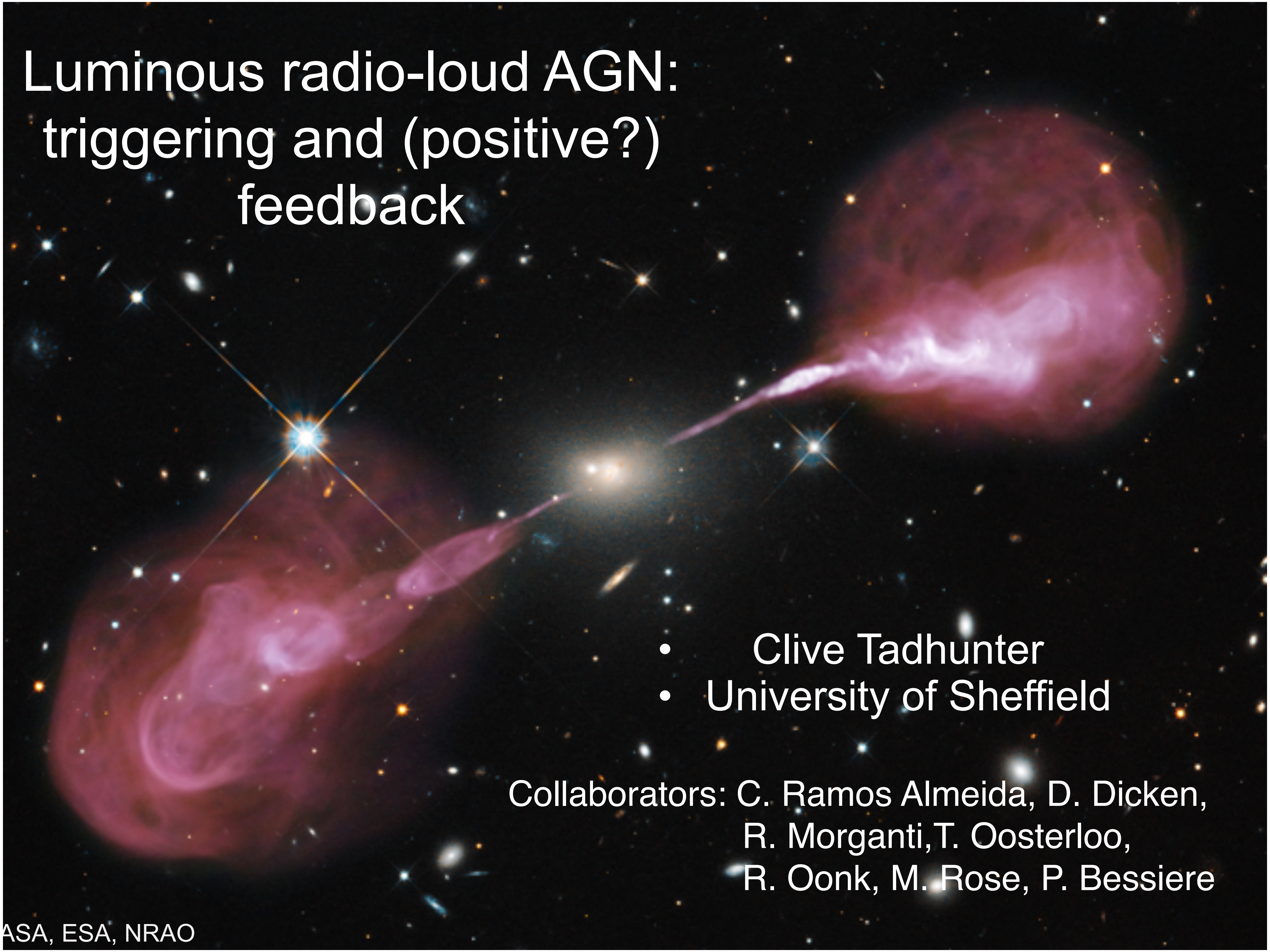
Luminous radio-loud AGN: triggering and (positive?) feedback

- Clive Tadhunter
- University of Sheffield

Collaborators: C. Ramos Almeida, D. Dicken, R. Morganti, T. Oosterloo, R. Oonk, M. Rose, P. Bessiere

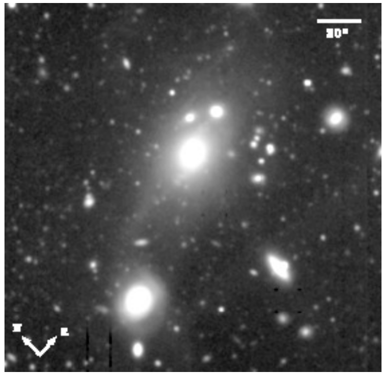


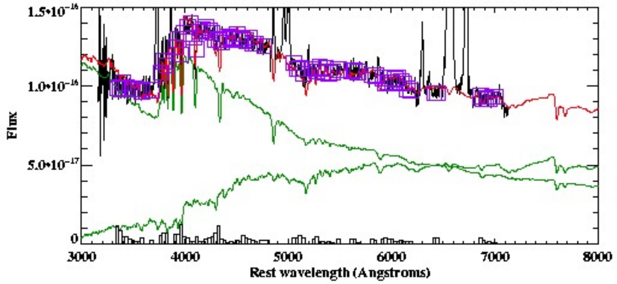
Investigating triggering mechanisms

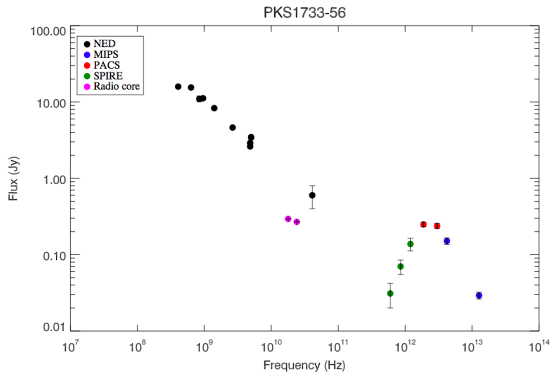
Galaxy morphologies and environments

Star formation

Cool ISM contents



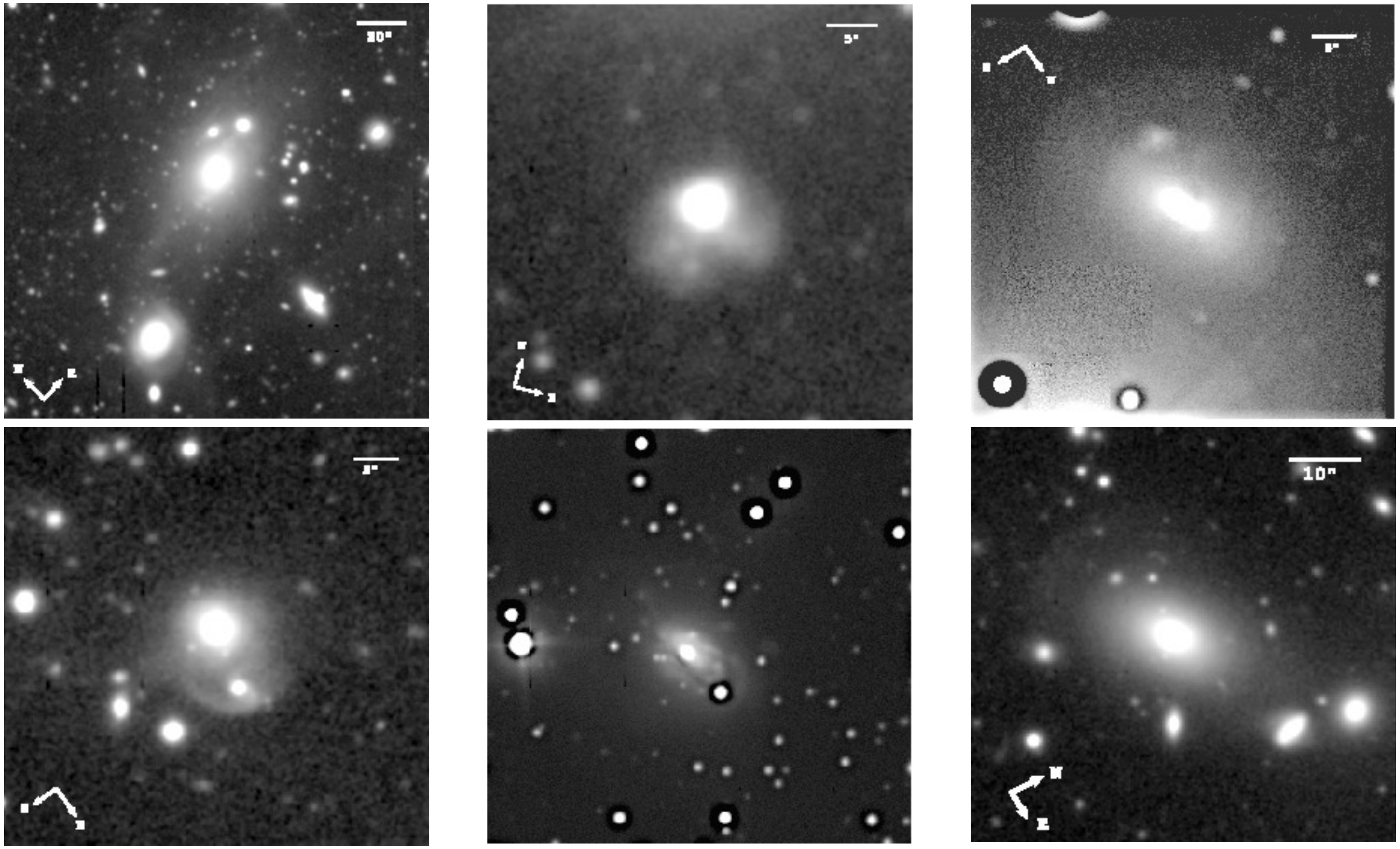




Deep Gemini, Spitzer & Herschel observations of the 2Jy sample

- Complete sample of 46 southern 2Jy radio sources with intermediate redshifts 0.05 < z < 0.7 and steep radio spectra (α > 0.5); $10^{25} < P_{1.4GHz} < 3\times10^{27}\,W\,Hz^{-1}$
- Best observed of all radio galaxy samples: deep X-ray (Chandra, XMM), optical (ESO3.6m/VLT/Gemini), mid-IR (Spitzer), far-IR (Herschel) and radio (VLA/ATCA) data…
- Optical classifications: 43% NLRG, 33% BLRG/QSO, 24% WLRG
- *Most sources are have nuclei of quasar-like luminosity (hidden from our direct view in the radio galaxies)*

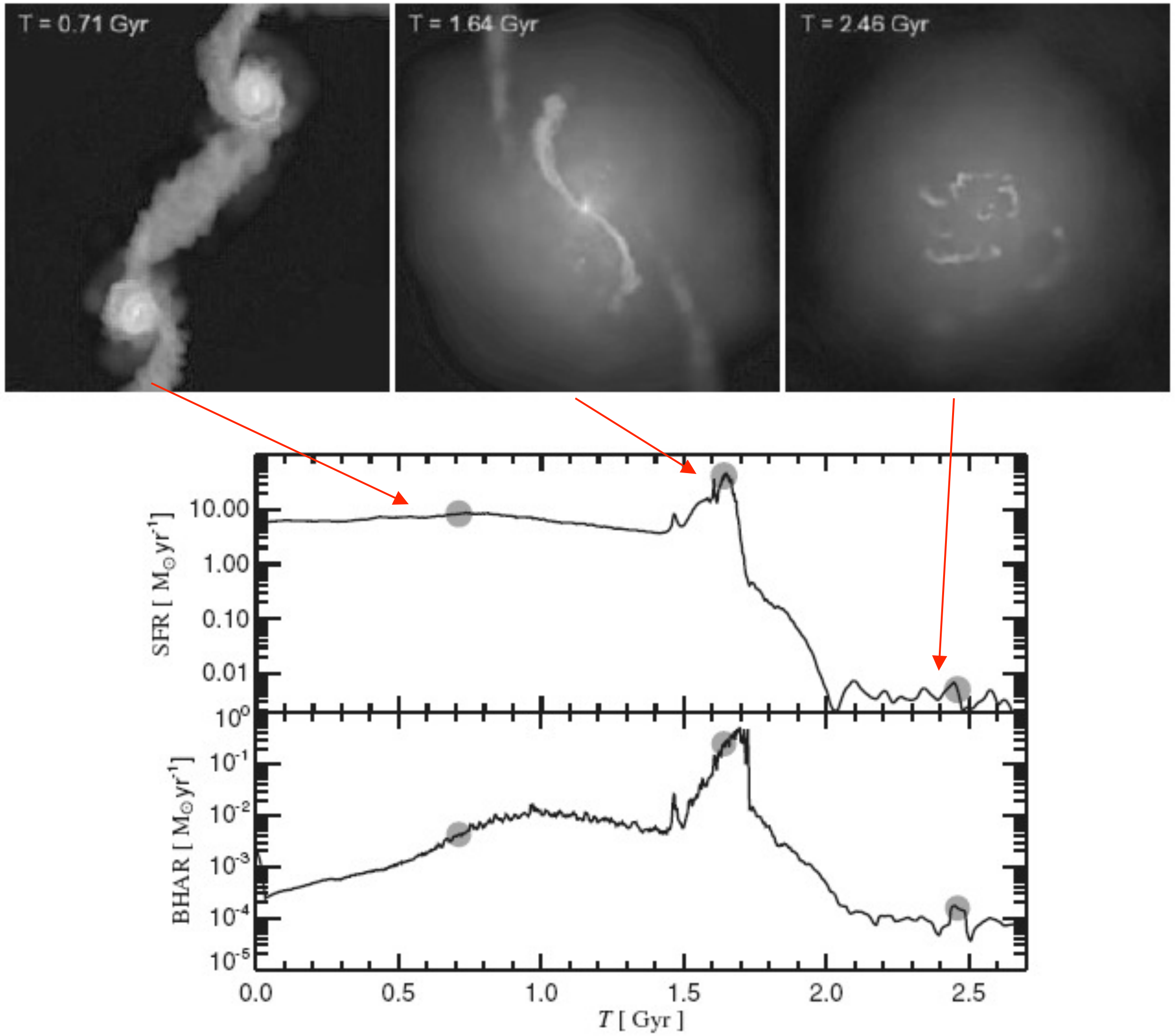
Deep Gemini imaging of the 2Jy sample



85% of the 2Jy sample show evidence for tidal features at relatively high surface brightness levels.

