Compact radio sources: triggering and feedback

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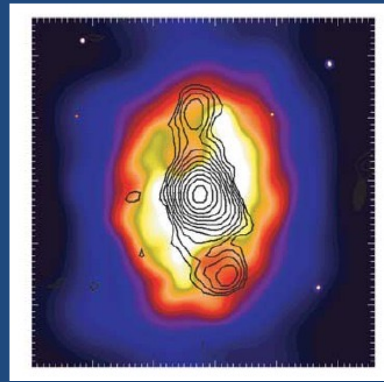
Different types of AGN feedback

- **Radio mode:**

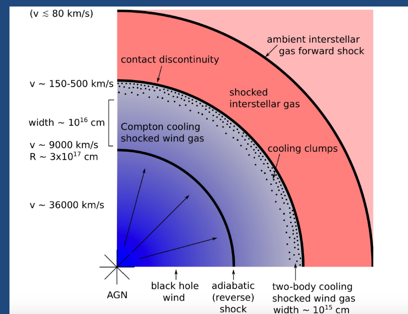
  - heating the hot ISM of host galaxies, groups and clusters and preventing it from cooling (0.01 – 1 Mpc).



McNamara et al. (2005)

- **Quasar mode:**

  - radiation pressure from AGN drives a hot wind close to the nucleus. The hot wind then shocks the ISM on larger scales, heating it and ejecting it from the galaxy (0.001 – 1 kpc?).



King & Pounds (2015)

Different types of AGN feedback

- Radio mode:

  - heating the hot ISM of host galaxies, groups and clusters and preventing it from cooling (0.01 – 1 Mpc);
  - driving shocks into the cool ISM of the host galaxies and thereby heating and ejecting it (0.01 – 30 kpc).

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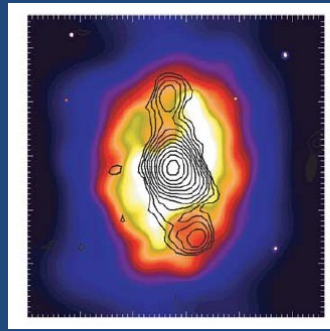
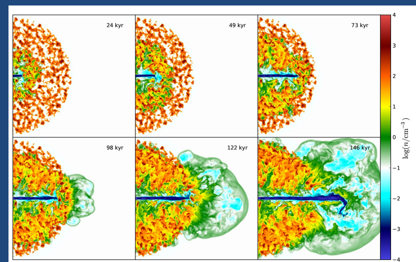
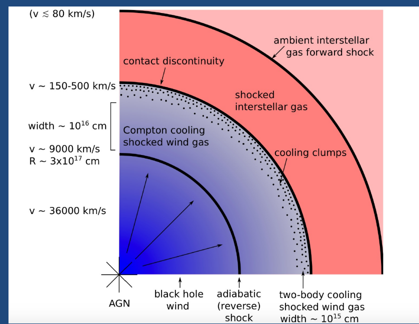


McNamara et al. (2005)



Wagner & Bicknell (2012)



King & Pounds (2015)

Triggering: host galaxy properties

Multi-wavelength observations of the 2Jy sample

- Complete sample of 47 southern ($\delta < +10^{o}$) radio sources with $S_{2.7GHz} > 2$ Jy, intermediate redshifts ($0.05 < z < 0.7$), high radio powers ($10^{25} < P_{1.4GHz} < 10^{28}$ W Hz^{-1})
- *Sample contains 9 CSS/GPS sources*

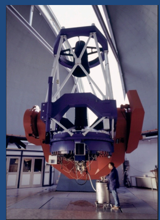
X-ray

XMM

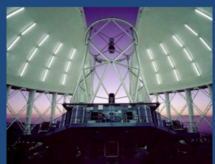
Chandra

Optical

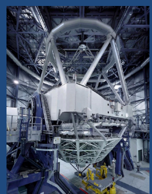
ESO 3.6m



ESO 2.2m



Gemini South

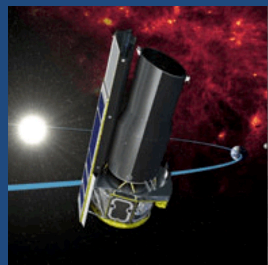


ESO VLT

Near-IR

ESO NTT

Mid-IR



Spitzer

Far-IR

Herschel

Sub-mm

APEX

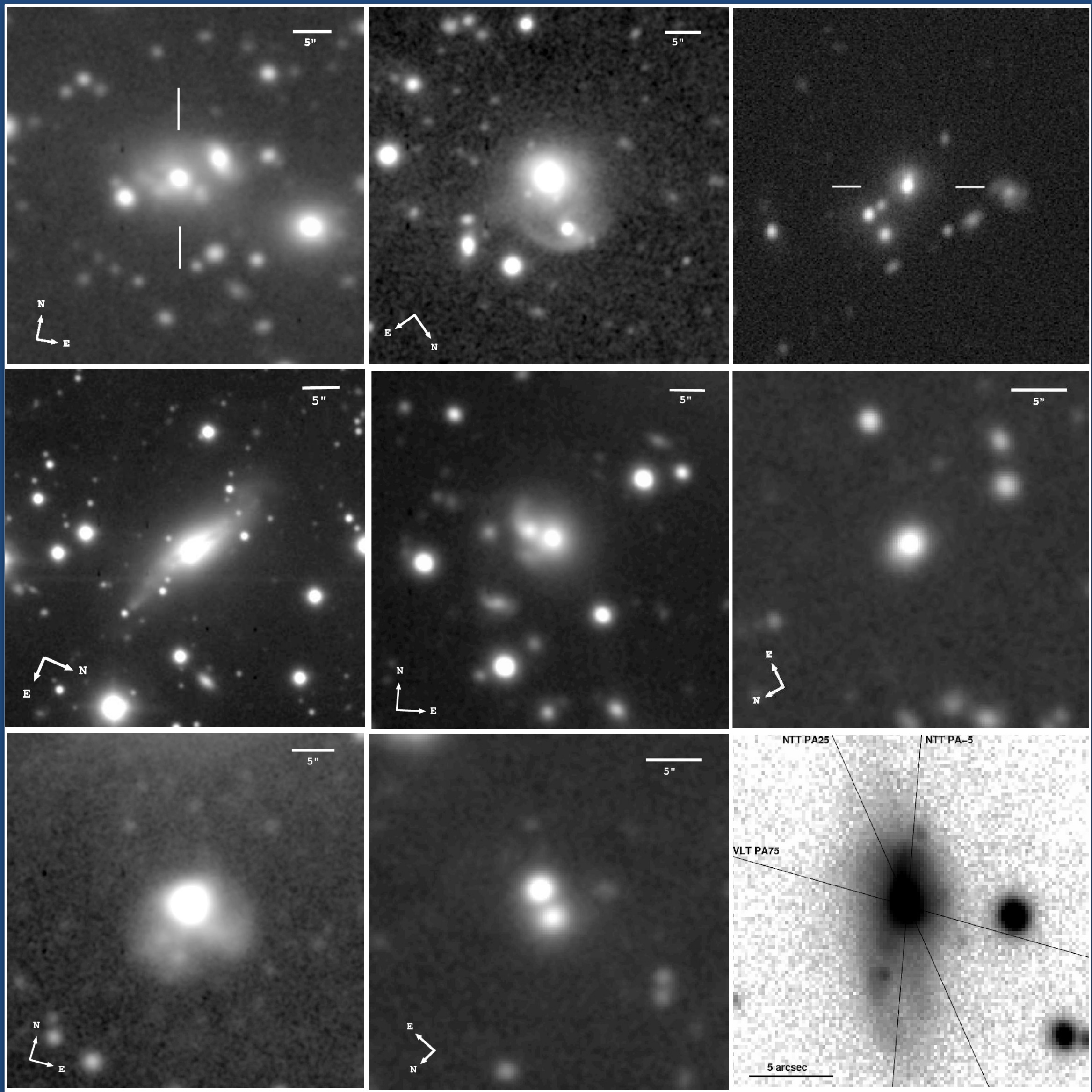
Radio

ATCA

VLA

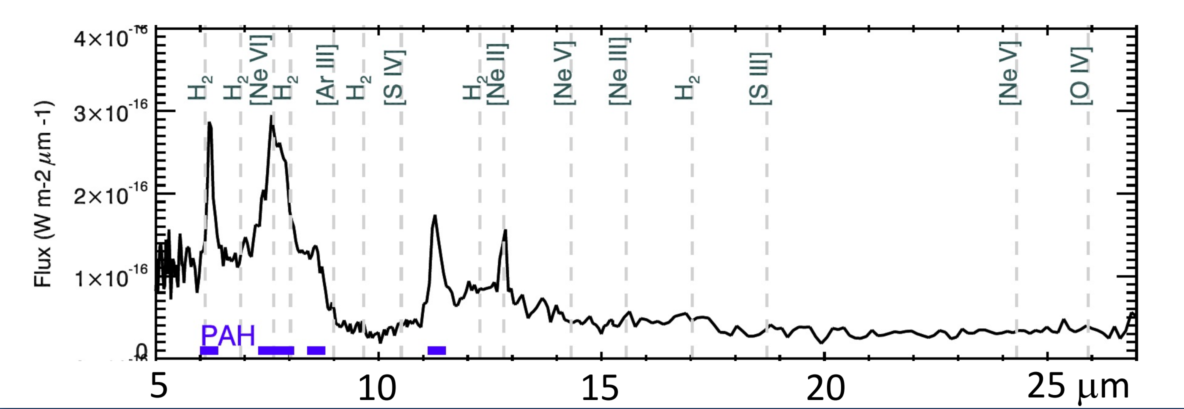
- Deep observations across the EM spectrum

Deep imaging of CSS/GPS host galaxies in 2Jy sample



- Massive ETG ($M_* \gtrsim 10^{11}\ M_\odot$)
- 8/9 (90%) show tidal features suggestive of galaxy mergers
- Similar to extended radio sources in these host galaxy properties

Star formation activity in CSS/GPS I. PAH feature detection (Spitzer)

