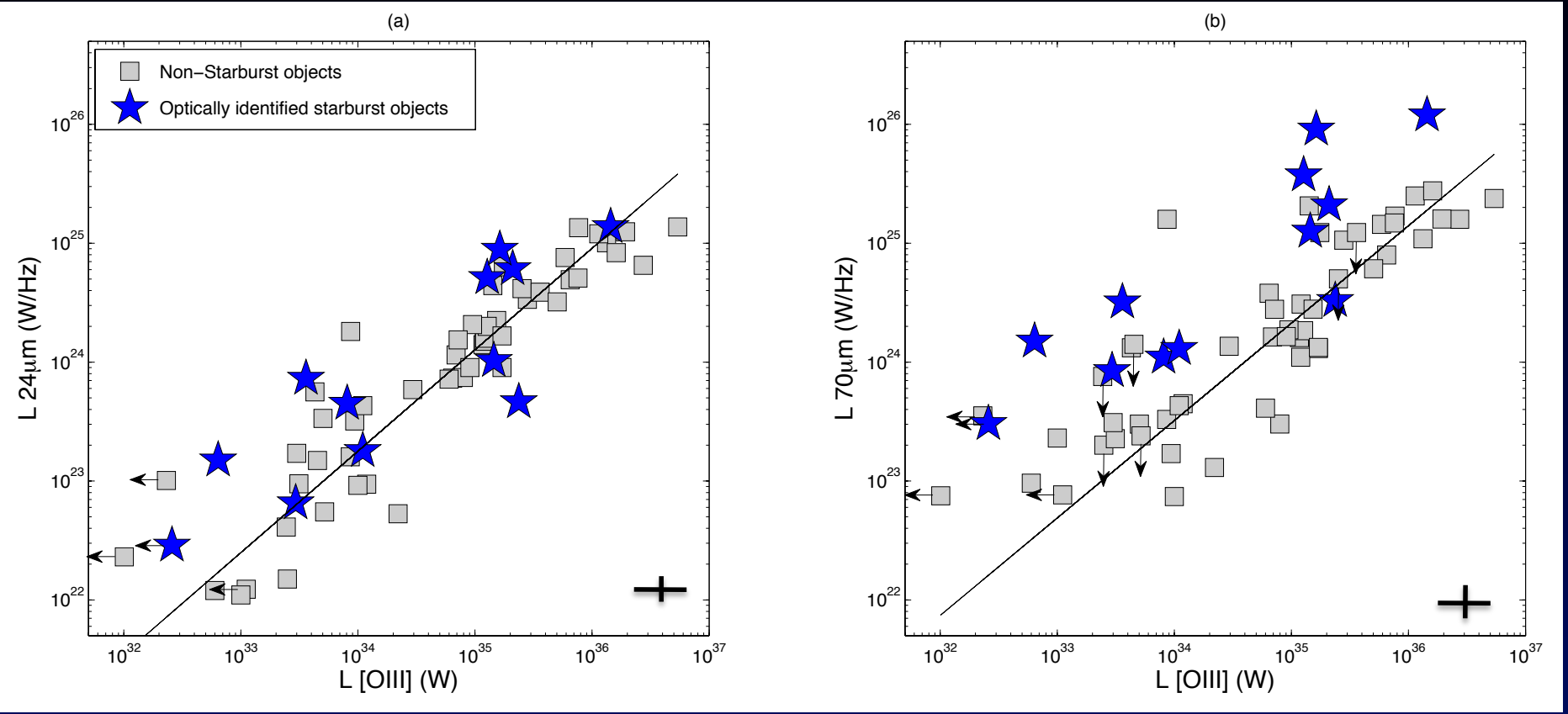
- Compact uniform torus can not produce the mid- to far-infrared spectral energy distribution (SED)
- Therefore a clumpy torus model was introduced
- But a compact torus + starburst can also explain the SEDs of AGN
- The origin of the thermal far-infrared emission was uncertain