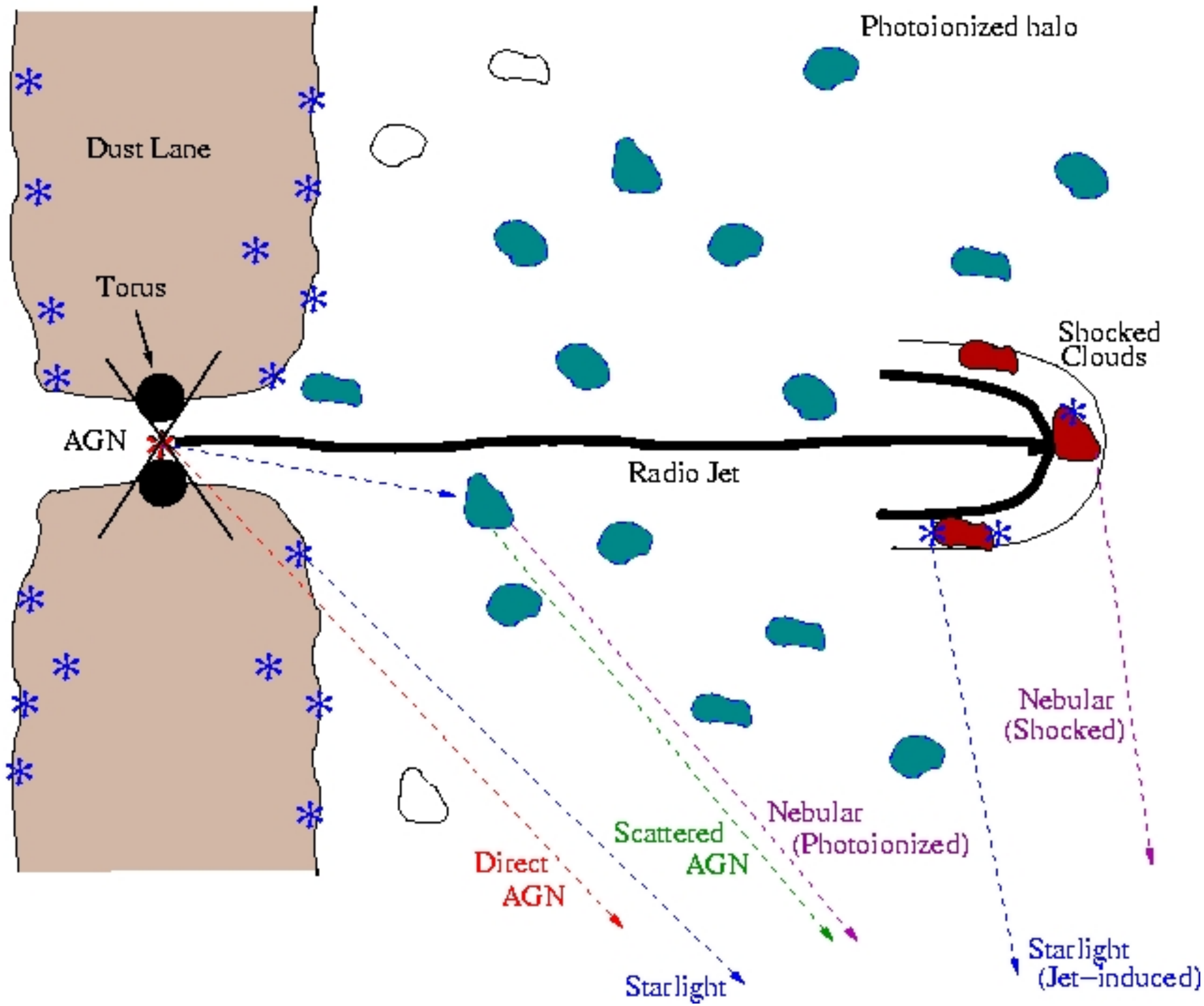
Ramos Almeida et al. (2011,2012)

AGN activity in major gas-rich mergers

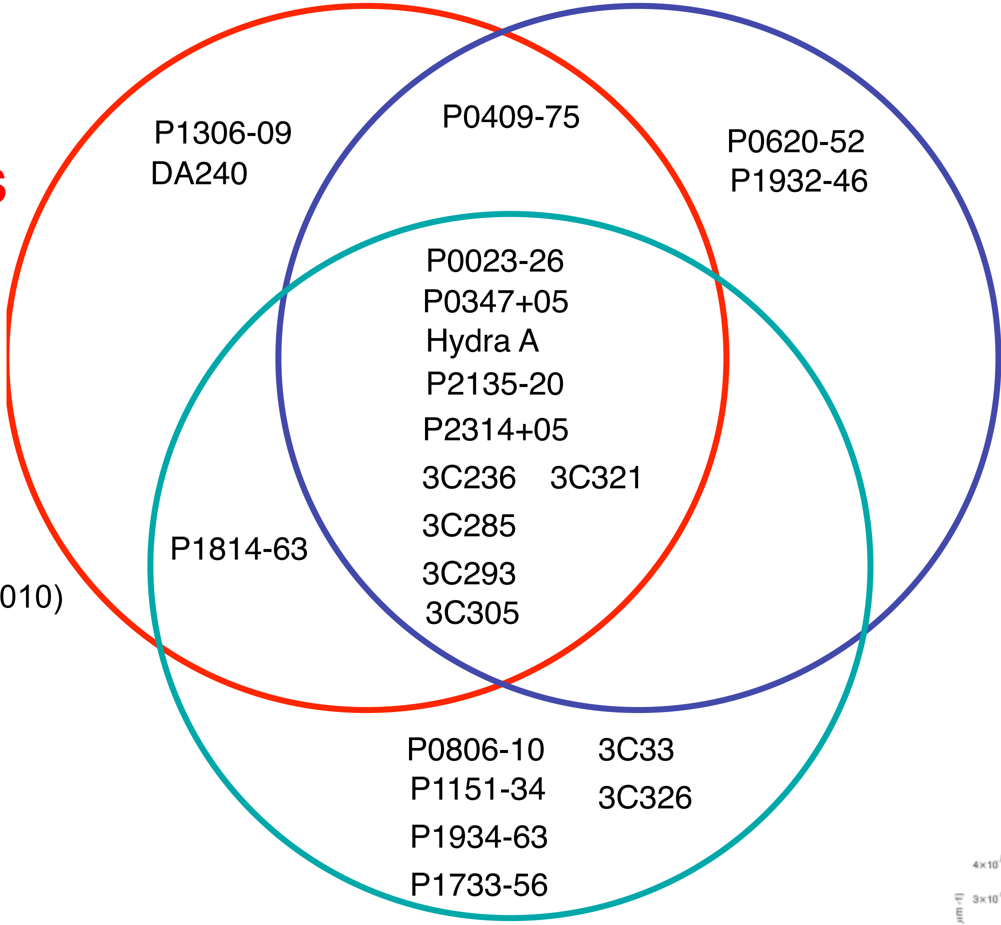


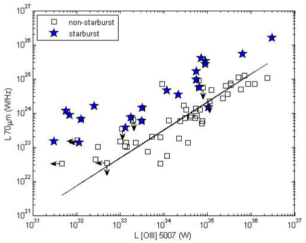
Springel et al. (2005)

Contributions to the UV excess in powerful radio galaxies

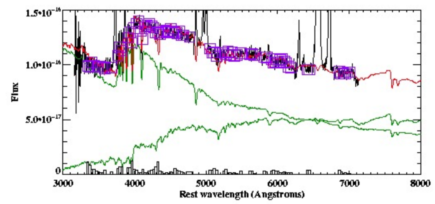


Star formation indicators in radio galaxies (2Jy+3CRR samples)

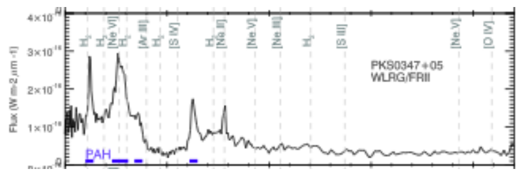




Dicken et al. (2009,2010)



Tadhunter et al. (2002,2005), Holt et al. (2007)



Dicken et al. (2012)

How massive is the gas/dust reservoir?

- Define quasar to have L_{bol}>10^{38} W (M_B < -23)
- Black hole must accrete >0.2 $M_{\odot}\ yr^{-1}$ to maintain activity
- Typical quasar lifetimes: ~10^6 - 10^8 yr

➔Mass accreted by SMBH over lifetime: ~2×10^5 - 2×10^7 $M_{\odot}$

- But, on the basis of the black hole mass/host galaxy correlations, for every 1 $M_{\odot}$ accreted by the black hole, ~500 $M_{\odot}$ stars must be formed in the bulge of the host galaxy

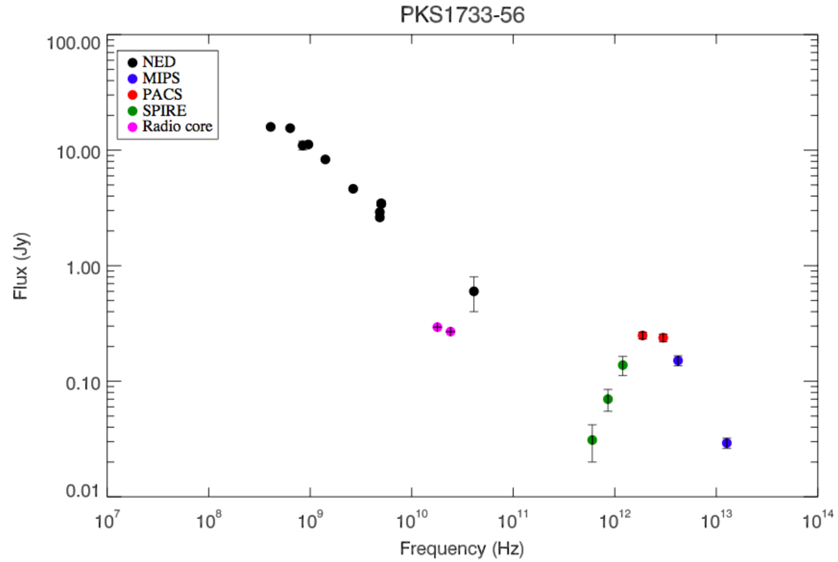
➔The *total* gas reservoir for a particular quasar triggering event is ~10^8 - 10^{10} M_{sun}

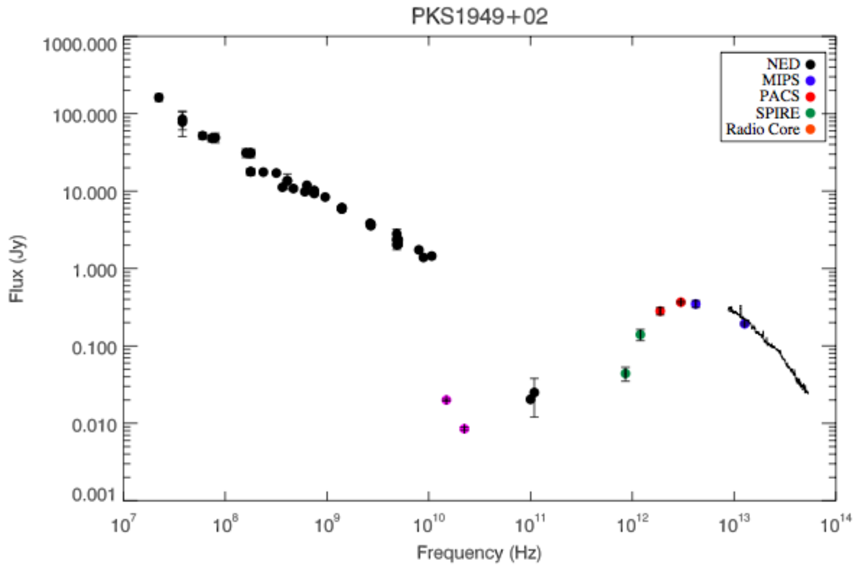
➔For typical quasar lifetime of ~10^7yr predict dust mass ~10^7 $M_{\odot}$ for M_{gas}/M_d=100

Determining dust masses using Herschel data for the 2Jy sample

- Initially assume a single temperature modified BB fit
- Preliminary fits to SEDs and colour-colour plots (objects with SPIRE data) ➔ β~1.2
- Determine dust temperatures (T_d) for non-SPIRE objects from 160/100 colour and β=1.2
- Dust masses follow from:

$$M_d = \frac{S_\nu D^2}{\kappa_\nu^m B(\nu, T_d)}$$

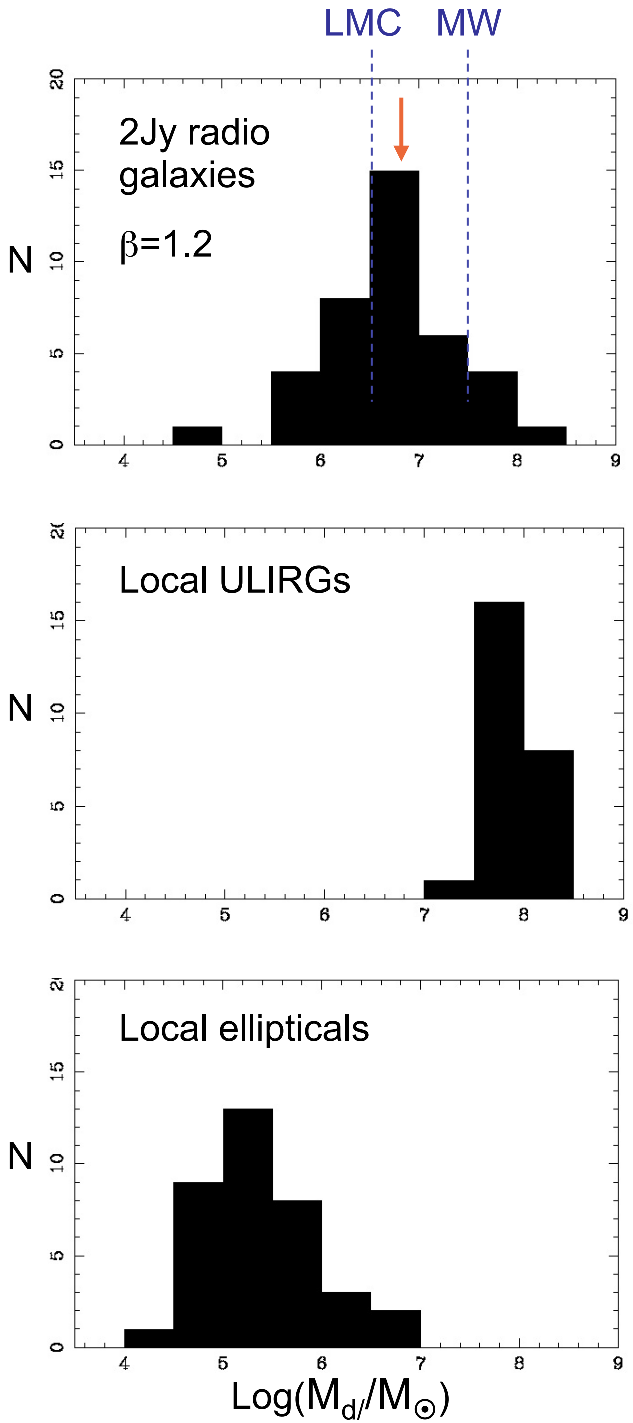




Dust mass results

Median dust masses	$\log_{10}(M_d/M_\odot)$
Radio Galaxies:	6.8
Local ULIRGs:	7.8
Local Ellipticals:	5.2
Prediction:	6.8

A minor merger with a gas-rich companion galaxy (~2xLMC) would provide a sufficient reservoir of cool gas to sustain quasar-like activity in a radio galaxy for ~10^7 yr; such reservoirs detected in most SLRG.