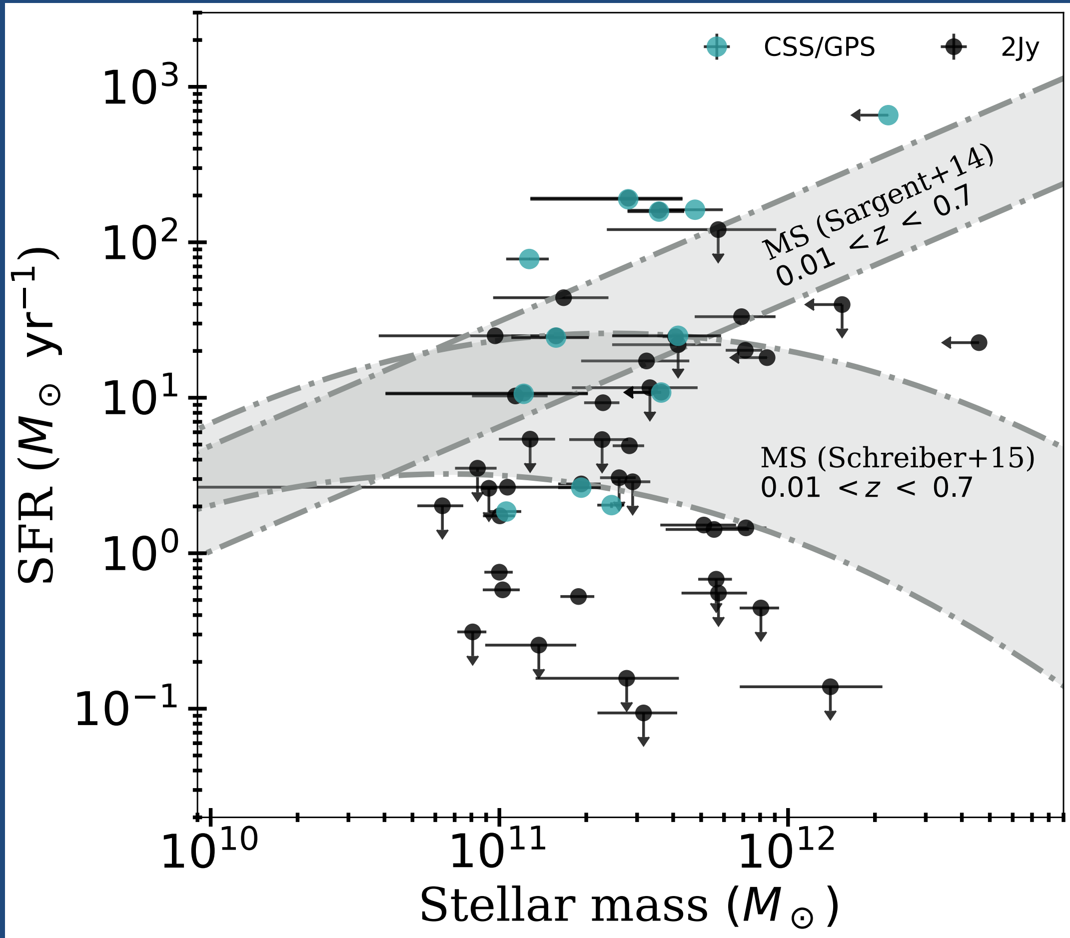


PAH features detected in:

- 8/10 (80%) of CSS/GPS sources (D < 30 kpc) in complete 2Jy (z < 0.7)+3RC (z < 0.1) sample of Dicken et al. (2012)
- 7/8 (88%) of nearby CSO (z < 0.26) in sample of Willet et al. (2010)
- 10/48 (21%) of extended radio sources in complete 2Jy (z < 0.7)+3CR(z<0.1)
- Consistent results obtained using optical and far-IR signs of SF activity (Tadhunter et al. 2011, Dicken et al. 2012)

➔ *CSS/GPS associated with higher levels of SF activity than their more extended counterparts*

Star formation activity in CSS/GPS II. Star formation rates from far-IR continuum



Bernhardt et al. (2021)

Explanations for enhanced SF activity in CSS/GPS

- Young radio sources observed closer to peaks of merger-induced starbursts (SB).

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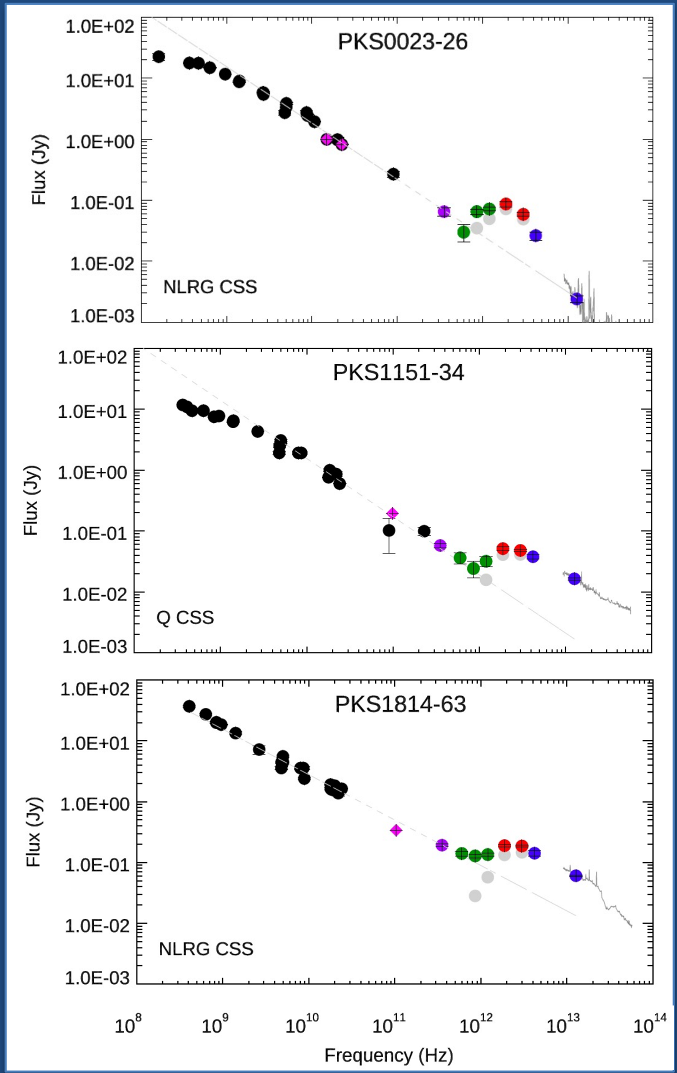
- Selection effect: radio flux boosted by strong jet-cloud interactions when RG triggered in relatively dense ISM environments (e.g. merger remnants), associated with prodigious SF activity

Determining dust masses using Herschel data for the 2Jy sample

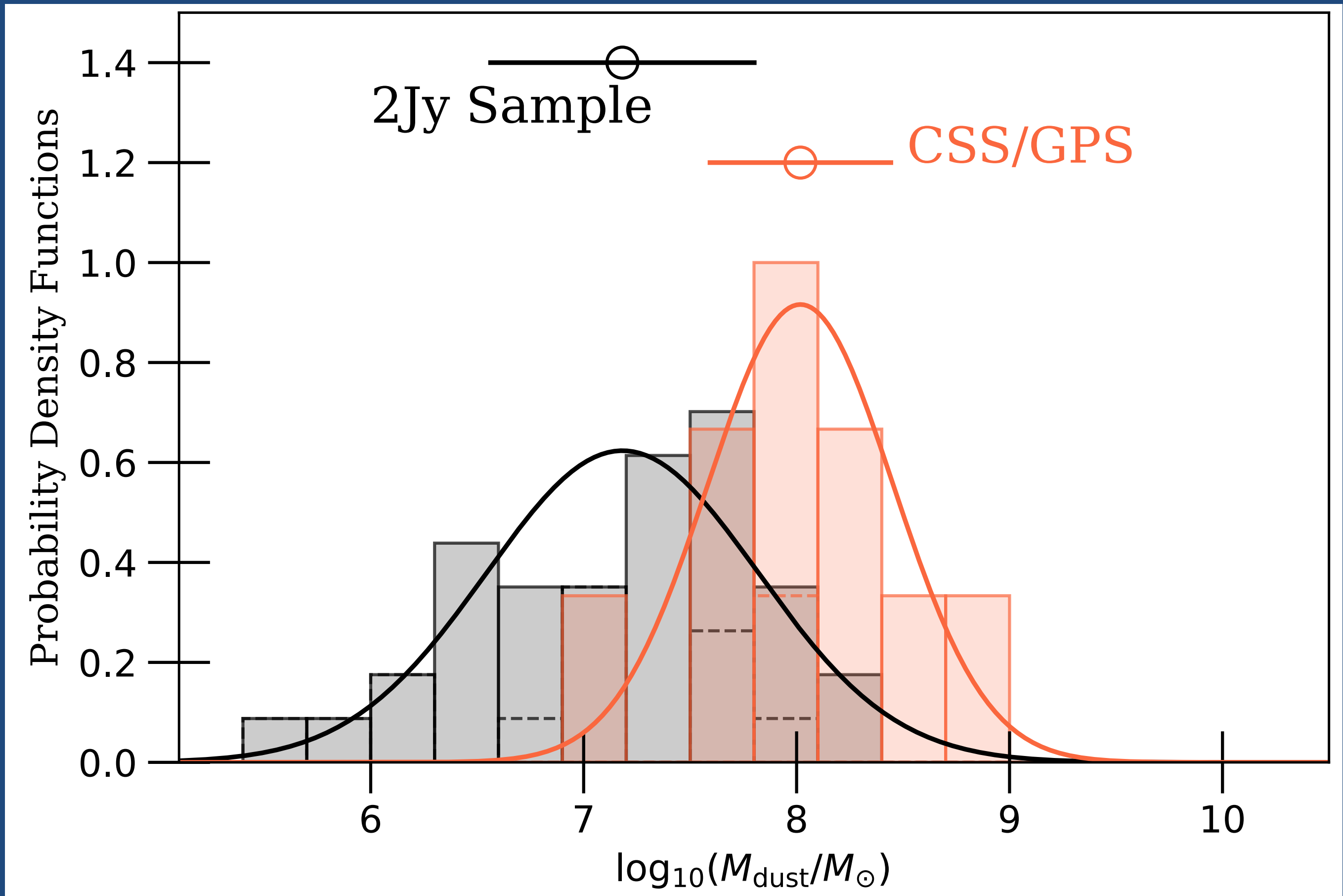
- Initially assume a single temperature modified BB fit
- Preliminary fits to SEDs and colour-colour plots (objects with SPIRE data) ➔ $\beta \sim 1.2$
- Determine dust temperatures (T_d) for non-SPIRE objects from 160/100 colour and $\beta = 1.2$
- Dust masses follow from:

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



Need to be careful about non-thermal contamination for CSS/GPS!