The origin of mid- and far-infrared emission



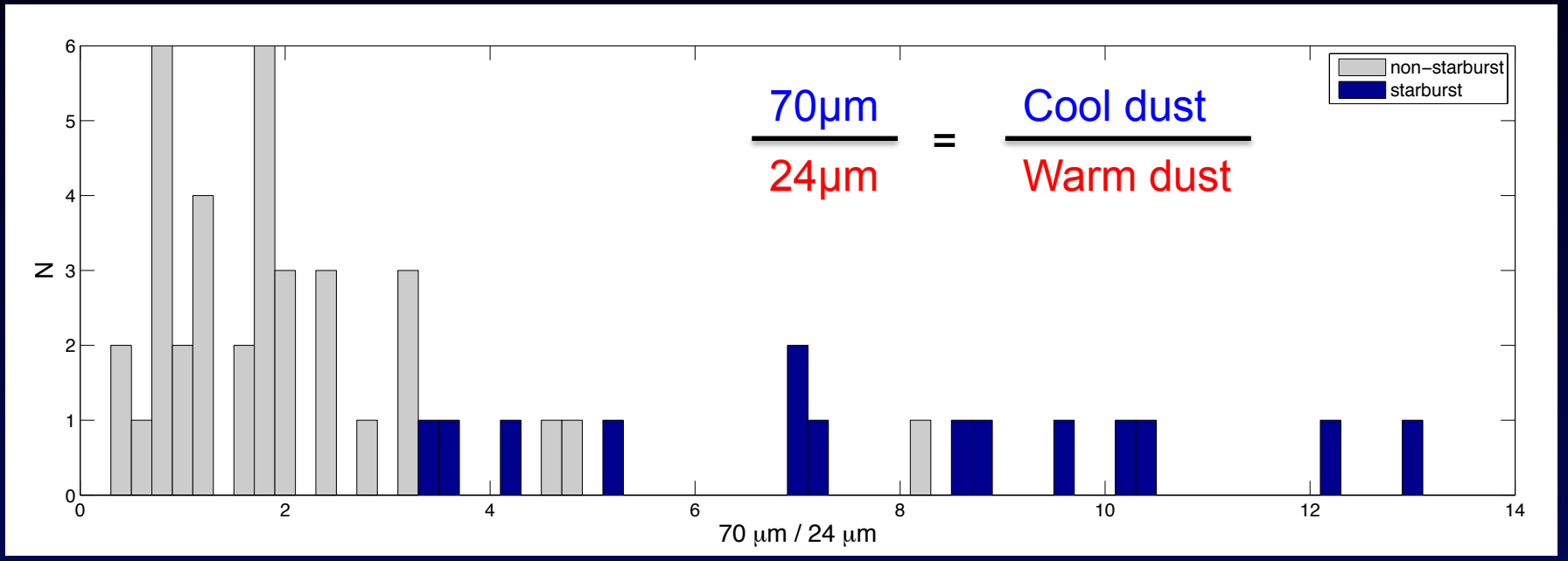
- L[OIII] is a good indicator of AGN power (Tadhunter et al. 1998; Simpson 1998; la Massa 2010)
- Correlations show that **AGN illumination is the primary heating mechanism for the of the mid- and far-infrared emitting dust**.
- Consistent with clumpy torus models but also a narrow-line cloud origin
- Added a sample of 17 3CRR FRII radio galaxies: z<1

Starburst Diagnostic Test 1: Optical Modelling



- Identified objects with young stellar populations through careful optical spectral synthesis modelling of the 2Jy Sample (Tadhunter et al. 2002; Wills et al. 2004, 2008; Holt et al. 2007)