Clements et al. (2010)

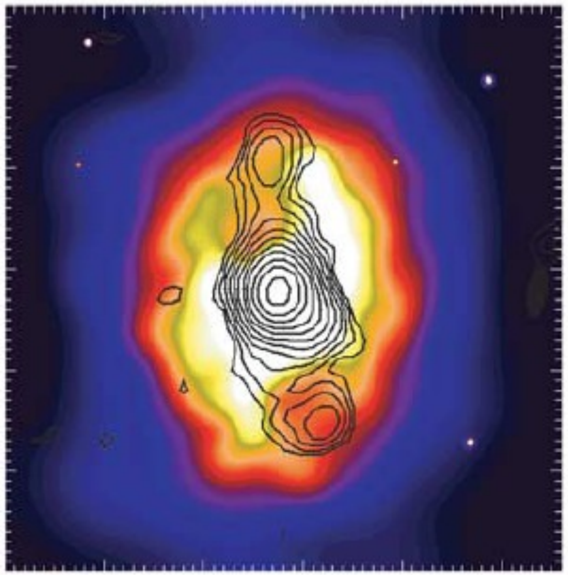
Martini et al. (2013)
Smith et al. (2012)

Triggering of powerful radio-loud AGN in the local Universe: summary

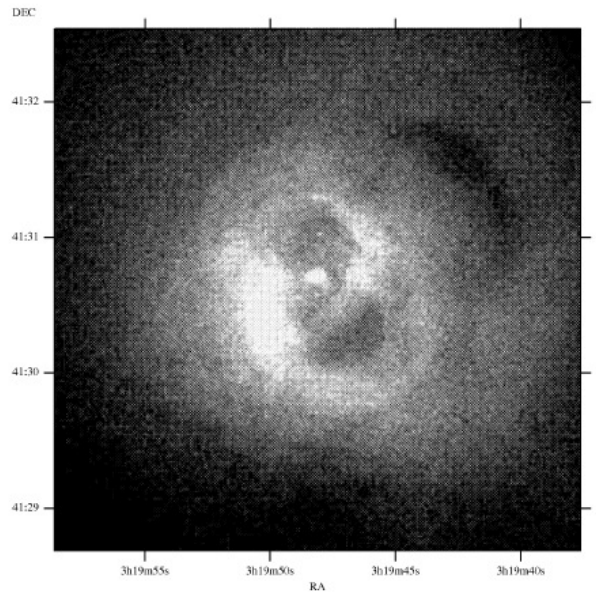
- Powerful radio-loud AGN are associated with massive elliptical galaxies ($2 \times 10^{11} < M_{star} < 2 \times 10^{12}\ M_{\odot}$)
- Local radio galaxies are diverse in terms of their detailed morphologies, star formation properties, and cool ISM contents
- A small but significant minority (<20%) are triggered in major, gas-rich mergers in which both the super-massive black holes and stellar masses of the host galaxies are growing rapidly
- But the majority of local radio galaxies represent the late time re-triggering of AGN activity via galaxy interactions and/or minor mergers (~2xLMC gas mass)

Jet-induced outflows and (positive?) feedback

Radio-excavated cavities in the X-ray haloes of low luminosity radio sources



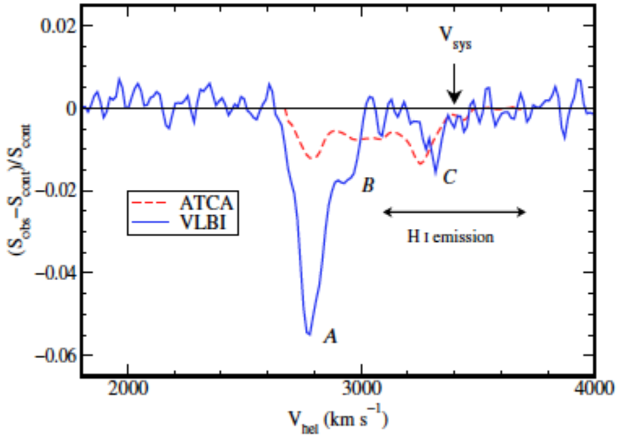
MS0735.6+7421
McNamara et al. (2005)



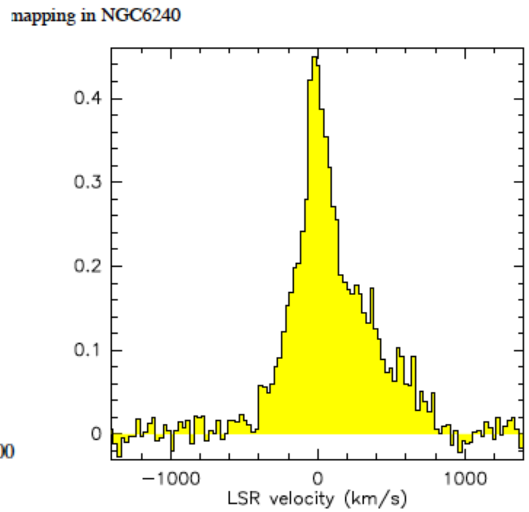
Perseus A
Fabian et al. (2003)

Energies associated with the X-ray cavities and shocks: ~10^{59} - 10^{62} erg

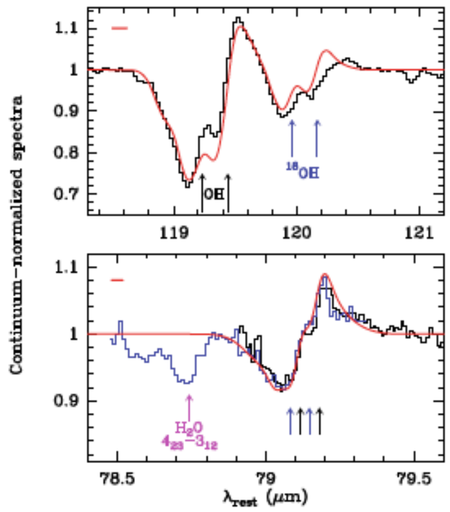
Neutral and molecular outflows in AGN



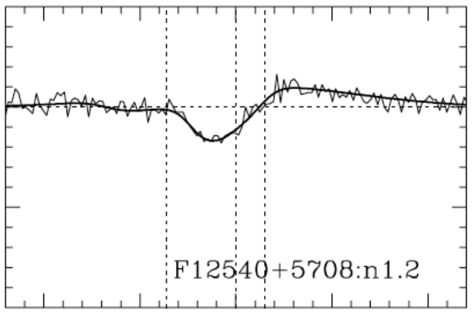
Neutral: HI 21cm
Morganti et al. (1998, 2005)



Molecular: CO
e.g. Feruglio et al. (2010 2013), Cicone et al. (2013)



Molecular: OH
Fisher et al. (2010), Veilleux et al. (2013)



Neutral: NaID
Rupke et al. (2005)

Broad wings detected up to 1,000s km/s in neutral and molecular gas in some AGN; the associated outflows are often more massive and energetic than the ionized gas outflows

The jet-driven, multi-phase outflow in the radio-loud Seyfert galaxy IC5063

HI 21cm outflow in IC5063

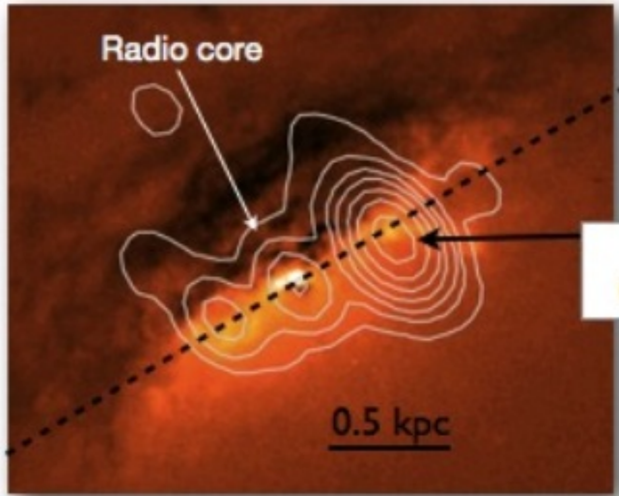
(z=0.011, P_{5GHz} = 3x10^{23} W Hz^{-1})

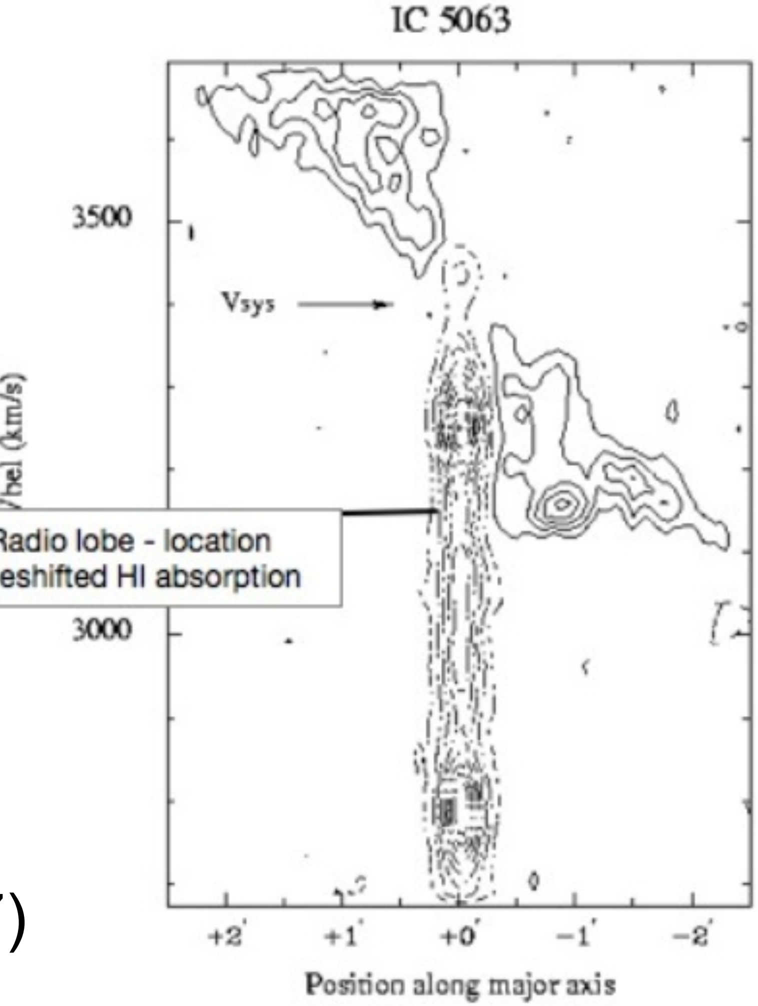
HI Outflow:

$$\dot{M} \sim 35\ M_{sun} yr^{-1}$$

$$\dot{E} \sim 7 \times 10^{42}\ erg\, s^{-1}$$

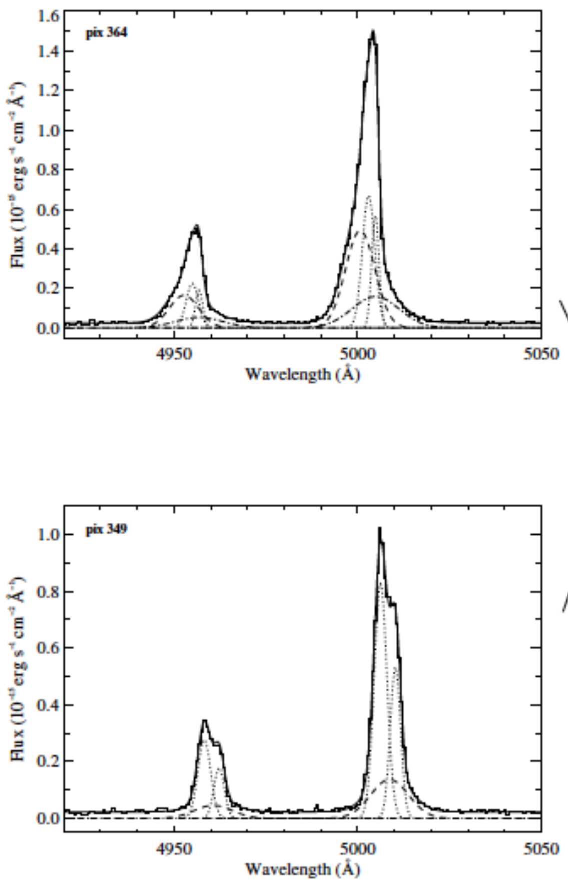
$$\dot{E} / L_{bol} \sim 0.08$$

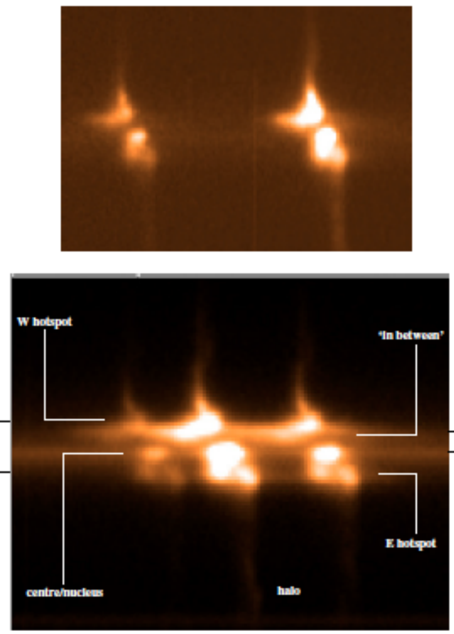


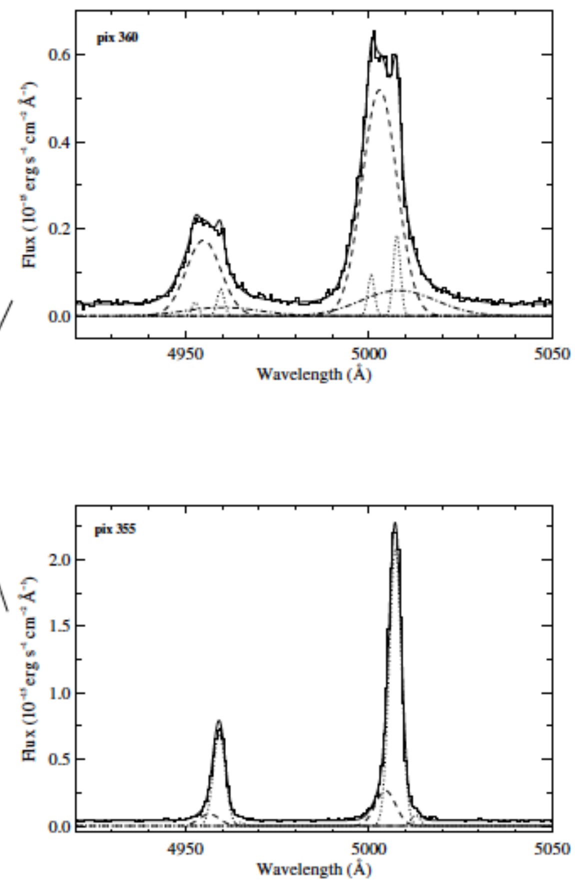


Morganti et al. (1998, 2007)
Oosterloo (2000)

Ionized gas ([OIII]) outflow in IC5063







Warm gas outflow:

$$\dot{M} \sim 0.08\ M_{sun} yr^{-1}$$

$$\dot{E} \sim 2 \times 10^{40}\ erg\, s^{-1}$$

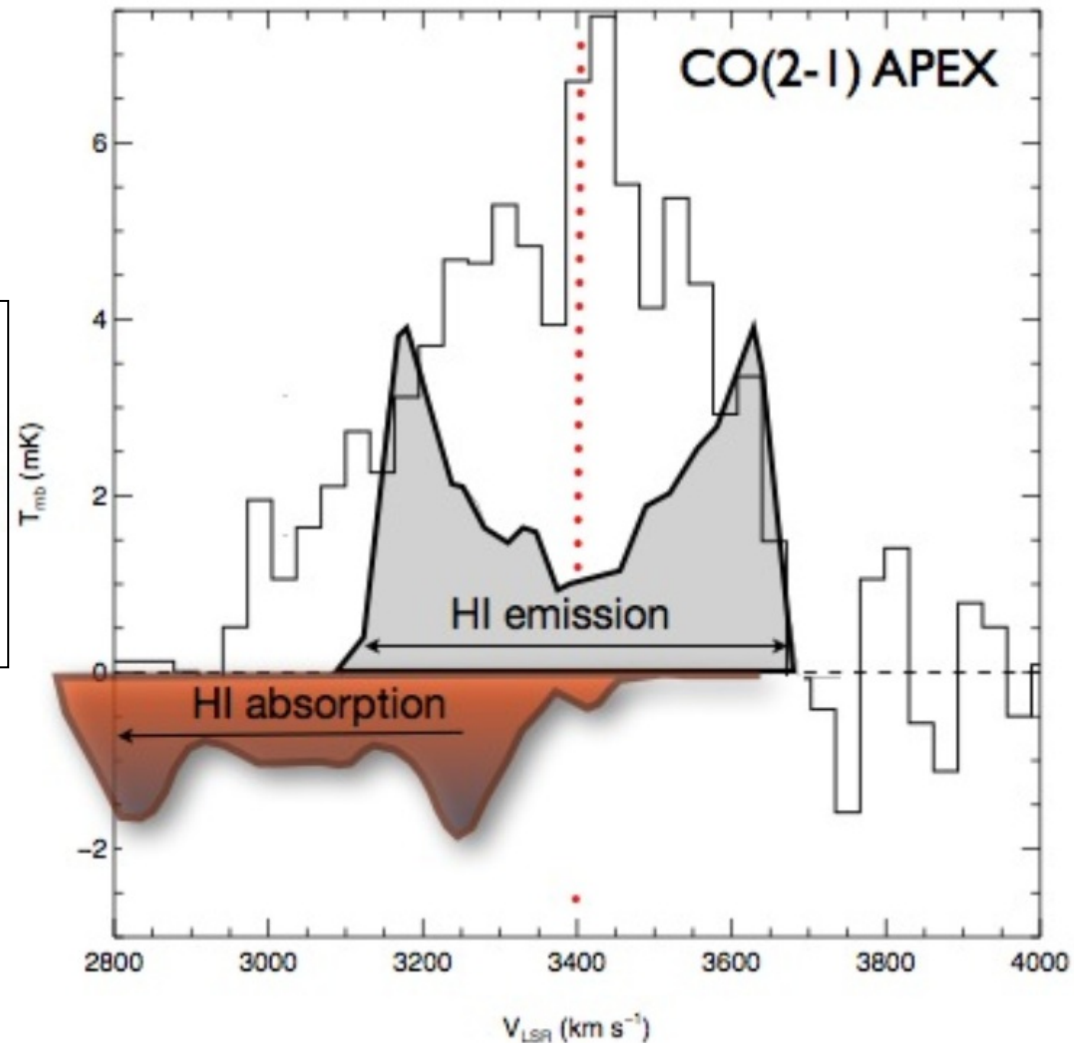
$$\dot{E} / L_{bol} \sim 3 \times 10^{-4}$$

Morganti et al. (2007)

A molecular outflow in IC5063?

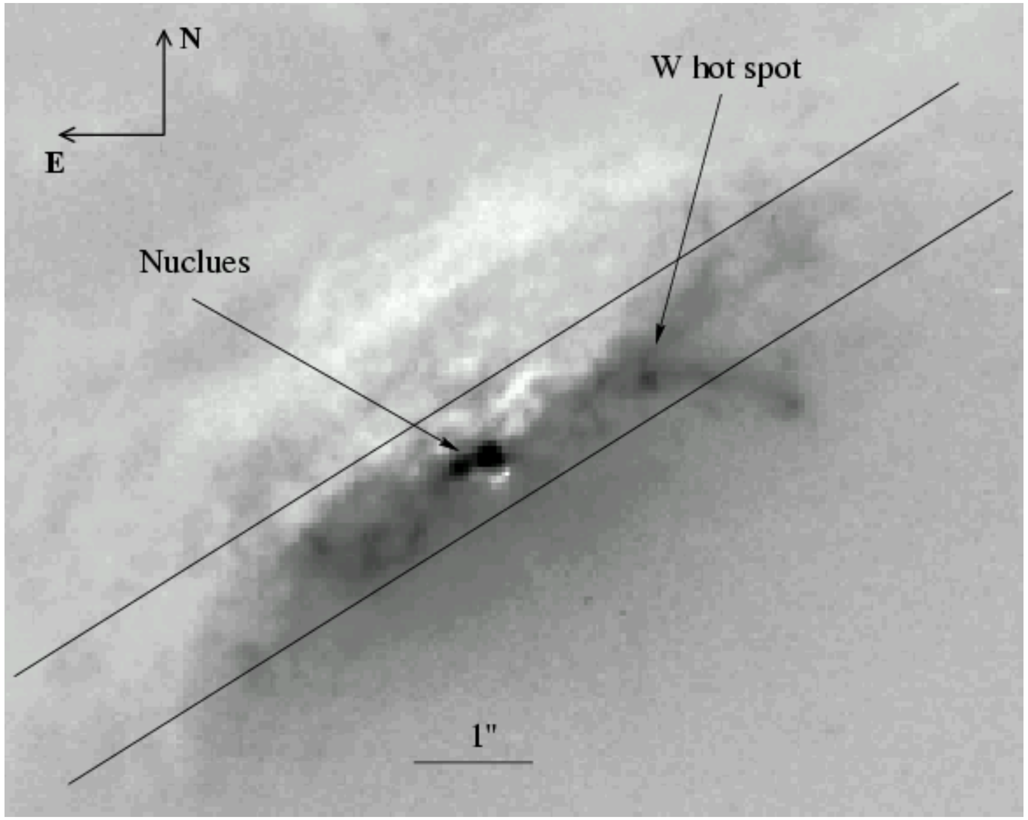
CO outflow:

$$2 \times 10^7 < M_{H_2} < 1.5 \times 10^8 M_{sun}$$
$$22 < \dot{M} < 130\ M_{sun} yr^{-1}$$
$$\dot{E} \sim 10^{43}\ erg\, s^{-1}$$
$$\dot{E}/L_{bol} \sim 0.1 - 0.2$$



Morganti et al. (2013)

ESO VLT/ISAAC observations of IC5063

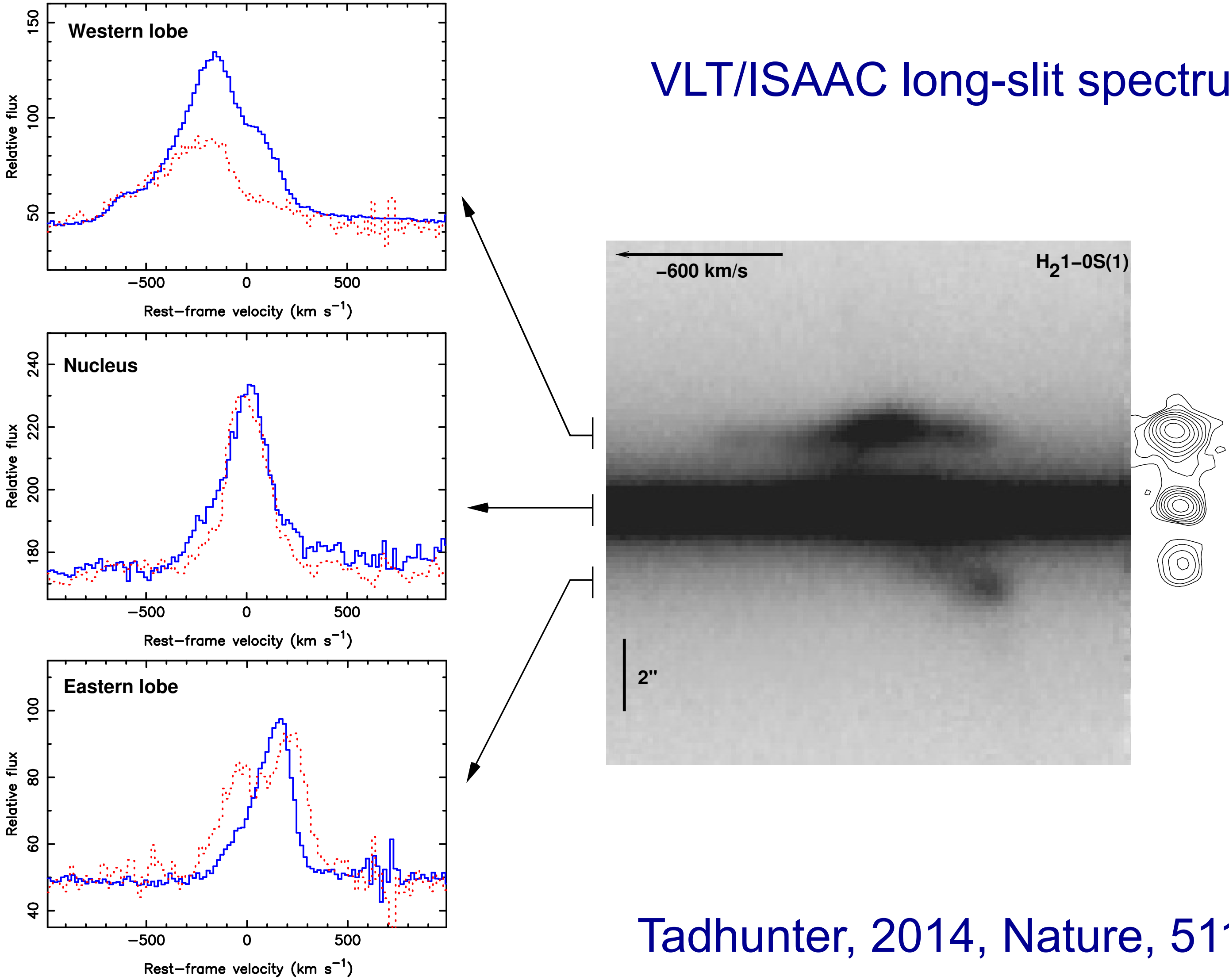


Slit aligned with radio axis

Near-IR (K-band) long-slit spectroscopy of IC5063 covering the H_2 1-0S(1) molecular hydrogen line