2Jy CSS/GPS – dust mass comparison

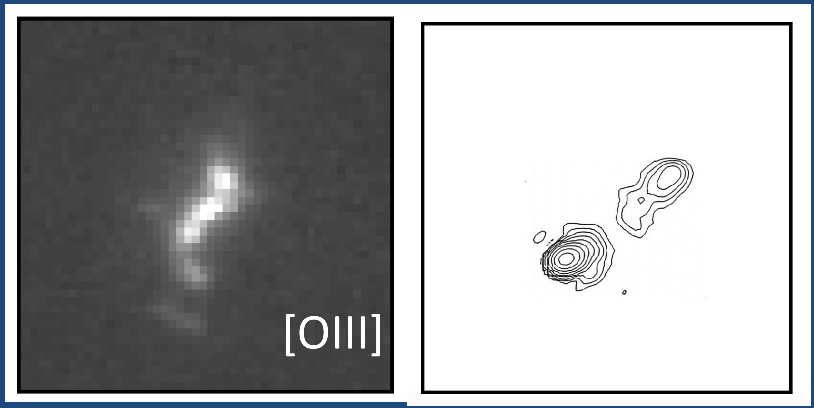


CSS/GPS richer in cool ISM than their extended radio galaxy counterparts!

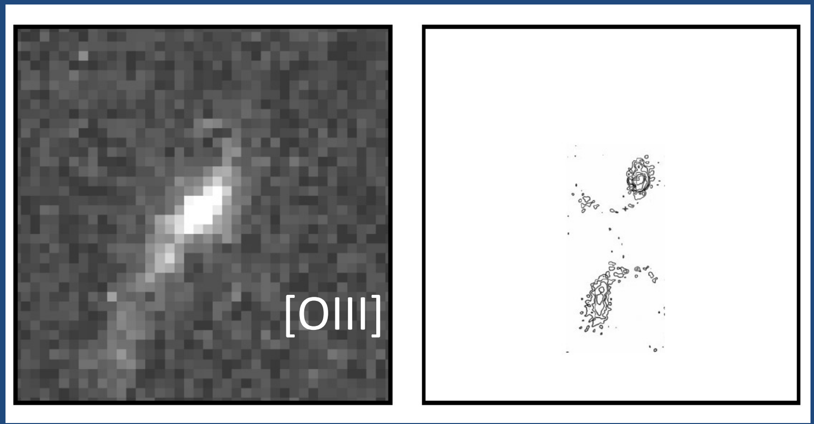
Feedback: jet-induced outflows

HST imaging: the alignment effect in CSS/GPS sources

3C303.1



3C268.3

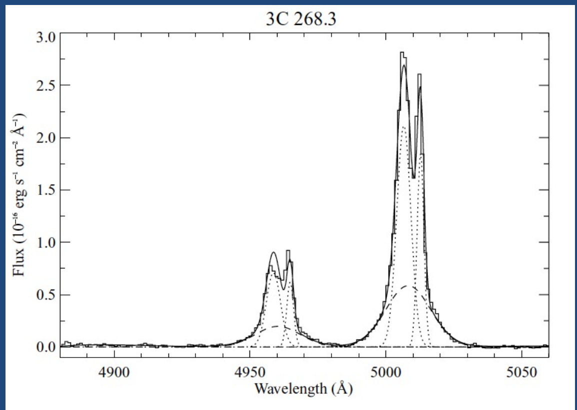


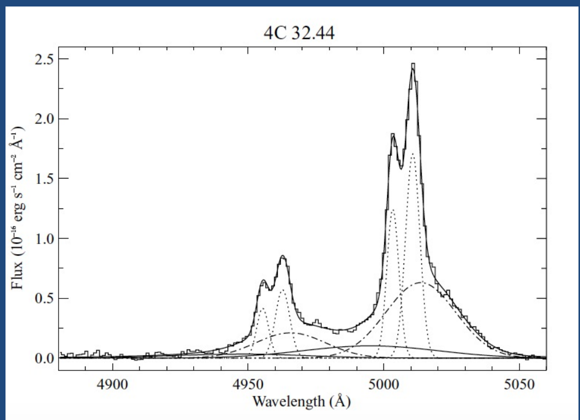
Some, but not all, CSS show an "alignment effect" similar to that observed in high-z RG.

➔Evidence for jet-induced shocks

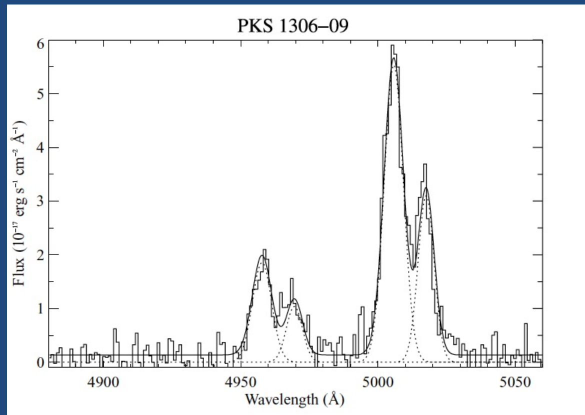
de Vries et al. (1997), Axon et al. (2000)

Kinematic evidence for warm outflows in CSS: emission-line profiles

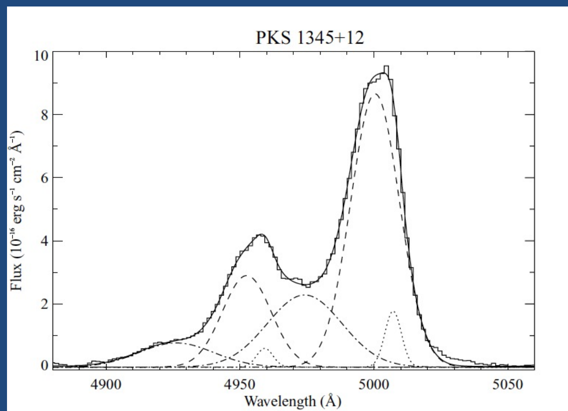


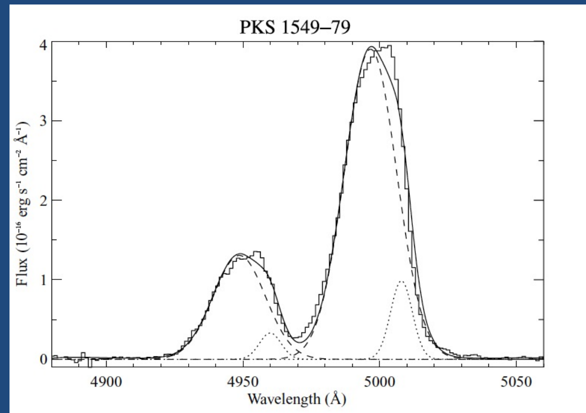


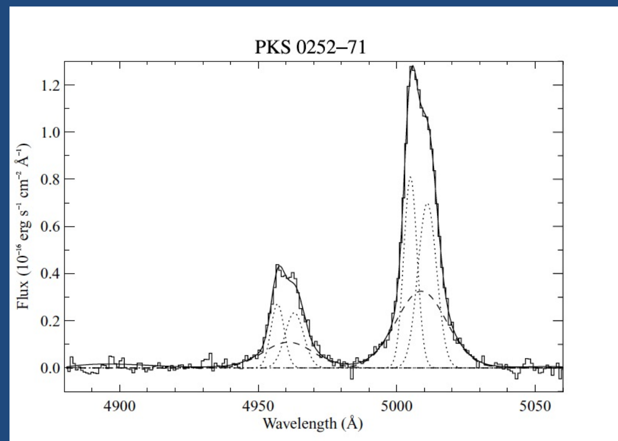
Gelderman & Whittle (1994)
Holt et al. (2008)



A large fraction of nearby CSS/GPS show unusually broad, multi-component [OIII] emission lines.







2Jy, 3CR, 4C CSS/GPS at $z < 0.3$

Quantifying the warm outflows in CSS/GPS

Calculating outflow properties:

$$\dot{M} \propto \frac{L(H\beta) v_{out}}{n_e r}$$

$$\dot{E} \propto \dot{M} \left(v_{out}^2 + \frac{(FWHM)^2}{1.85} \right)$$

$$\dot{p} = \dot{M} v_{out}$$

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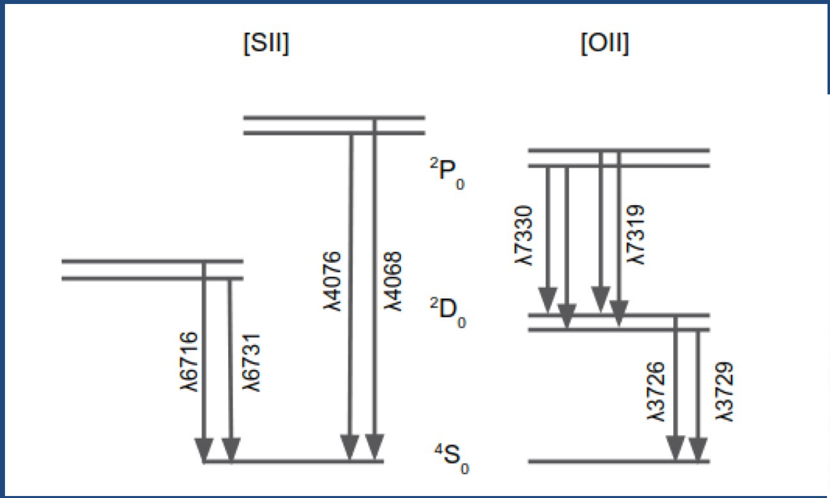
Outflow velocity estimates affected by uncertain geometry/projection effects.