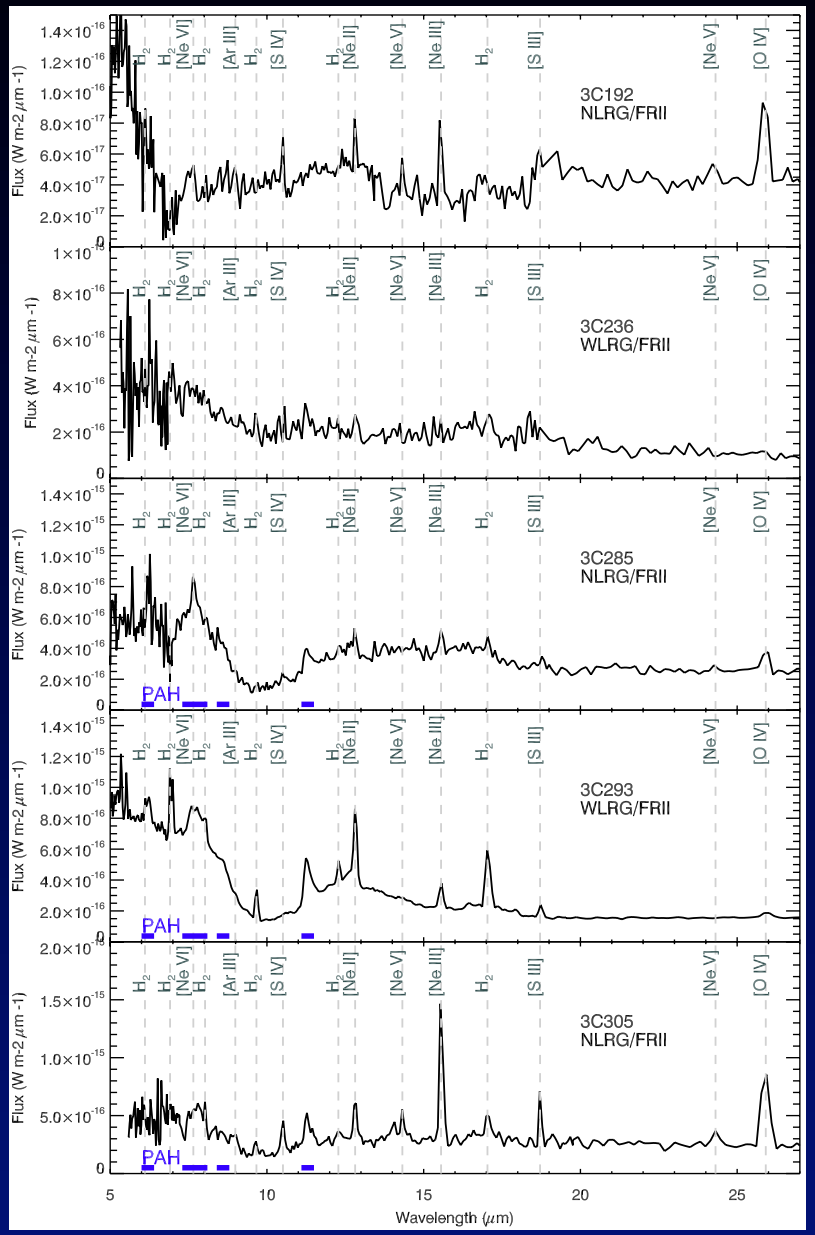
Starburst test 2: color



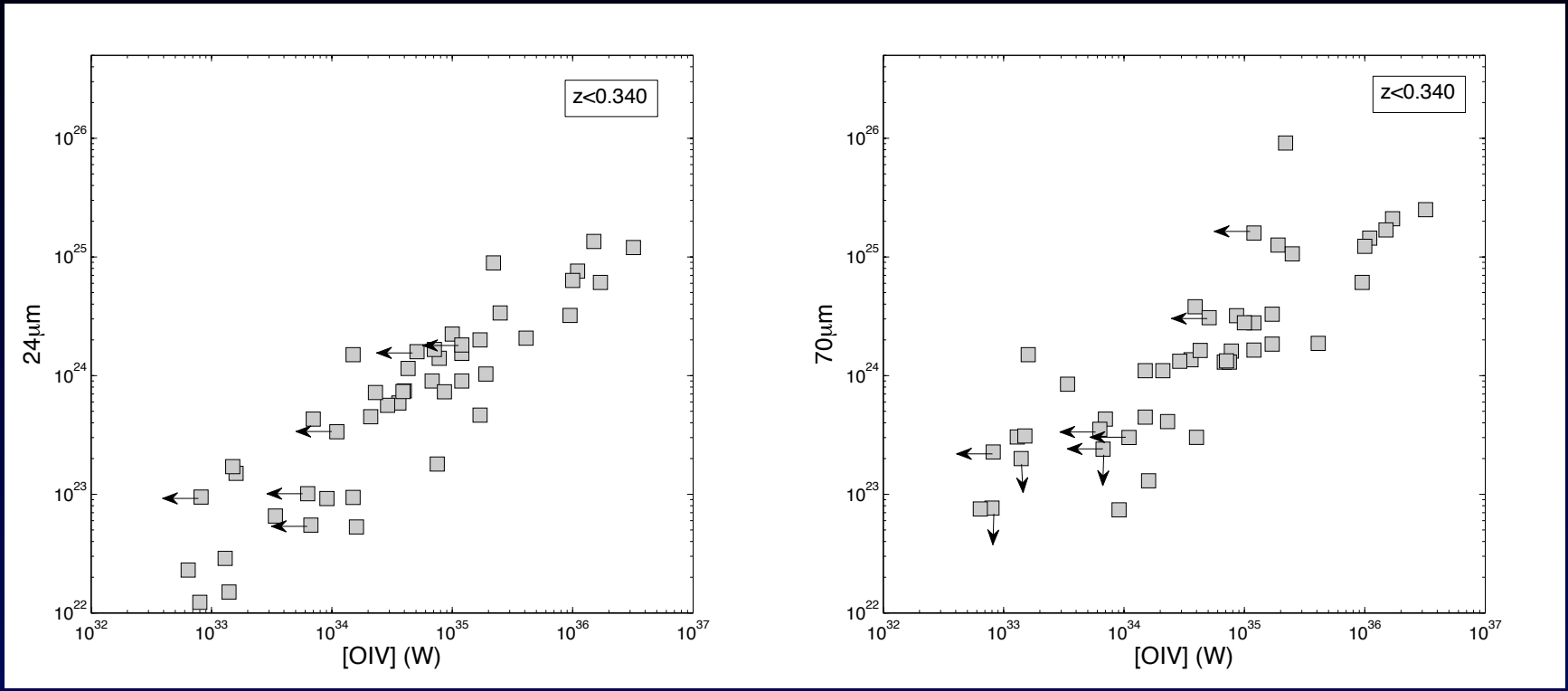
- Starburst radio galaxies tend towards cooler infrared colours

Spitzer IRS mid-infrared spectra

- Second successful 2Jy sample proposal to observe with Spitzer's mid-infrared spectrograph
- **Spectral range:** 5-36μm
- **Detection rate:** Nearly all 46 objects before the cryogenic coolant ran out; just missed out on 2
- We see a large diversity in the mid-infrared spectral shapes, dust features and fine structure lines