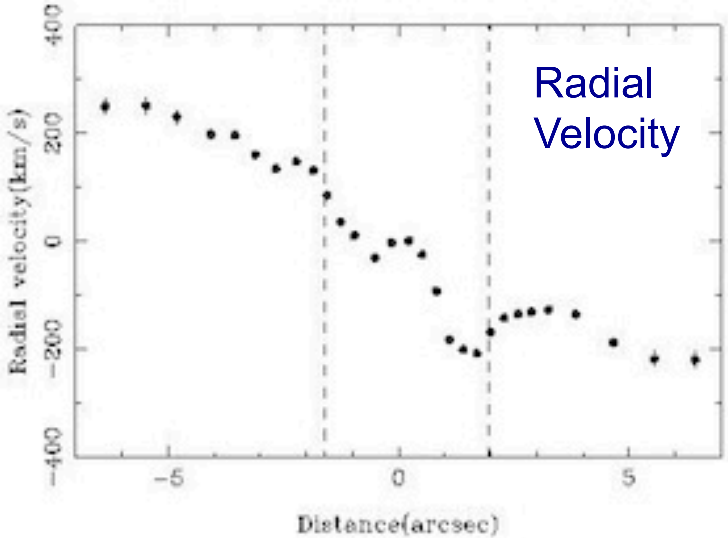
Warm molecular outflows in IC5063 I line profiles

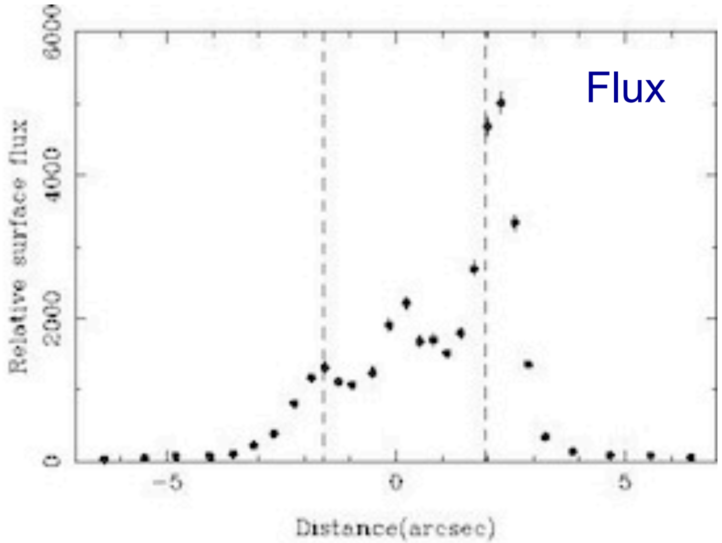
VLT/ISAAC long-slit spectrum

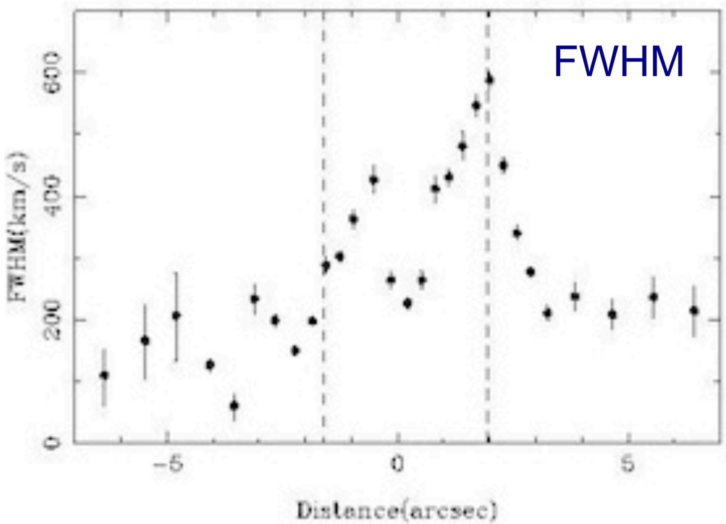


Tadhunter, 2014, Nature, 511, 440

Warm molecular outflows in IC5063 II spatial variation in H_2 properties







Warm H_2 temperature:~ 2,000 K
Mass of H_2: ~820 M_{sun}

Tadhunter et al. (2014)

Acceleration of the molecular gas in IC5063?

- Shocks driven by expanding radio lobes:

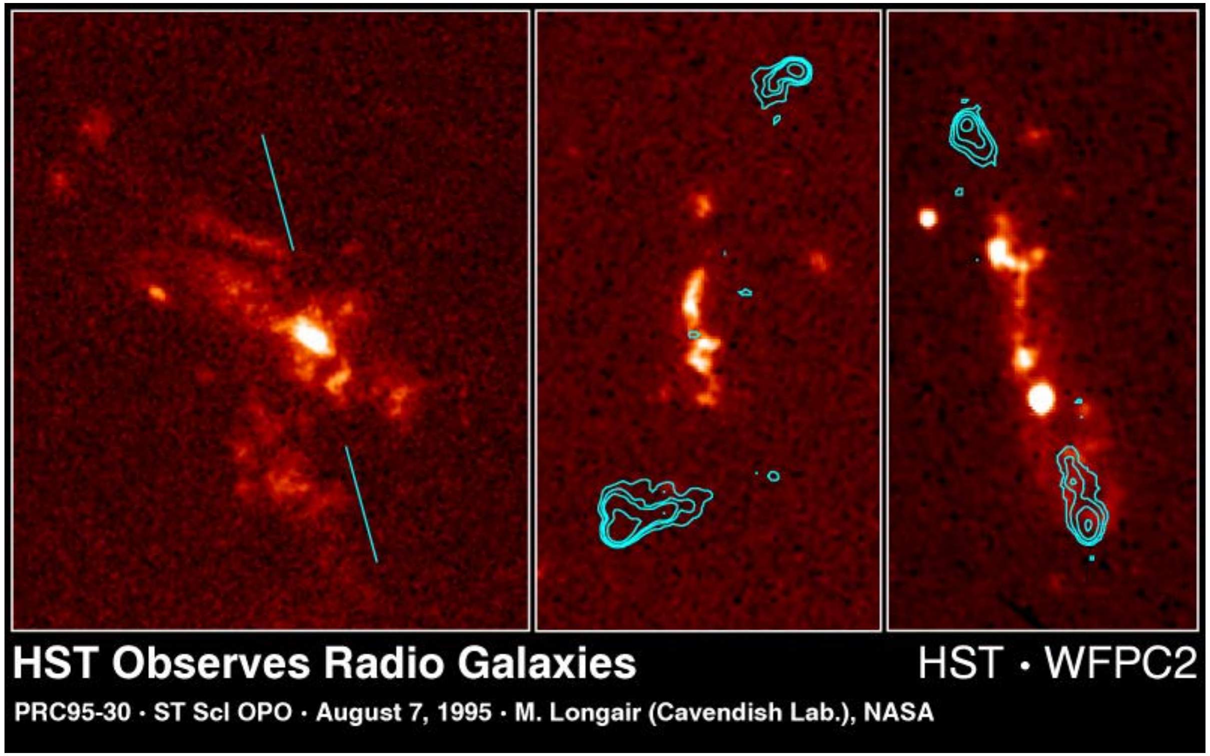
  - dense molecular clouds entering the fast shock are accelerated and heated to high temperatures ($T>10^6$ K);
  - ionized gas emission lines ($T\sim10^4$ K), then warm molecular emission lines (T~2,000 K), then cold molecular emission lines (T<100 K) emitted as gas cools down.

  (But how are the molecules formed?)

- Slow entrainment and ablation of clouds by fast low density wind:

  - clouds simultaneously heated and accelerated as they are entrained in the wind;
  - may lead to the destruction of the clouds…

The alignment effect in high-z radio galaxies: evidence for jet-induced star formation?



The UV continuum structures of high-z radio galaxies (z~1) are closely aligned with the radio jet axes in a high proportion of objects

e.g. McCarthy et al. (1987), Rees (1989), Gaibler et al. (2012)

Conclusions

- Although massive giant elliptical galaxies, powerful radio galaxies are diverse in their detailed morphologies, star formation properties and gas contents.
- Most, but not all, powerful radio galaxies in the local Universe represent late-time retriggering of activity via minor gas-rich mergers
- Jet-driven outflows detected in all gas phases; they are sufficiently powerful to affect the evolution of their host galaxies
- The feedback effect of AGN is not necessarily destructive

Investigating triggering mechanisms

Galaxy morphologies and environments

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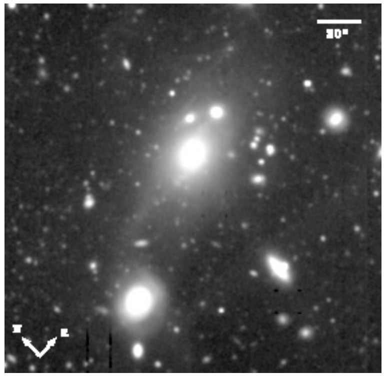
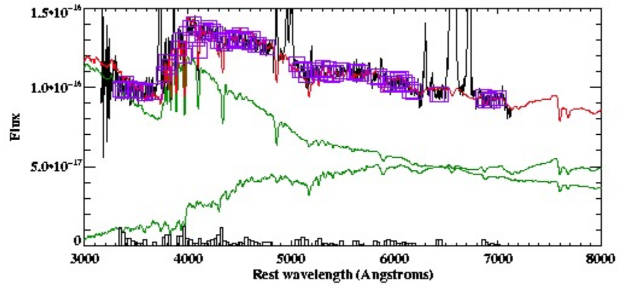
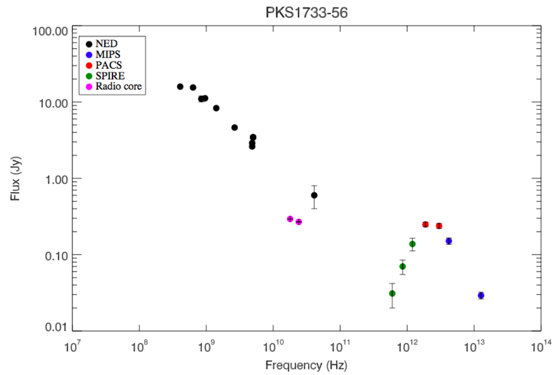
Cool ISM contents