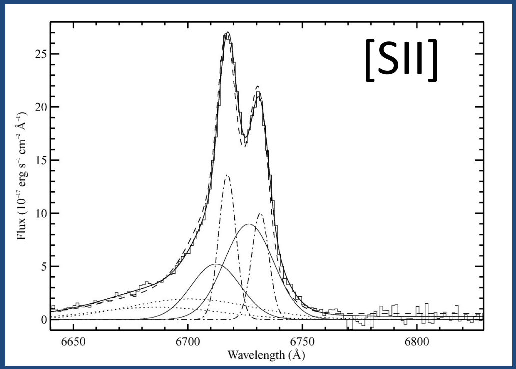
Radius uncertain, especially in most compact sources…

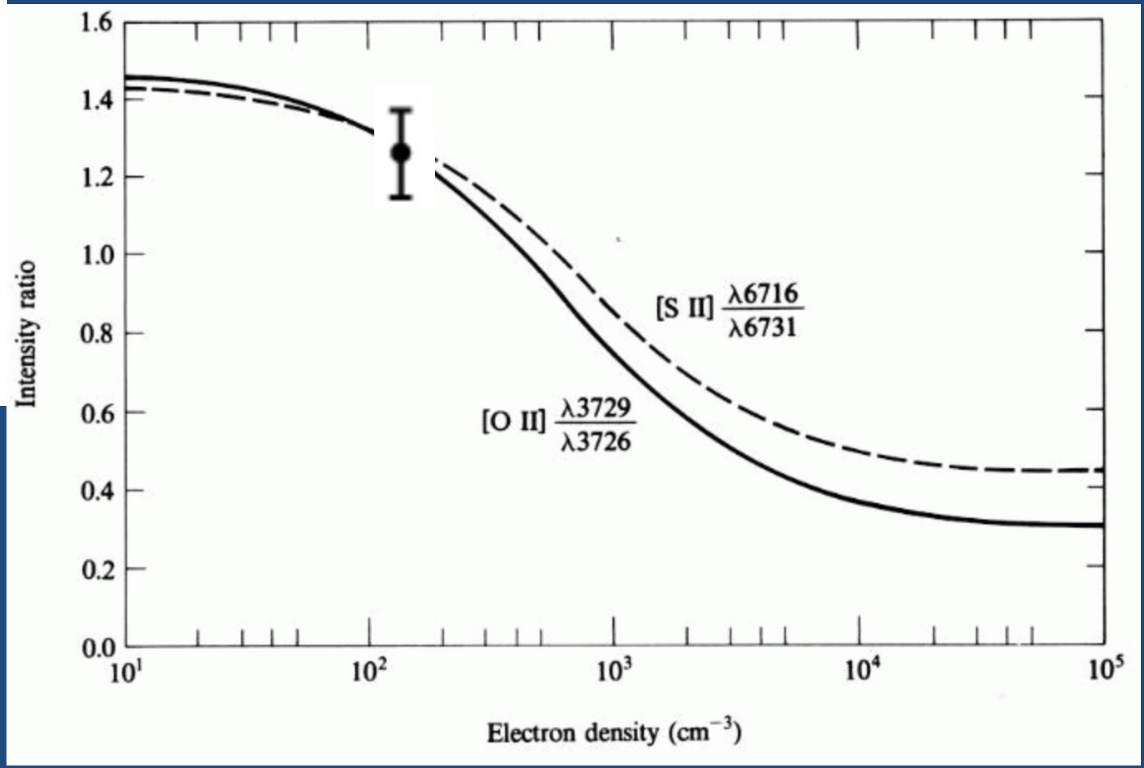
Emission-line luminosity uncertain due to dust extinction

Density uncertain due blending of key diagnostic emission lines.

[SII]6717/6731 and [OII]3729/3726 density diagnostics



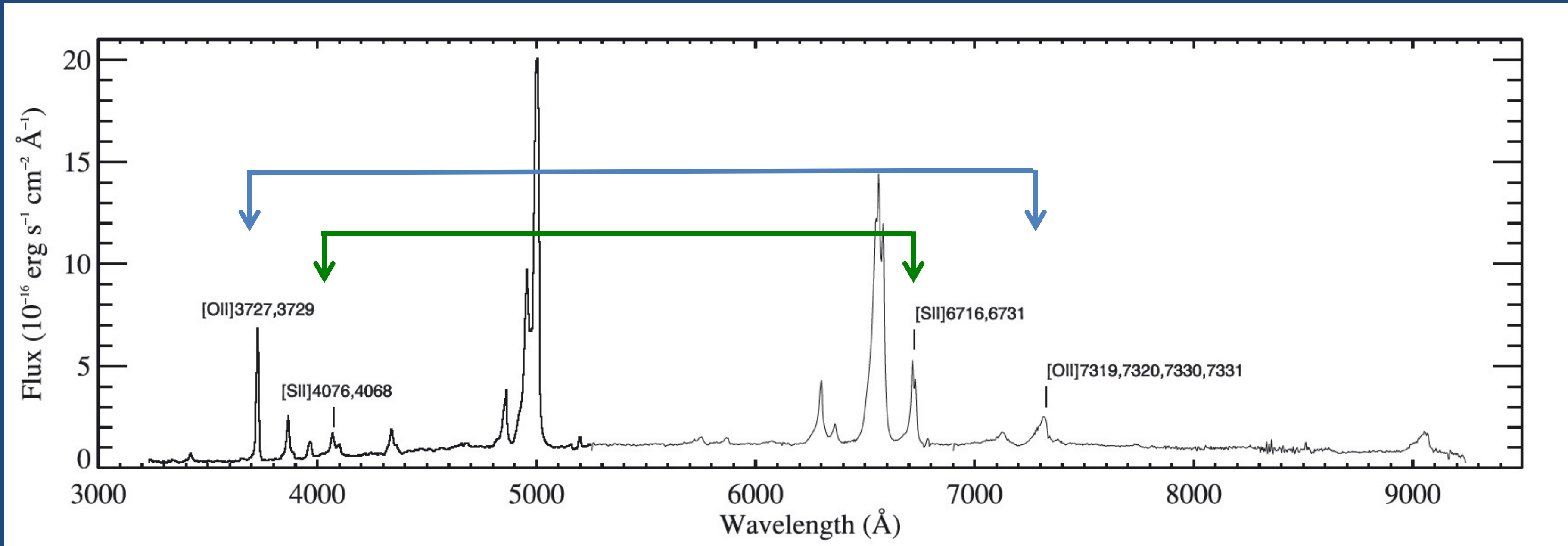




Non-linear (asymptotic) behaviour of relation between line ratios and densities makes it challenging to measure both low densities ($n_e<10^2$ cm^{-3}) and high densities ($n_e > 10^{3.5}$ cm^{-3})

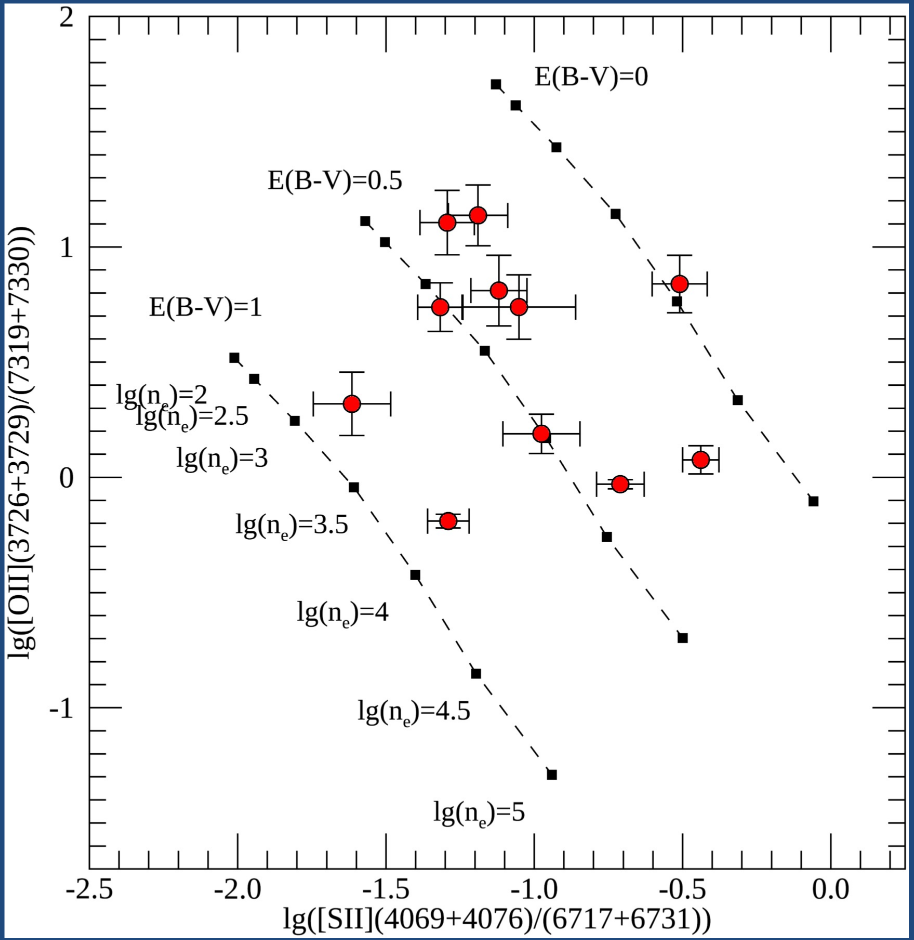
VLT/Xshooter observations of 11 nearby CSS/GPS sources at low redshifts (z < 0.7)

Transauroral [OII] and [SII] ratios



Holt et al. (2011), Santoro et al. (2020)