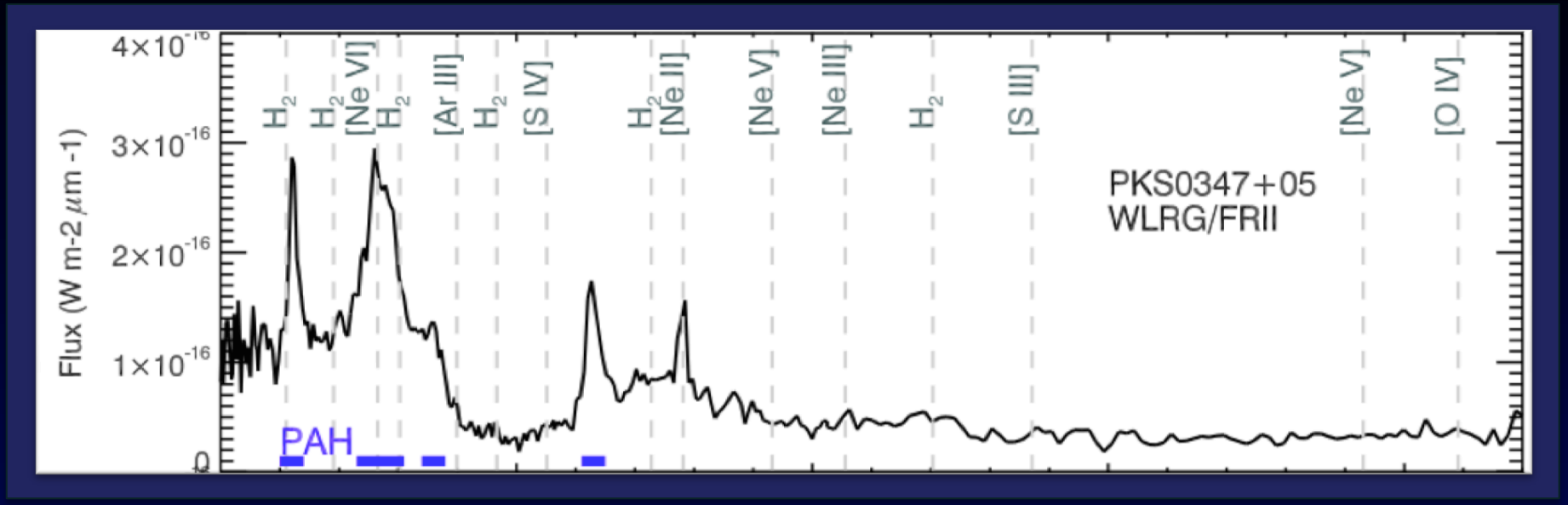


Spitzer IRS mid-infrared spectra

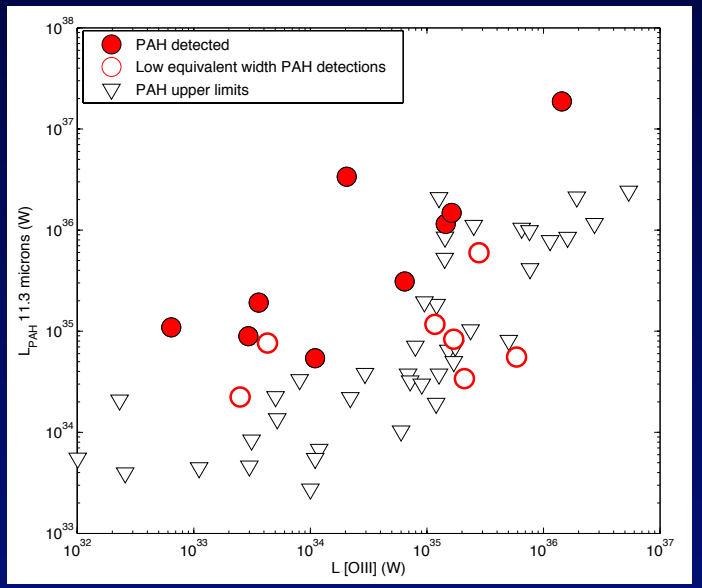


- Plotting [OIV] λ25.89μm vs L24 and L70μm

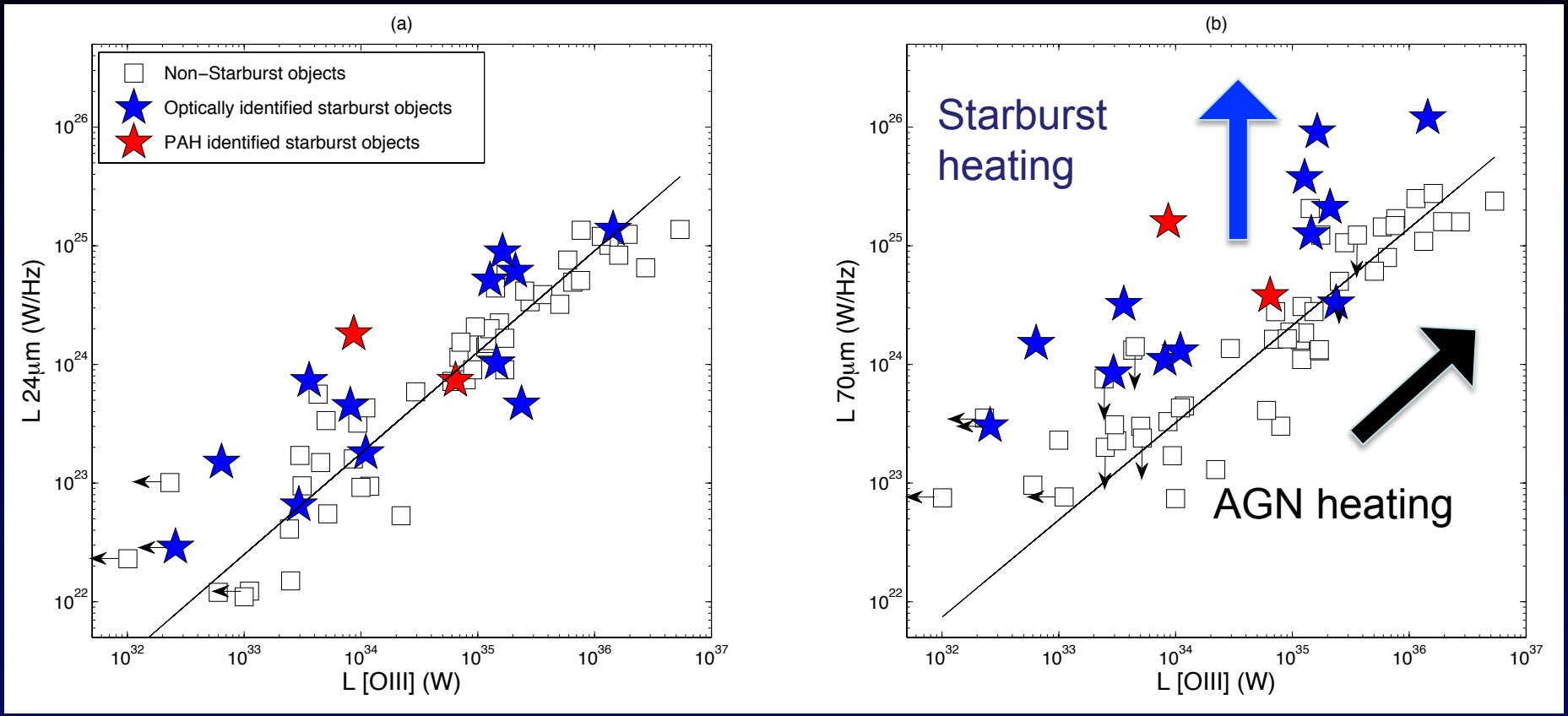
Starburst Diagnostic Test 3: PAH



- **The aim**: to look for starburst tracing Polycyclic Aromatic Hydrocarbons (PAH) in the mid-IR spectra
- PAH is advantageous over optical modelling because the AGN strong continuum can mask signatures
- Searching for hidden starburst population
- Optical and PAH starburst identifications agree well (7/9) so no optically obscured starburst population



Starburst test 4: far-infrared excess



- 2 new identifications of starburst objects from PAH detection
- Infrared excess performs well as an indicator of starburst