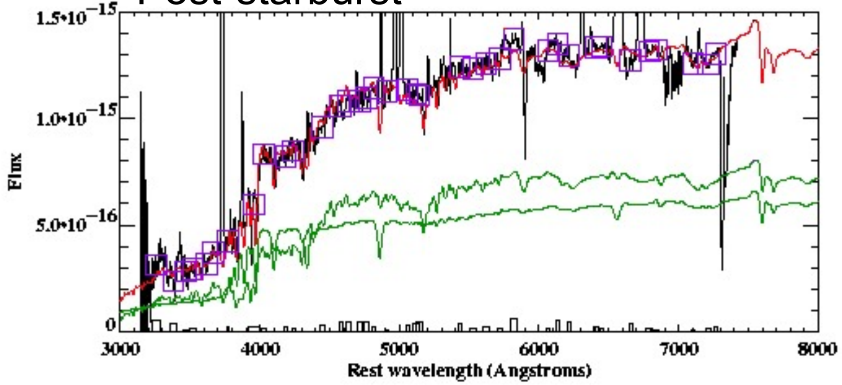




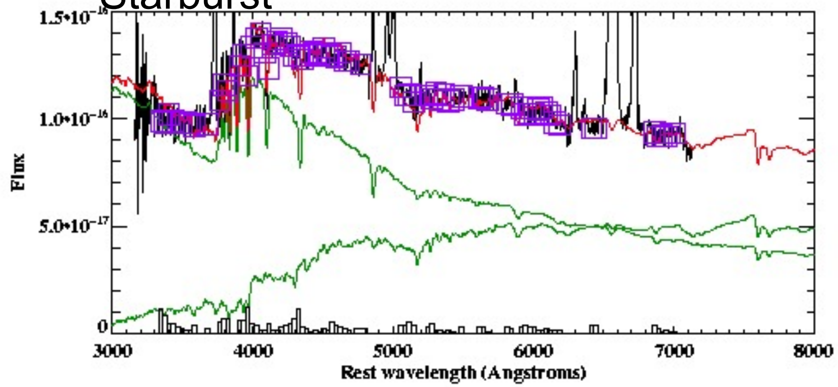


Optical evidence for star formation in radio galaxies

Post-starburst



Starburst

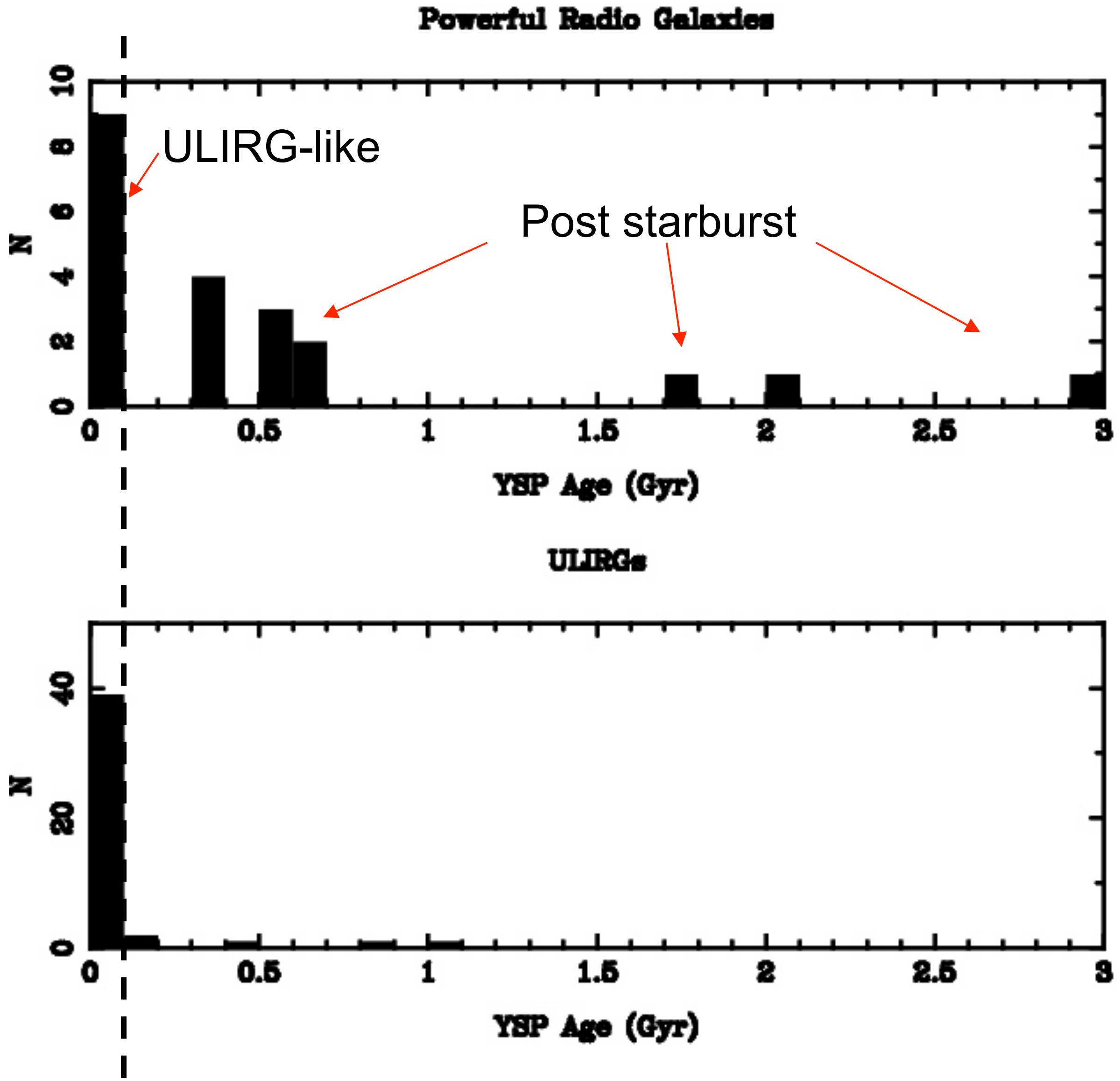


3C305 YSP Properties
Age: 0.4 - 0.6 Gyr
Mass:1.5+/-0.5x10^{10} M_{sun}
(16-40% of total stellar mass)
Post starburst

3C459 YSP Properties
Age: 0.05 Gyr
Mass:4x10^{9} M_{sun}
(>5% of total stellar mass)
Starburst (ULIRG)

The young stellar populations (YSP) in radio galaxies show a diversity of properties, but they are detected in only ~20-35% of objects…

The Ages of the YSP in ULIRG and PRG



Tadhunter et al. (2005)
Holt et al. (2006,2007)
Wills et al. (2008)
Tadhunter et al. (2011)

Rodriguez-Zaurin et al.
(2007,2008,2009,2010)

Typical maximum age of radio source

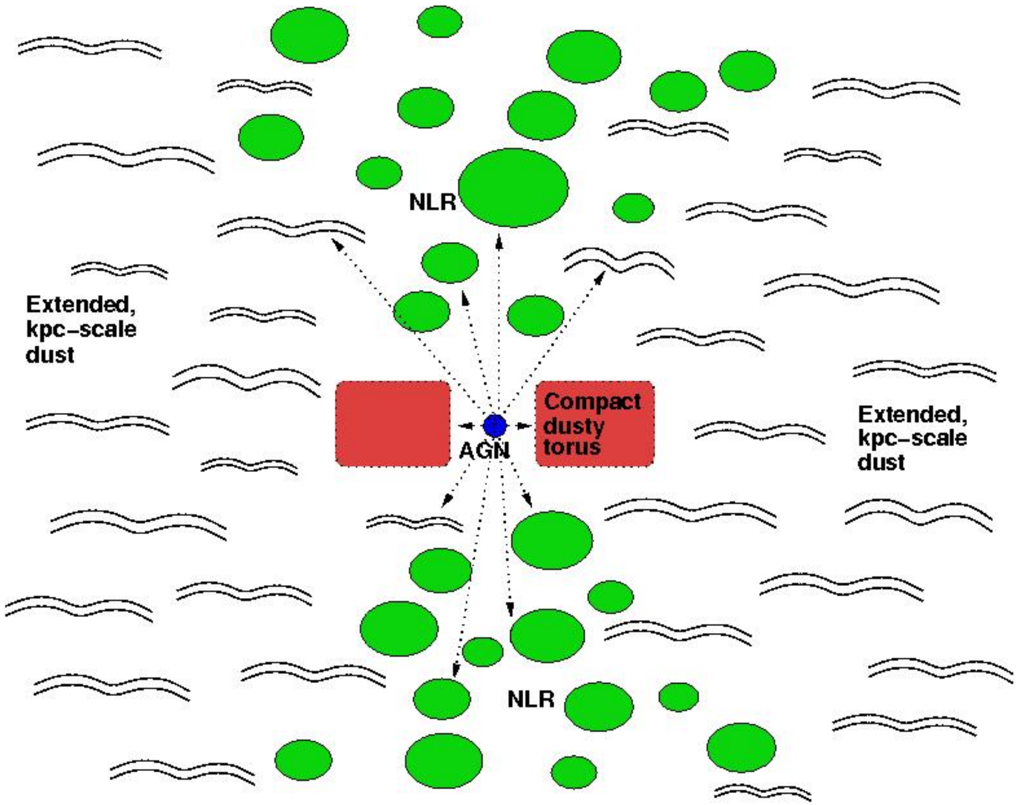
A simple model for the dust/emission line structures

- Assume that both the emission lines and MFIR emission produced by AGN illumination

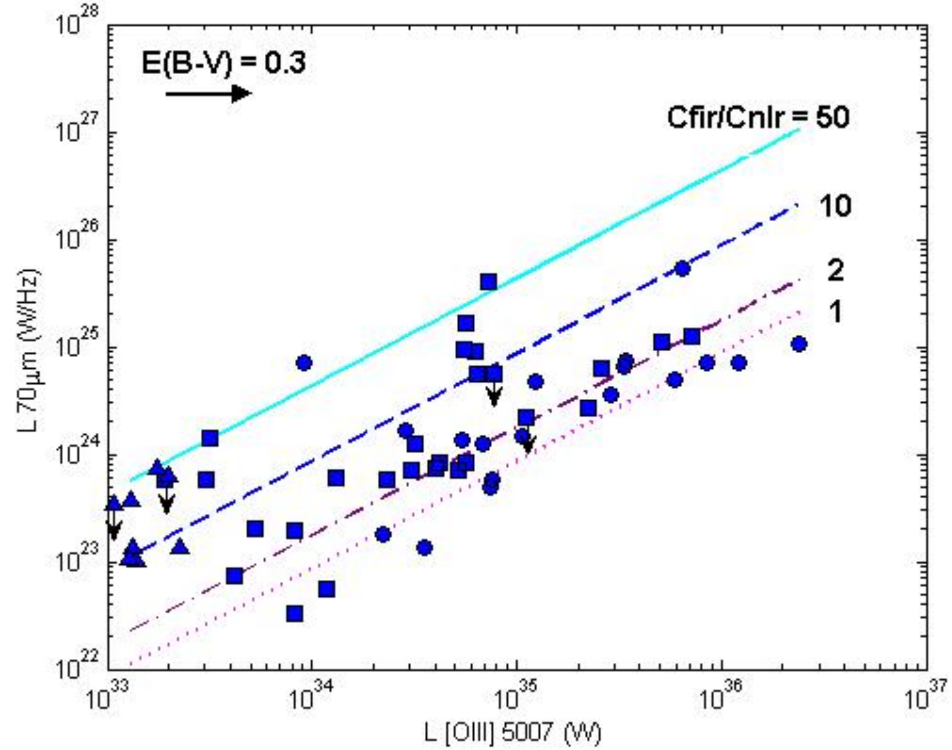
- Covering factors of mid-IR and far-IR emitting dust structures, and NLR: C_{mir}, C_{fir} and C_{nlr}

$$L_{24\mu m} = 1 \times 10^{-12} L_{[OIII]} \frac{C_{mir}}{C_{nlr}}$$

$$L_{70\mu m} = 9 \times 10^{-12} L_{[OIII]} \frac{C_{fir}}{C_{nlr}}$$



Energetic feasibility of AGN illumination



Dicken et al. (2009)

- Allowing for a modest amount of intrinsic extinction, it is plausible that much of the far-IR continuum is in most radio galaxies is produced by AGN illumination of the NLR clouds

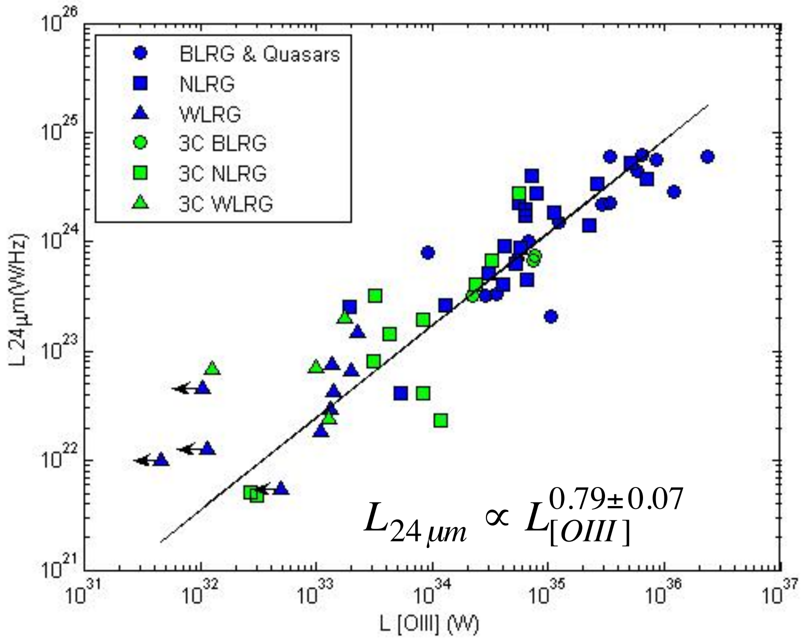
$\frac{C_{fir}}{C_{nlr}} \sim 12.5,\ 0.02 < C_{nlr} < 0.08$

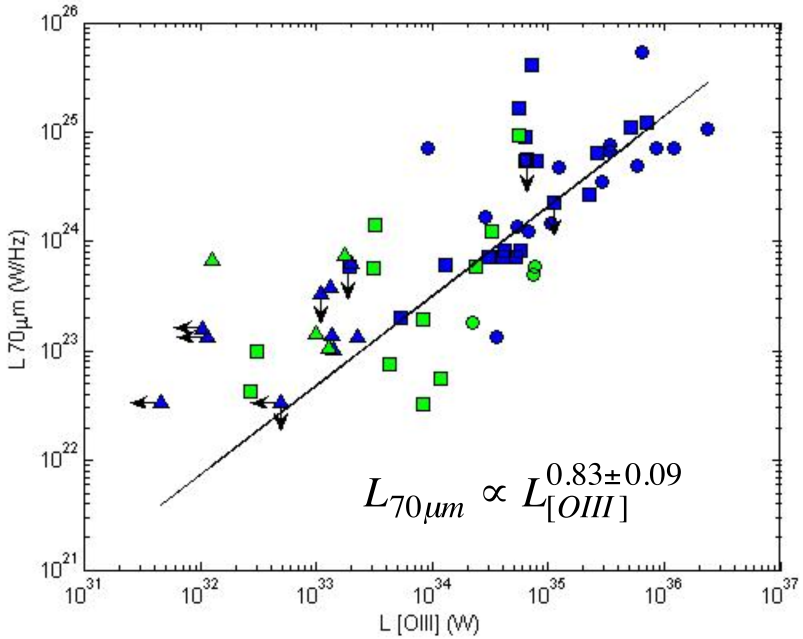
$\Rightarrow 0.25 < C_{fir} < 1.0$

Correlations between MFIR and optical properties

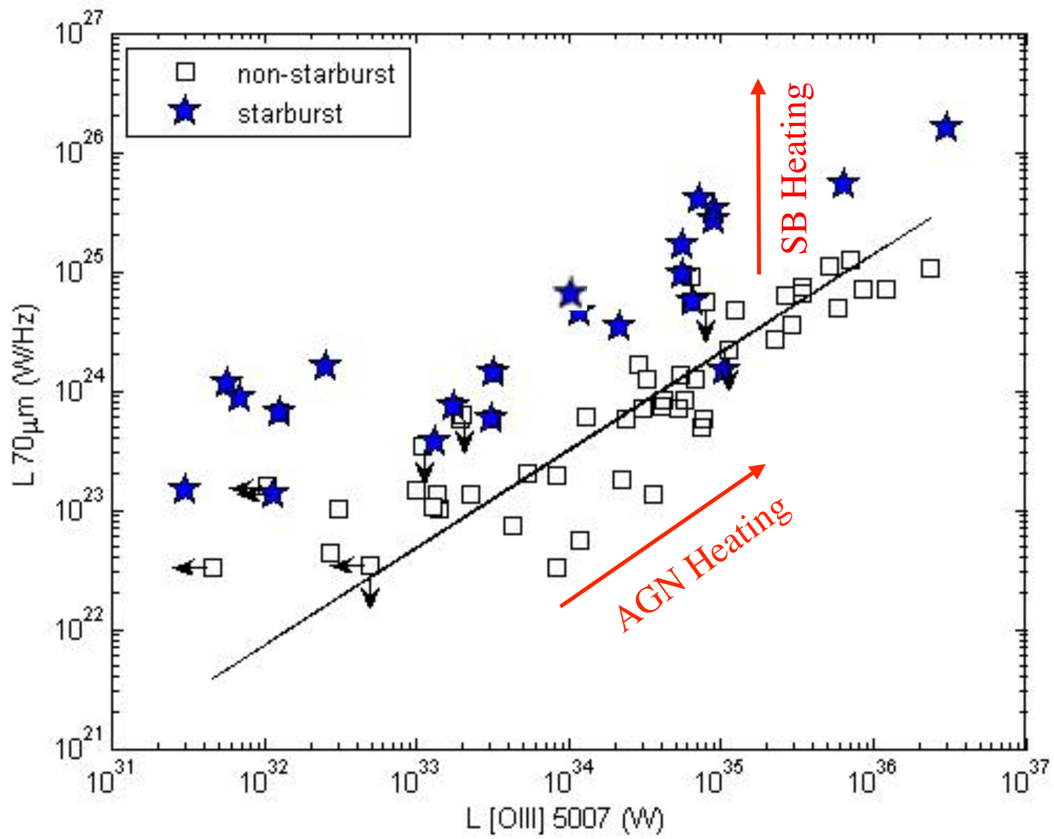
- The 24μm luminosity is strongly correlated with the [OIII]λ5007 emission line luminosity.
- The 70μm luminosity is also strongly correlated with the [OIII] luminosity, but with increased scatter.
- The slopes of the 24μm and 70μm correlations are similar.