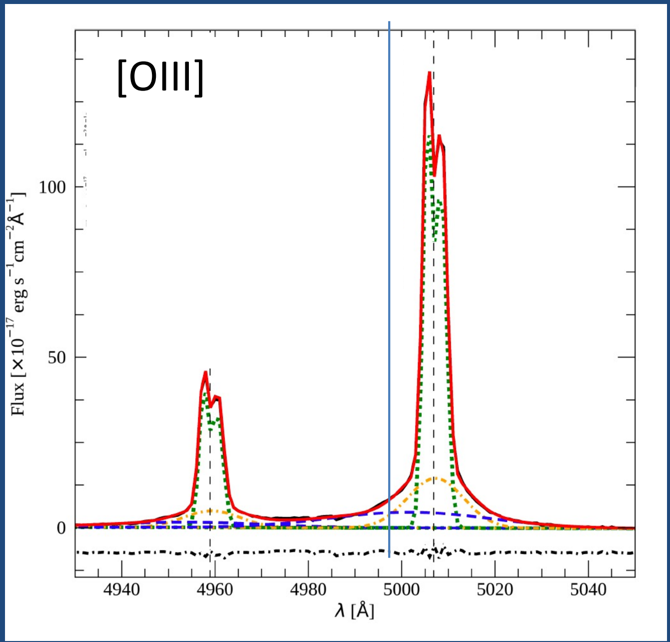
VLT/Xshooter observations of 11 nearby CSS/GPS sources at low redshifts (z < 0.7)

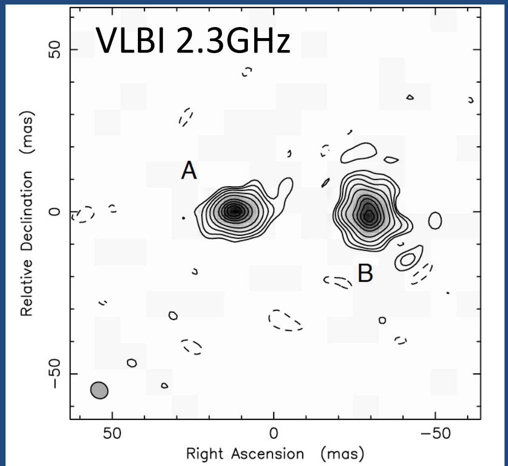


- Relatively high densities in the broad, outflowing components of the emission lines: $10^{2.5} < n_e < 10^{5.0}$ cm^{-3}
- Modest to high reddening 0.0 < E(B-V) < 1.0

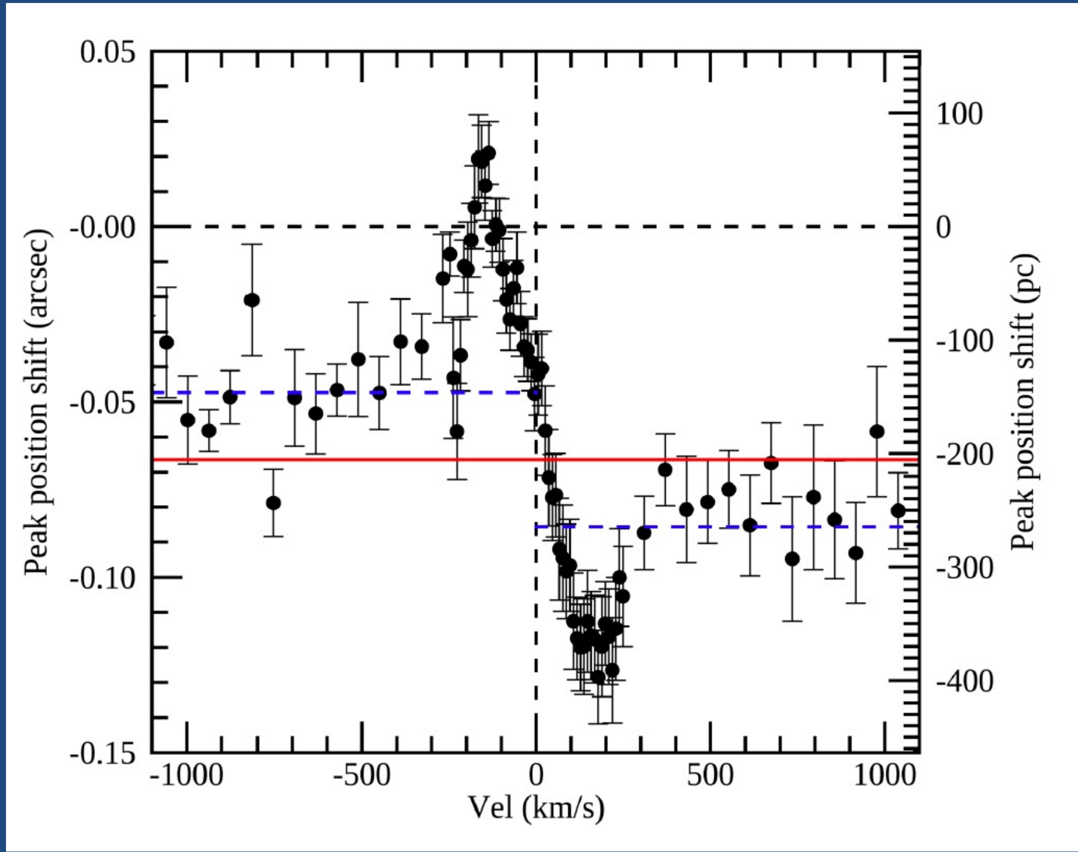
Santoro et al. (2021)

Measuring the outflow radius in the archetypal GPS PKS1934-63 using spectroastrometry





Tzioumis et al. (2002)



Santoro et al. (2018)

Radius of [OIII] outflow: 59+/-12 pc
Radius of radio source: 66+/-0.45 pc

Warm outflow properties of CSS/GPS sources

- Complete sample of all 9 CSS/GPS sources in the 2Jy sample with 0.05 < z < 0.7 plus two other low-z CSS/GPS sources in ULIRGs ($P_{1.4GHz} > 10^{25}$ W Hz^{-1}; D < 15 kpc): Santoro et al. (2021)
- Results:

$$0.1 < \dot{M} < 15\ M_{\odot}\ yr^{-1}$$

$$4\times10^{40} < \dot{E} < 1\times10^{43}\ erg\ s^{-1}$$

$$0.003 < \dot{E}/L_{bol} < 2\%$$

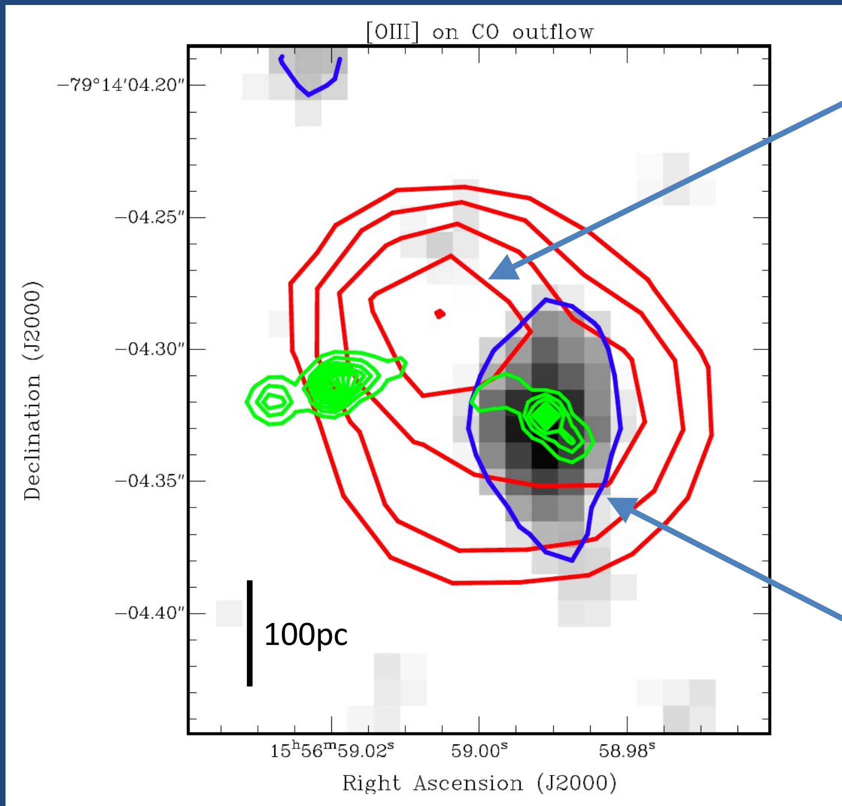
- Surprisingly modest $\dot{M}$, $\dot{E}$ etc.:

  - similar to warm outflows in nearby, radio-quiet ULIRGs (Rose et al. 2018, Spence et al. 2018);

  - $\dot{E}/L_{bol}$ below the ~5-10% required in some galaxy evolution models and simulations.