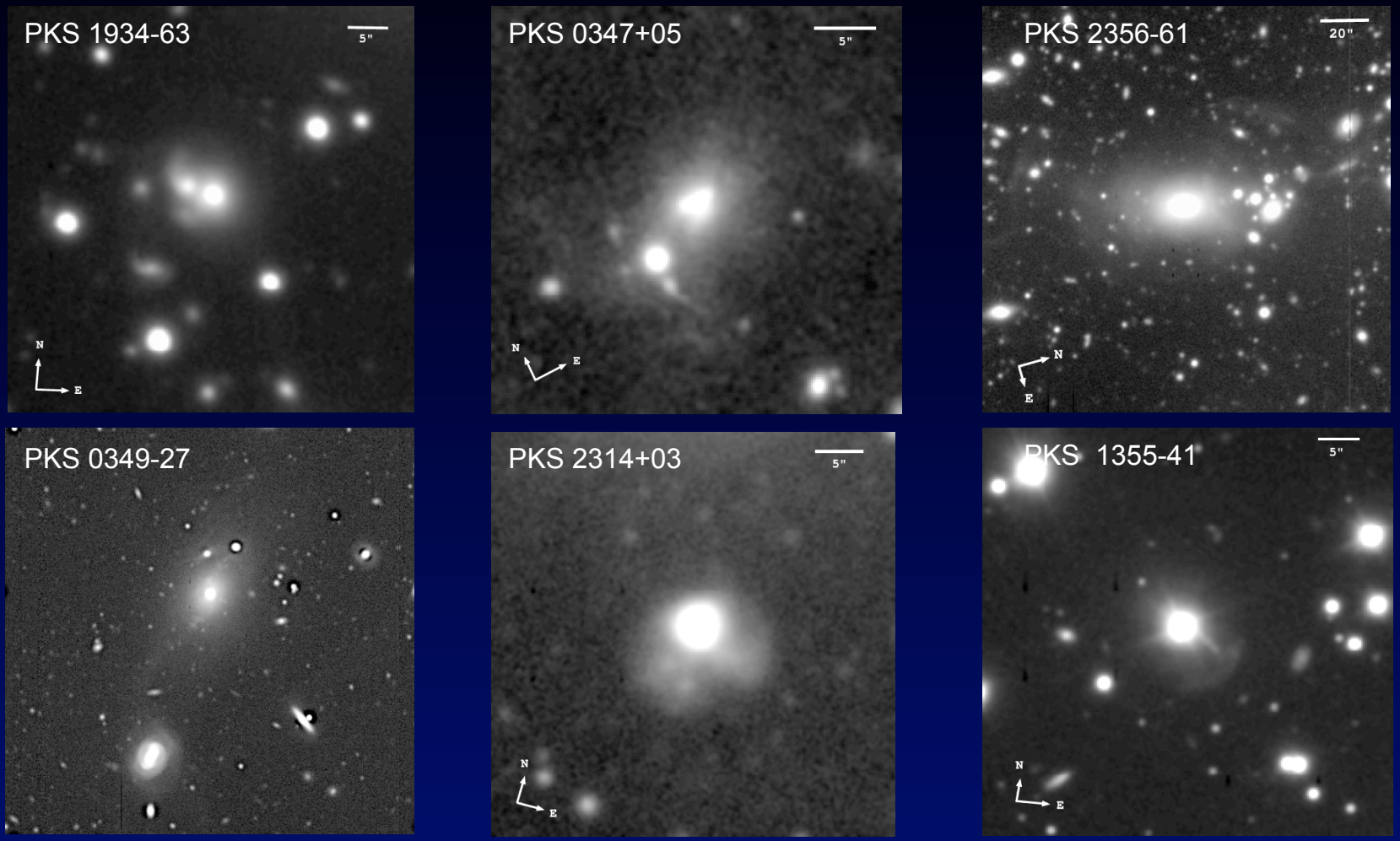
The Result from the 4 starburst tests

STARBURST DETECTIONS IN THE 2JY AND 3CRR SAMPLES

Name	other	Optical	PAH	Color	Far-IR	Name	other	Optical	PAH	Color	Far-IR
0023−26		✔	✔	✔	✔	1814−63		U	low	–	✔
0034−01	3C15	–	–	–	–	1839−48		–	–	–	–
0035−02	3C17	–	–	–	–	1932−46		✔	–	✔	–
0038+09	3C18	–	–	–	–	1934−63		–	low	–	–
0039−44		–	–	–	–	1938−15		–	–	–	–
0043−42		–	–	–	–	1949+02	3C403	–	–	–	–
0105−16	3C32	–	–	U	–	1954−55		–	–	–	–
0117−15	3C38	–	–	–	–	2135−14		U	U	–	–
0213−13	3C62	–	–	–	–	2135−20	OX−258	✔	✔	✔	✔
0235−19	OD−159	–	–	–	–	2211−17	3C444	–	U	U	–
0252−71		–	–	U	–	2221−02	3C445	–	–	–	–
0347+05		U	✔	✔	✔	2250−41		–	–	–	–
0349−27		U	–	–	–	2314+03	3C459	✔	✔	✔	✔
0404+03	3C105	–	–	–	–	2356−61		–	–	–	–
0409−75		✔	–	✔	✔	3C33		–	low	–	–
0442−28		–	–	–	–	3C35		–	U	U	–
0620−52		✔	–	✔	–	3C98		–	–	–	–
0625−35	OH−342	–	–	–	–	DA240		–	U	✔	✔
0625−53		–	–	U	–	3C192		–	–	–	–
0806−10	3C195	–	low	–	–	4C73.08		–	U	–	–
0859−25		–	–	–	–	3C236		✔	(low)	–	✔
0915−11	Hydra A	✔	✔	✔	✔	3C277.3		–	U	–	–
0945+07	3C227	U	–	–	–	3C285		✔	✔	✔	✔
1136−13		U	–	–	–	3C293		✔	✔	✔	✔
1151−34		U	low	–	–	3C305		✔	✔	✔	✔
1306−09		U	–	–	✔	3C321		✔	low	–	✔
1355−41		U	–	–	–	3C326		–	low	U	–
1547−79		U	–	–	–	3C382		U	–	–	–
1559+02	3C327	–	–	–	–	3C388		–	–	U	–
1602+01	3C327.1	–	–	–	–	3C390.3		U	–	–	–
1648+05	Herc A	–	U	U	–	3C452		–	–	–	–
1733−56		U	✔	✔	–						