Tadhunter et al. (2007),
Dicken et al. (2008, 2009, 2010)





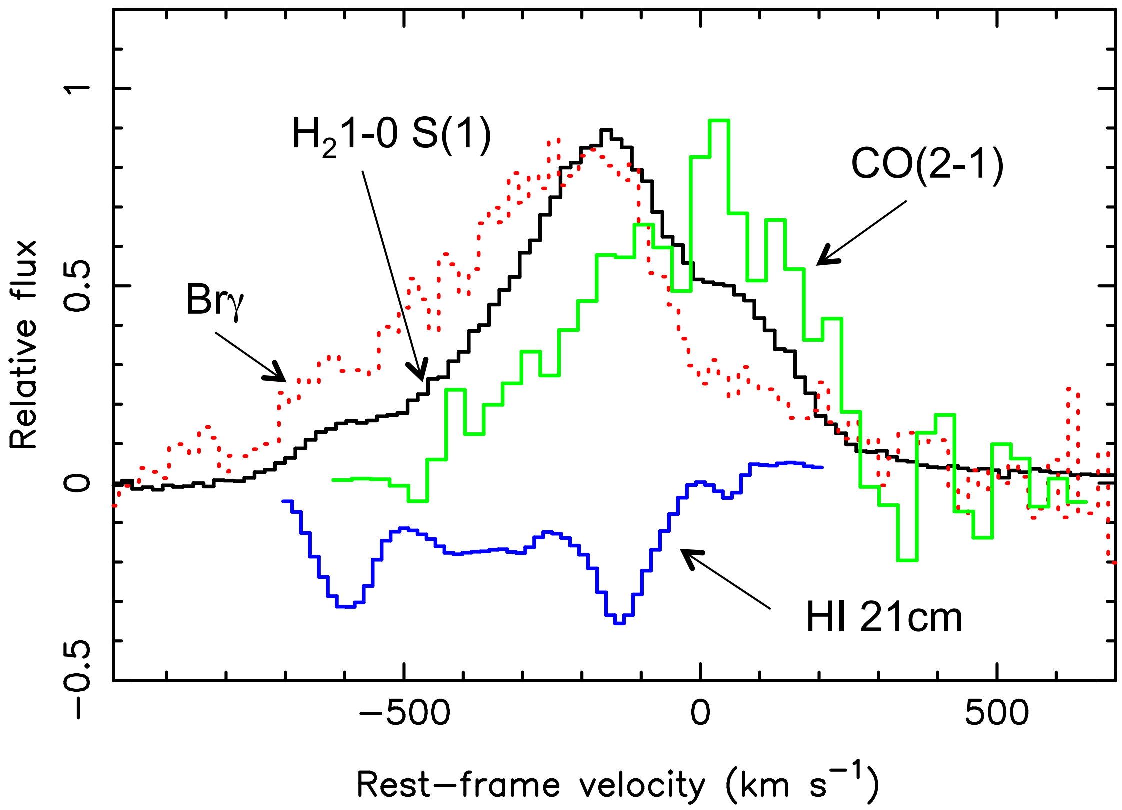
The starburst contribution to the far-IR



- The far-IR emitting dust is predominantly heated by AGN illumination
- Starburst heating only significant in a minority of objects (~17 -- 35%)

Tadhunter et al. (2007)
Dicken et al. (2009, 2010)

Warm molecular outflows in IC5063 III multi-phase profile comparison



Tadhunter et al. (2014)

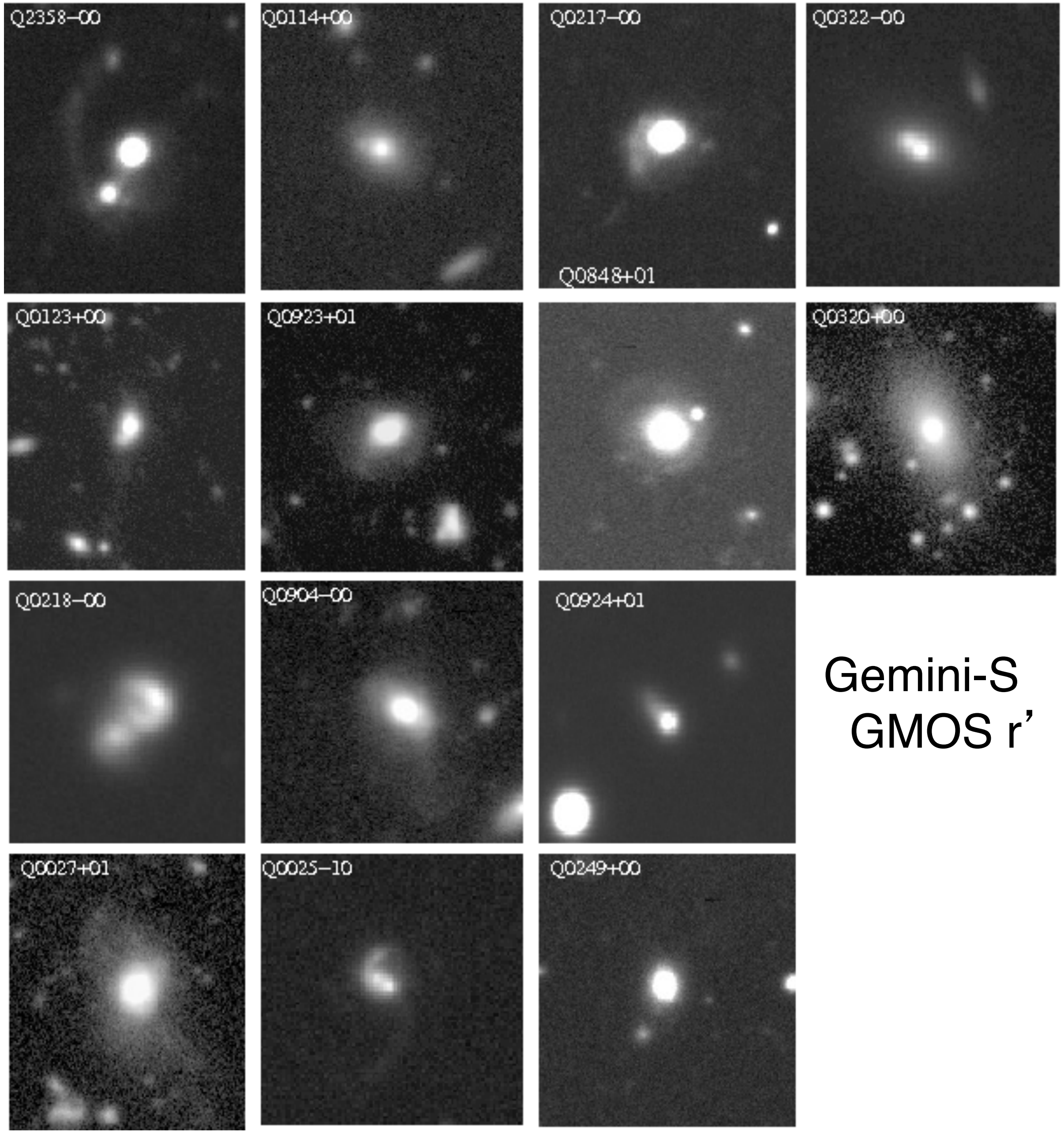
Gemini imaging of optically-selected quasar 2 objects

- 20 quasar 2s
- 0.3 < z < 0.41
- $L_{[OIII]} > 10^{35} W$

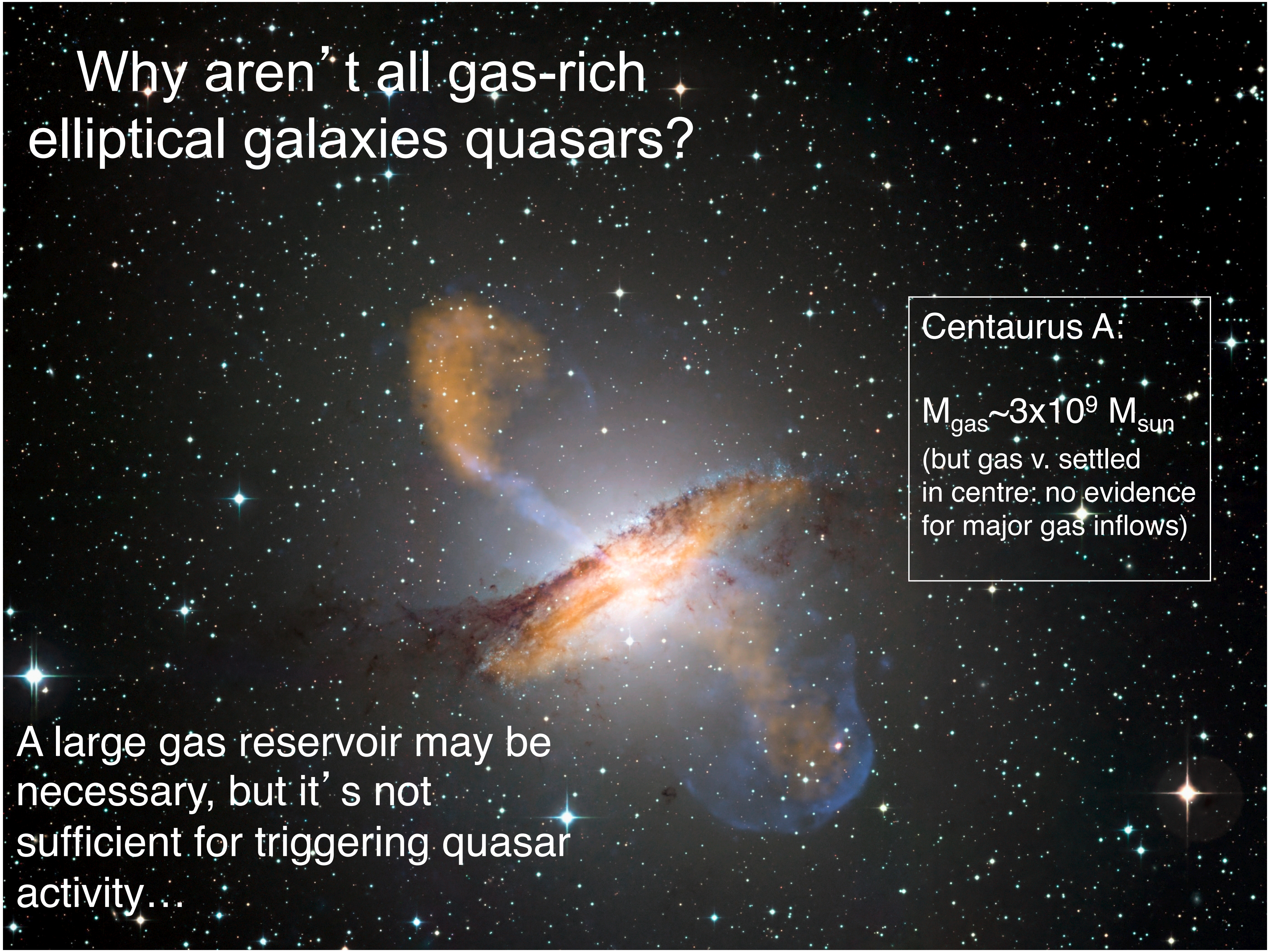
(Zakamska et al. 2003)

75% of quasar 2s show evidence for tidal interactions

Bessiere et al. (2012)



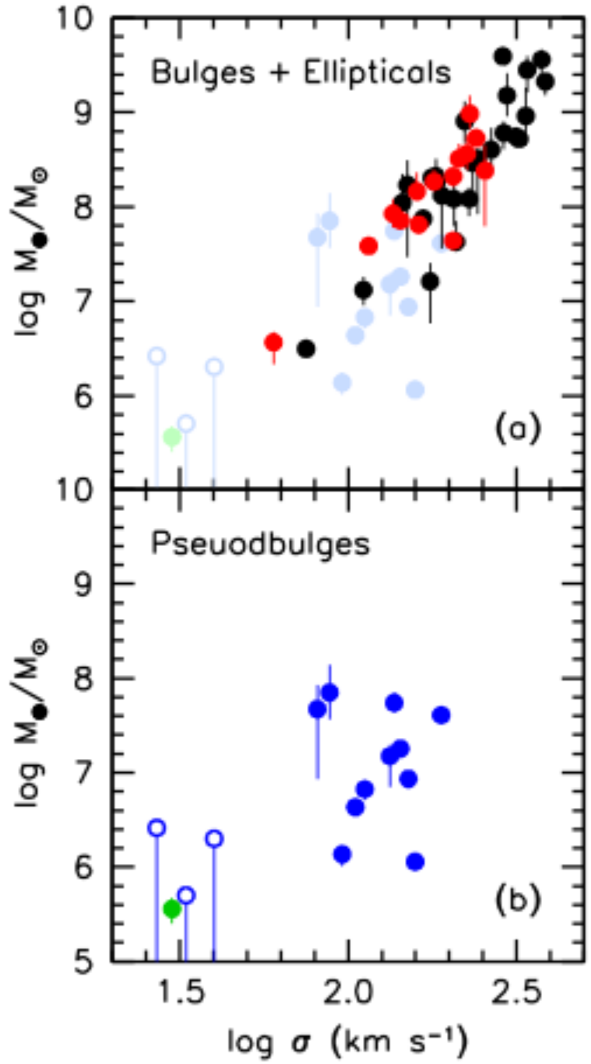
Gemini-S GMOS r’


Why aren't all gas-rich elliptical galaxies quasars?
Centaurus A:
M_{gas}~$3x10^9$ M_{sun}
(but gas v. settled in centre: no evidence for major gas inflows)
A large gas reservoir may be necessary, but it's not sufficient for triggering quasar activity…

A dichotomy in AGN triggering mechanisms?