Importance of cooler ISM phases: the case of the young quasar PKS1549-79 (z=0.1525)

Oosterloo et al. (2019)



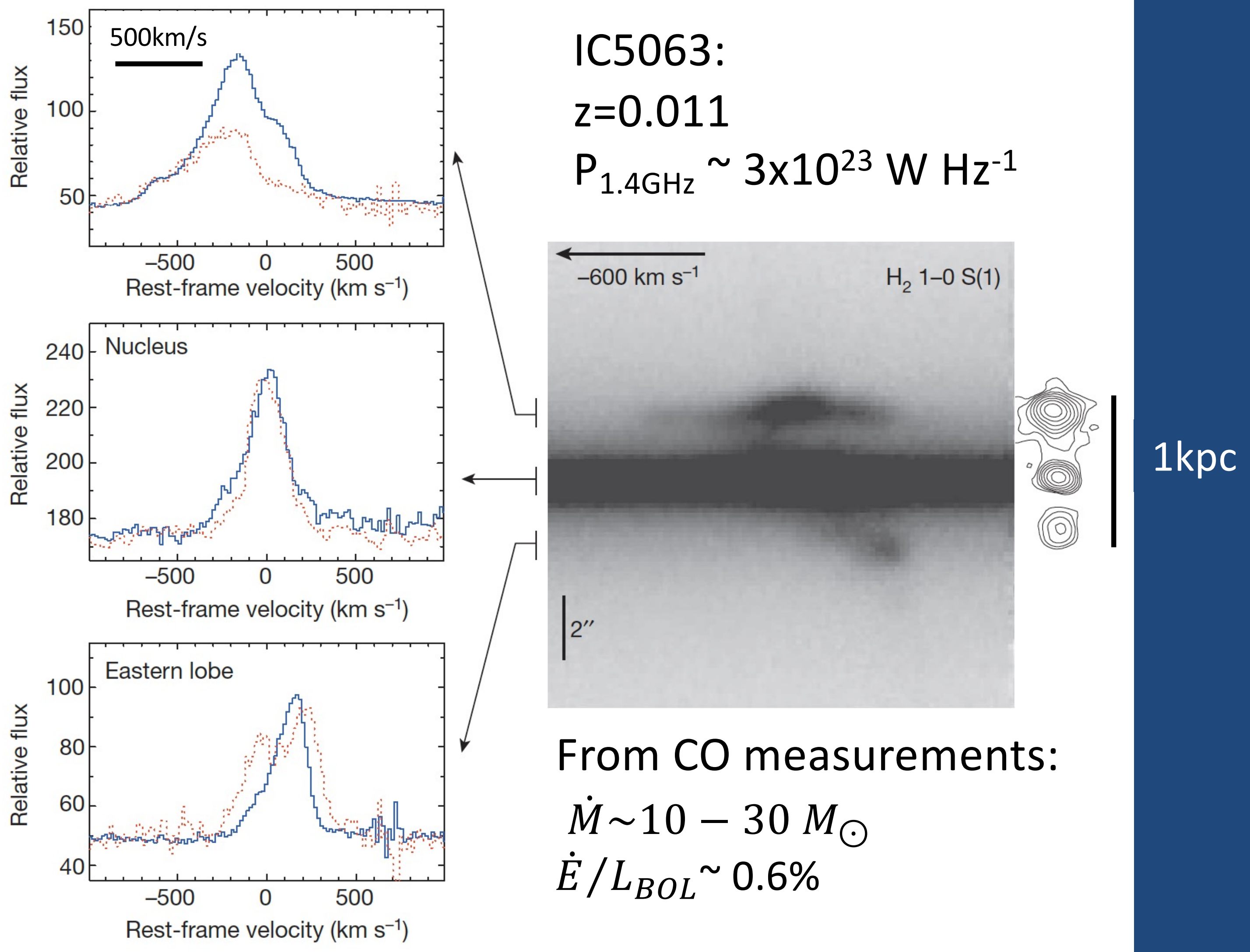
Red: [OIII] outflow (HST)
Grey: CO outflow (ALMA)
Green: 100GHz radio source (ALMA)

[OIII] outflow:
$r = 190$ pc
$\dot{M} = 8\ M_{\odot}\ yr^{-1}$
$\dot{E} = 9\times10^{42}$ erg s^{-1}
$\dot{E}/L_{bol} = 0.2\%$

CO(1-0) outflow:
$r < 120$ pc
$\dot{M} = 650\ M_{\odot}\ yr^{-1}$
$\dot{E} = 2\times10^{44}$ erg s^{-1}
$\dot{E}/L_{bol} = 5\%$

Molecular outflow more compact, massive and energetic!.

Jet-induced feedback not only important in the most powerful CSS/GPS!



IC5063:
z=0.011
$P_{1.4GHz}$ ~ $3x10^{23}$ W Hz^{-1}

From CO measurements:

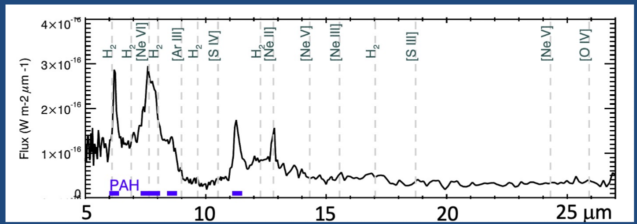
$\dot{M} \sim 10 - 30\ M_{\odot}$

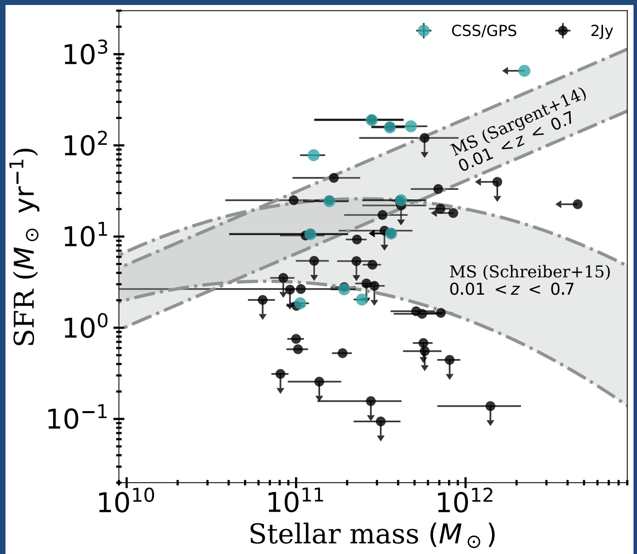
$\dot{E}/L_{BOL}$~ 0.6%

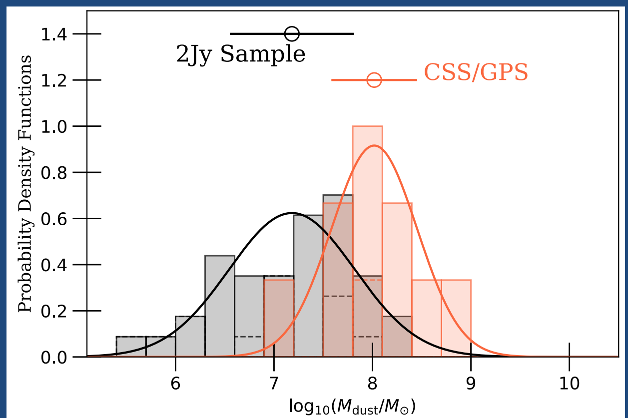
Morganti et al. (2013, 2015), Tadhunter et al. (2014), Oosterloo et al. (2017)

Are CSS/GPS imposters in flux limited samples?

CSS/GPS as imposters in flux-limited radio samples





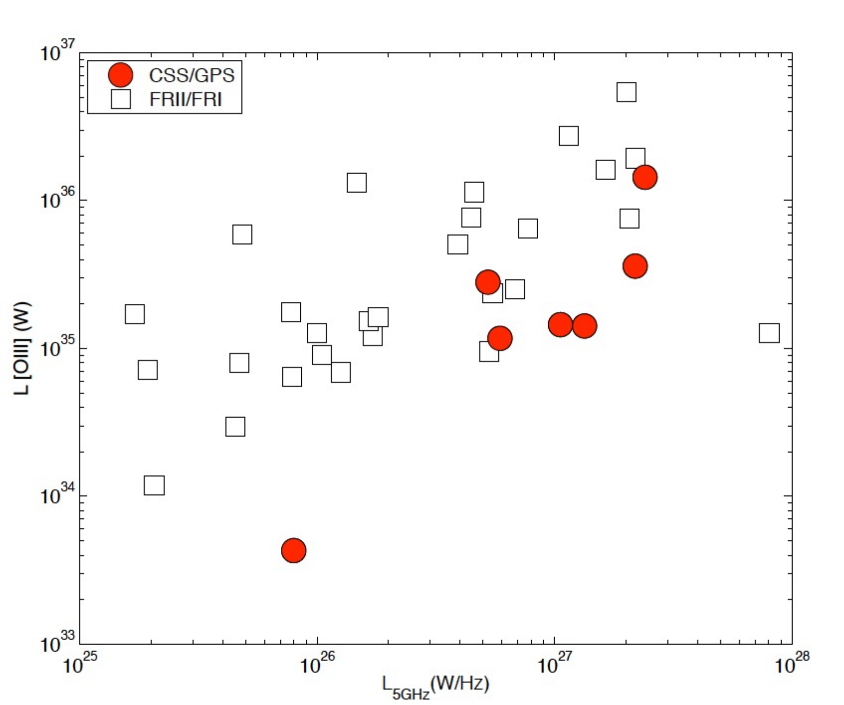


- Clear evidence that CSS/GPS have both enhanced SFR and more massive cool ISM compared with extended radio sources
- Consistent with the idea that CSS/GPS triggered in relatively dense gaseous environments, that are associated with high SFR.
- Strong jet-cloud interactions boost the radio emission, leading to sources of intrinsically lower jet power being preferentially selected in flux-limited radio samples.