- A maximum of 35% of radio galaxies have evidence for starburst (Dicken et al. 2011)
- Perhaps radio galaxies are not triggered in mergers?

Comparison with Gemini optical images



- 85% of the 2Jy sample show optical evidence for mergers (Ramos Almeida et al. 2010)

Consequences for AGN evolution

- We find no evidence for a link between major galaxies mergers and the triggering of radio galaxies:
  - The triggering of radio galaxies is likely to be due to more than one type of merger/interaction
  - Such a scenario is consistent with episodic radio activity e.g. X-radio sources
- AGN feedback: low rate of starburst is consistent with AGN feedback but is not needed to explain the observations
- Caution is needed when interpreting the far-infrared and sub-mm emission from distant radio galaxies

Conclusions and Futures Work

- The AGN is largely responsible for heating the dust that emits at mid- to far-infrared wavelengths
- We find good agreement between 4 starburst diagnostics used for the radio galaxies
- Starburst are only present in <35% of radio-loud AGN
- Mergers are evident in a high percentage (>85%) of radio-loud AGN however AGN and starburst need not be concurrent
- Future work:
  - Mid-infrared fine structure line studies
  - Silicate absorption/emission and mid-infrared spectral shapes
  - Longer wavelength observations (Herschel/ALMA)

http://2jy.extragalactic.info/