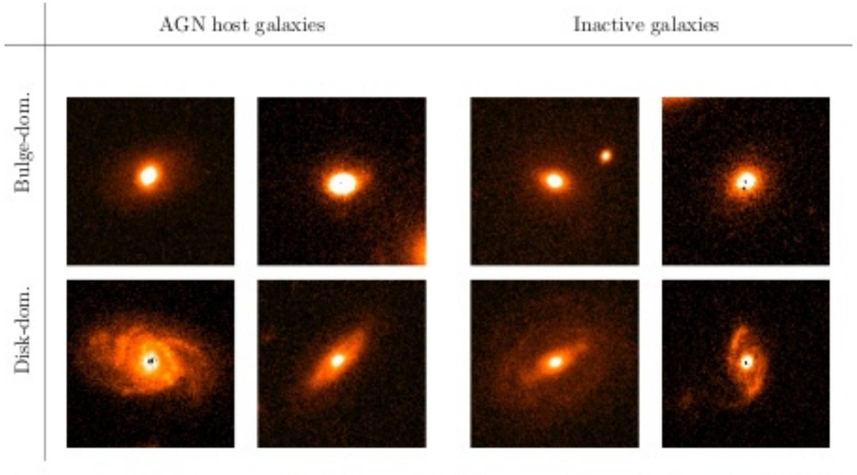
- Spiral galaxies with pseudobulges don't appear to show strong evidence for M_{bh} vs σ relationship
- Suggested that pseudobulges and their black holes form by secular processes (Seyferts?), whereas classical bulges form by gas-rich mergers (quasars?)

Kormendy et al. (2011)



Triggering of moderate luminosity AGN

Seyfert: $L_{bol} < 5 \times 10^{37}\,W\,;\ \dot{M} \leq 0.1\,M_{sun}\ yr^{-1}$

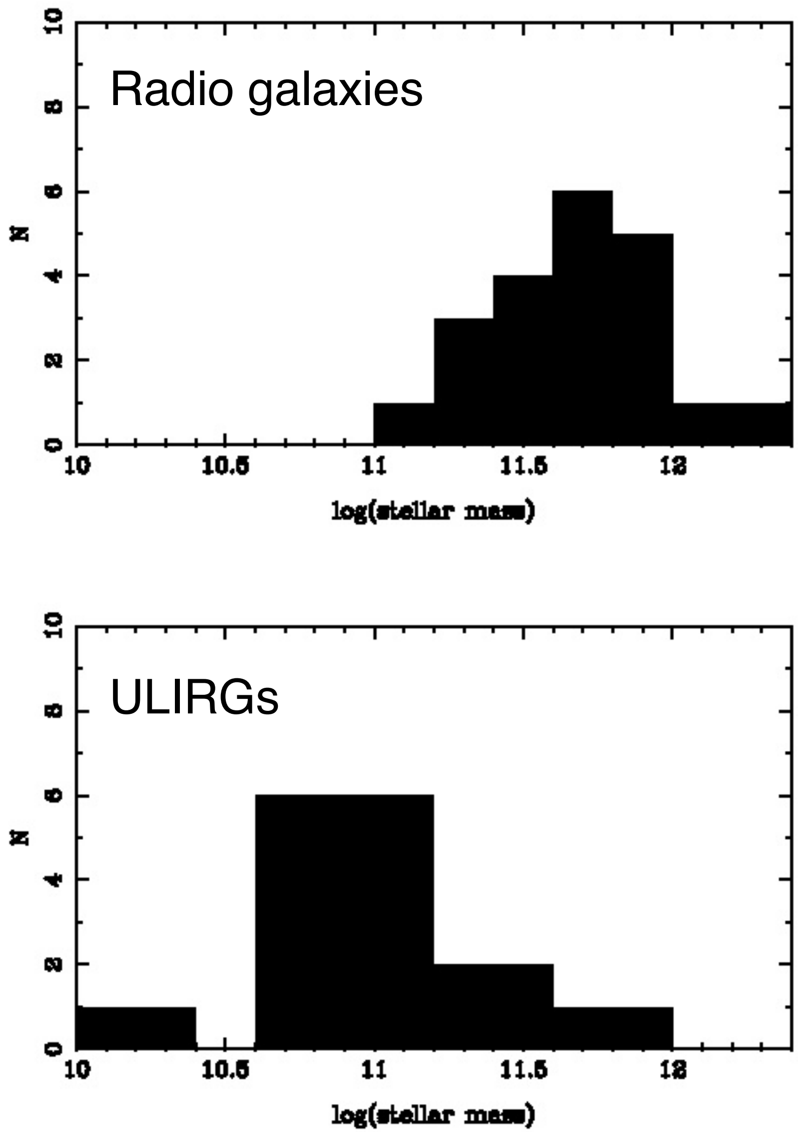


Cisternas et al. (2010) (see also Grogin et al. 2005)

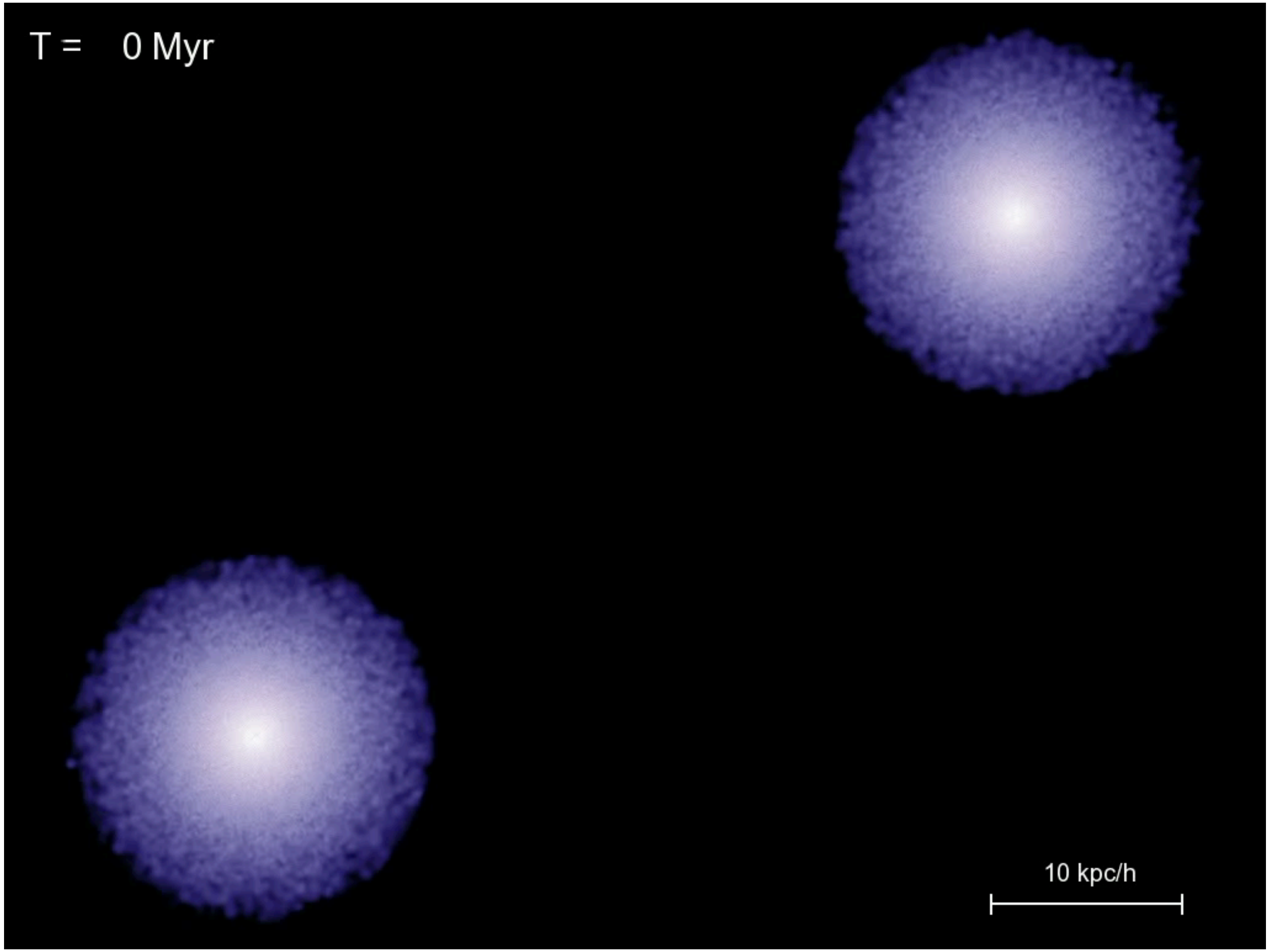
- Deep field studies find no evidence for a higher rate of mergers or interactions in the hosts of moderate luminosity AGN compared with well-matched control samples
- This suggests that secular processes (e.g. bars, disk instabilities, slow cold gas accretion, satellite galaxy accretion) may trigger such AGN

Stellar masses of starburst radio galaxies

Comparison of their stellar masses suggests that only the most massive ULIRGs are capable of becoming radio galaxies

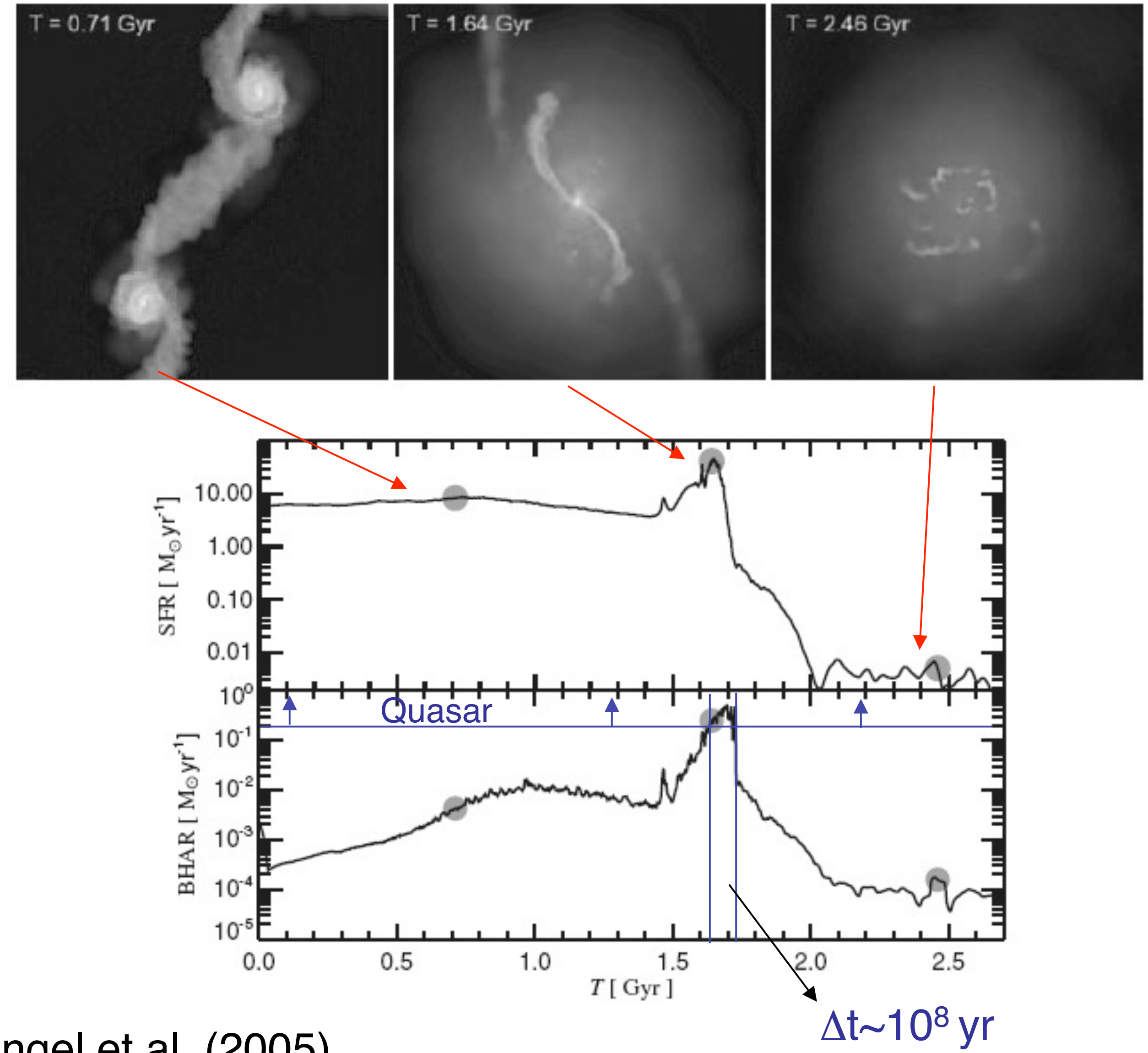


Triggering AGN in galaxy mergers



di Matteo et al. (2005)

AGN activity in major gas-rich mergers



Springel et al. (2005)

Outstanding issues

- Are there alternative triggering mechanisms for luminous quasar-like AGN (other than mergers)?
- How does the gas get from a ~100pc scale to a sub-pc scale?
- What's the relationship between luminous radio-loud and radio-quiet AGN?
- Does the triggering mechanism change with redshift?
- What's the relative energetic importance of the different gas phases in the outflows?
- How do the molecular outflows work in detail?

Future prospects: ALMA

- CO observations:
  - molecular gas masses: does quasar triggering require a large reservoir of cool gas?
  - molecular gas kinematics: to what extent does quasar triggering depend on the kinematical state of the gas?