Tadhunter et al. (2011), Morganti et al. (2011). Dicken et al. (2012)

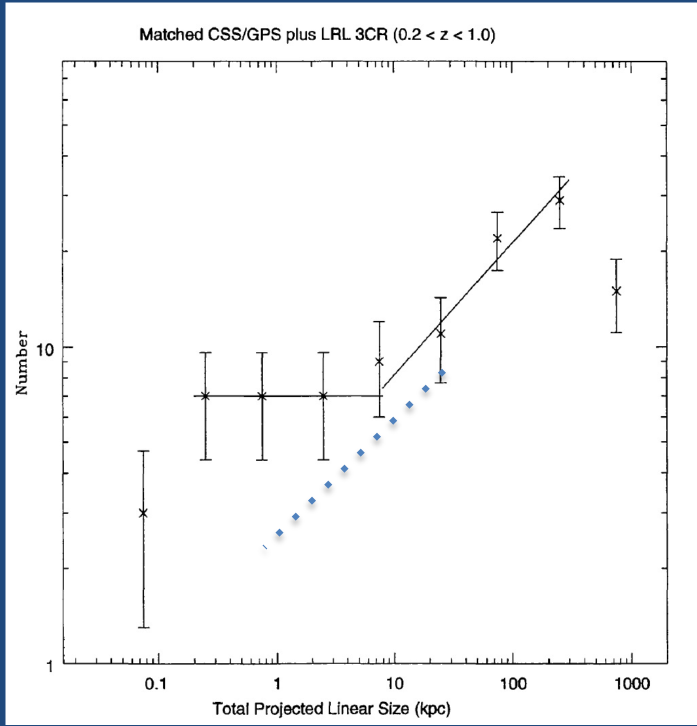
Further evidence that CSS/GPS are imposters

Complete 2Jy sample (0.05 < z < 0.7)



Morganti et al. (2011)

LRL 3CR sample (0.2 < z < 1)



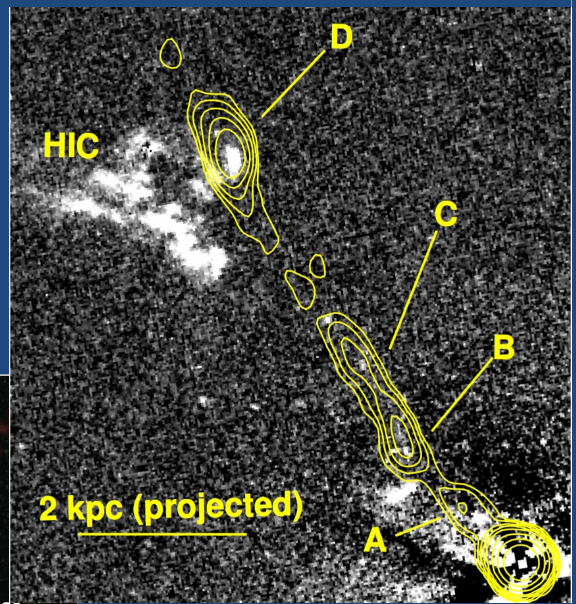
O'Dea & Baum (1997)

CSS/GPS have systematically higher radio powers for given [OIII] luminosity.

Too many compact radio sources, based on extrapolation of N vs linear size correlation for LRL extended sources.

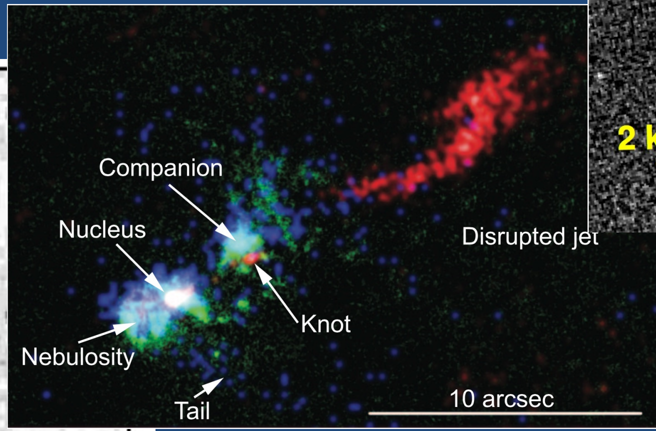
Jet-cloud interactions enhance radio emission!

PKS2152-69



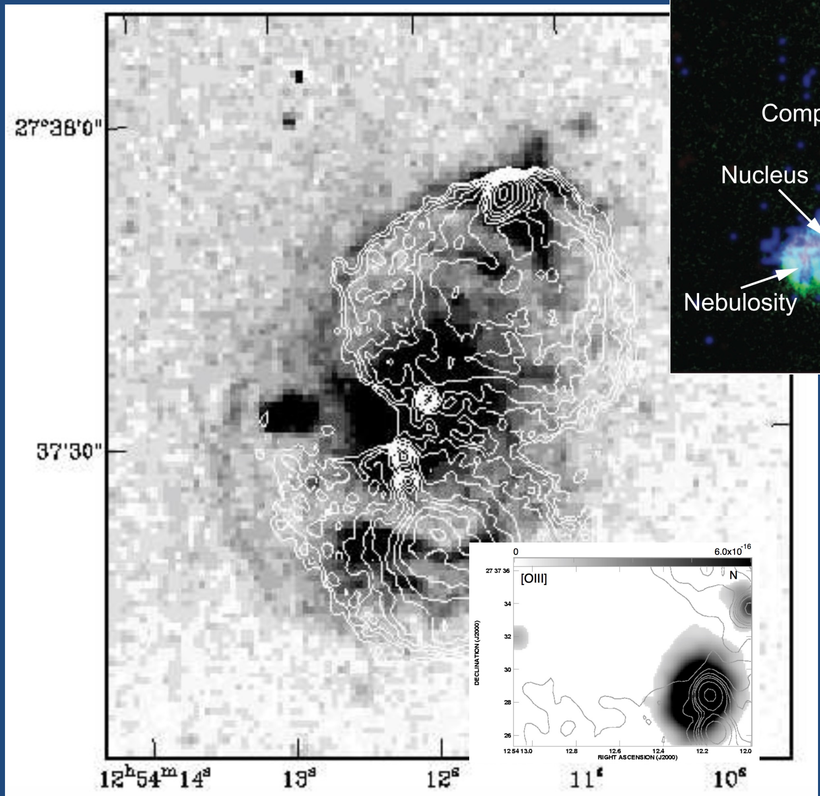
Worrall et al. (2013)

3C321



Evans et al. (2008)

Coma A



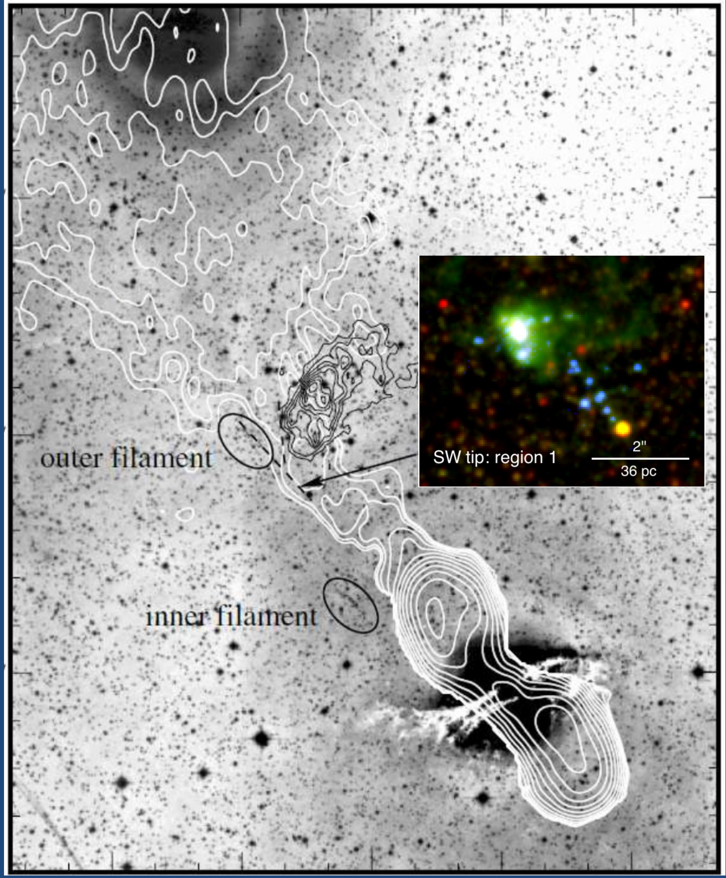
Tadhunter et al. (2000),
Solorzano-Innarea (2003)

Conclusions

- Host galaxies of CSS/GPS are massive elliptical galaxies, but a high proportion show tidal features suggestive of triggering in galaxy mergers
- High star formation rates and cool ISM masses suggest that CSS/GPS may have been triggered in relatively gas-rich environments compared with their extended radio AGN counterparts
- CSS/GPS drive massive warm outflows that are capable of disrupting the cool ISM on kpc-scales; but not clear that this feedback is powerful enough to affect the entire host galaxies
- Much of the mass in the jet-driven outflows may be tied up in neutral and molecular outflows which are more energetic
- CSS/GPS may be “imposters” in flux-limited samples

Evidence for jet-induced star formation

Cen A filaments



Crockett et al. (2012)

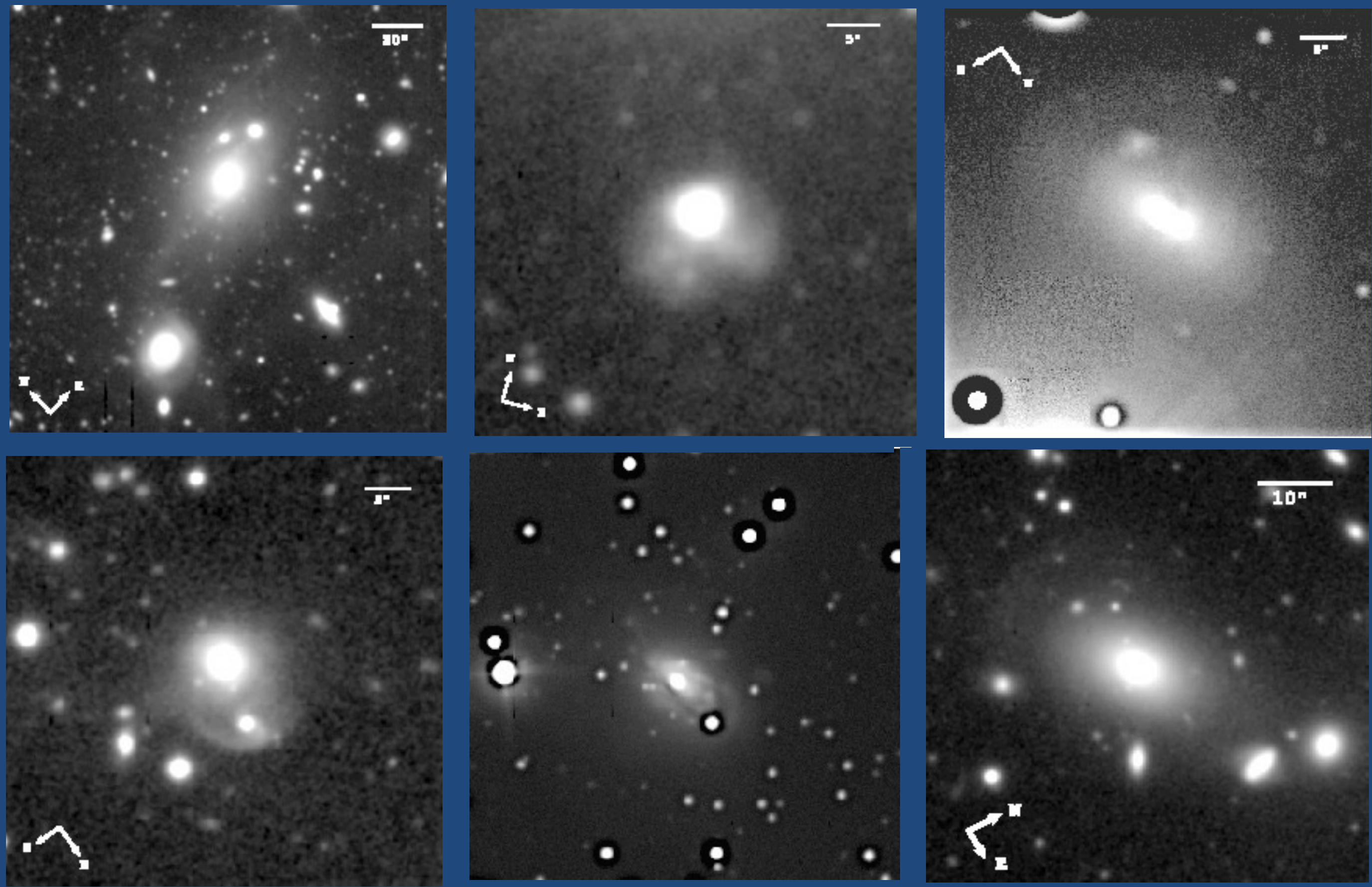
Minkowski's object

Croft et al. (2006)

Theory: Rees (1989), Gaibler et al. (2012)

There's convincing evidence for jet-induced SF associated with jets in some nearby, low-luminosity FRI sources. But does this mechanism work at higher radio powers?

Deep Gemini imaging of the 2Jy sample

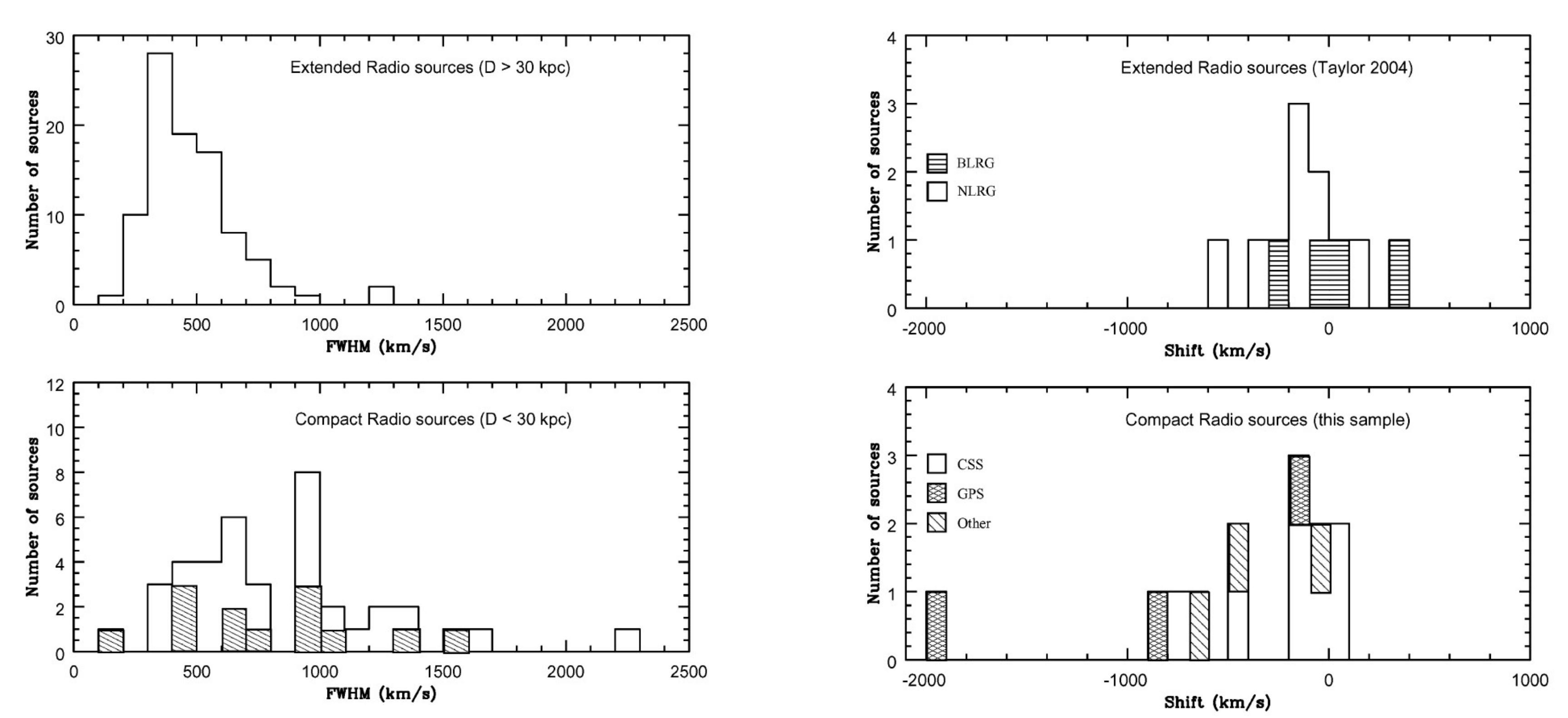


3σ SB depth:
μ_r=27 mag arcsec^{-2};
faintest detected features:
μ_r=26.5 mag arcsec^{-2}

96% of the 26 rodio-loud quasars in the $0.05 < z < 0.7$ 2Jy sample show evidence for tidal features or close double nuclei.

Ramos Almeida et al. (2011,2012)

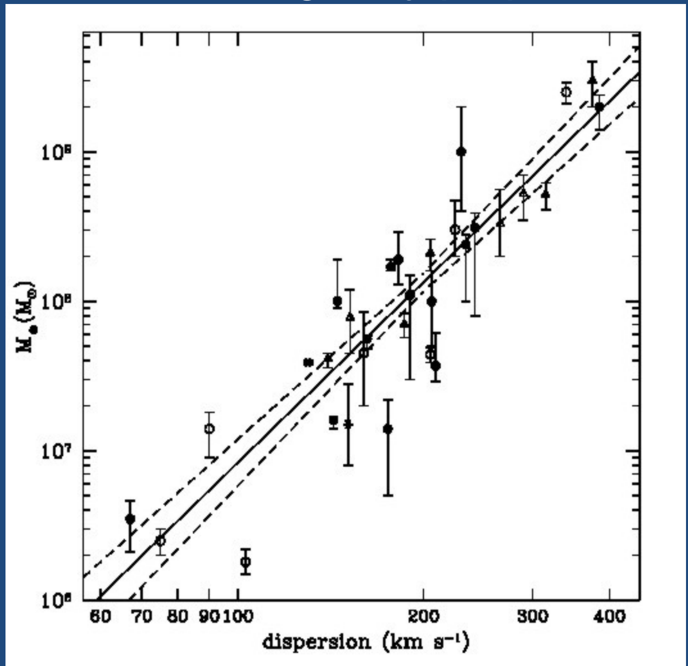
Kinematic evidence for warm outflows in CSS II. Comparison with extended FRII sources



CSS/GPS sources show evidence for more extreme emission line kinematics than extended FRII sources: broader, more blueshifted and more asymmetric [OIII]λ5007 profiles (Holt et al. 2008).

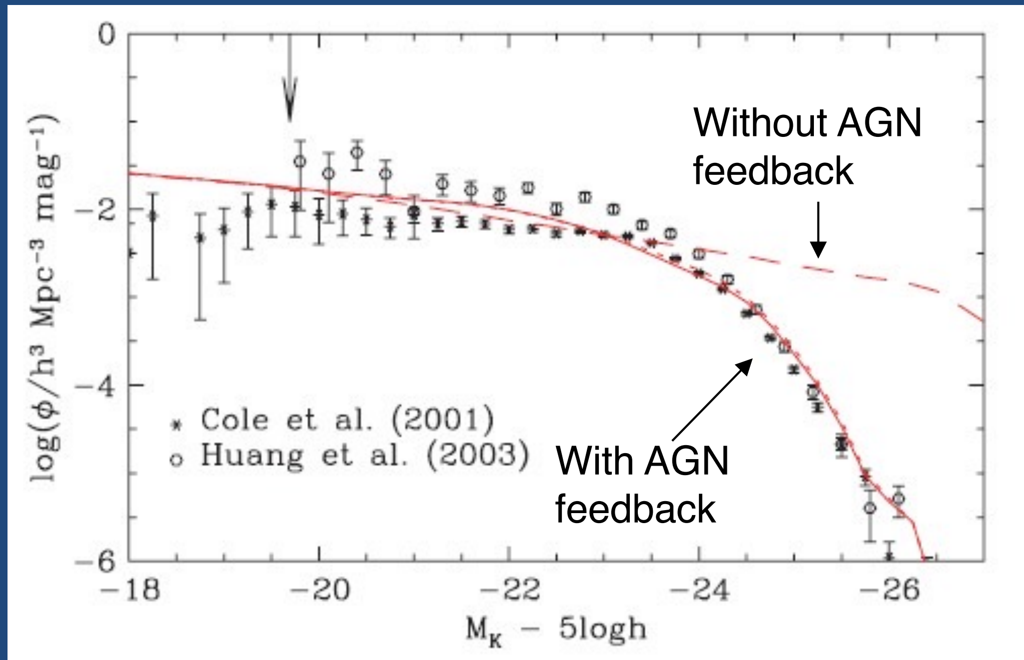
AGN feedback and galaxy evolution

Black hole vs. galaxy properties



Tremaine et al. (2002)

Galaxy luminosity function

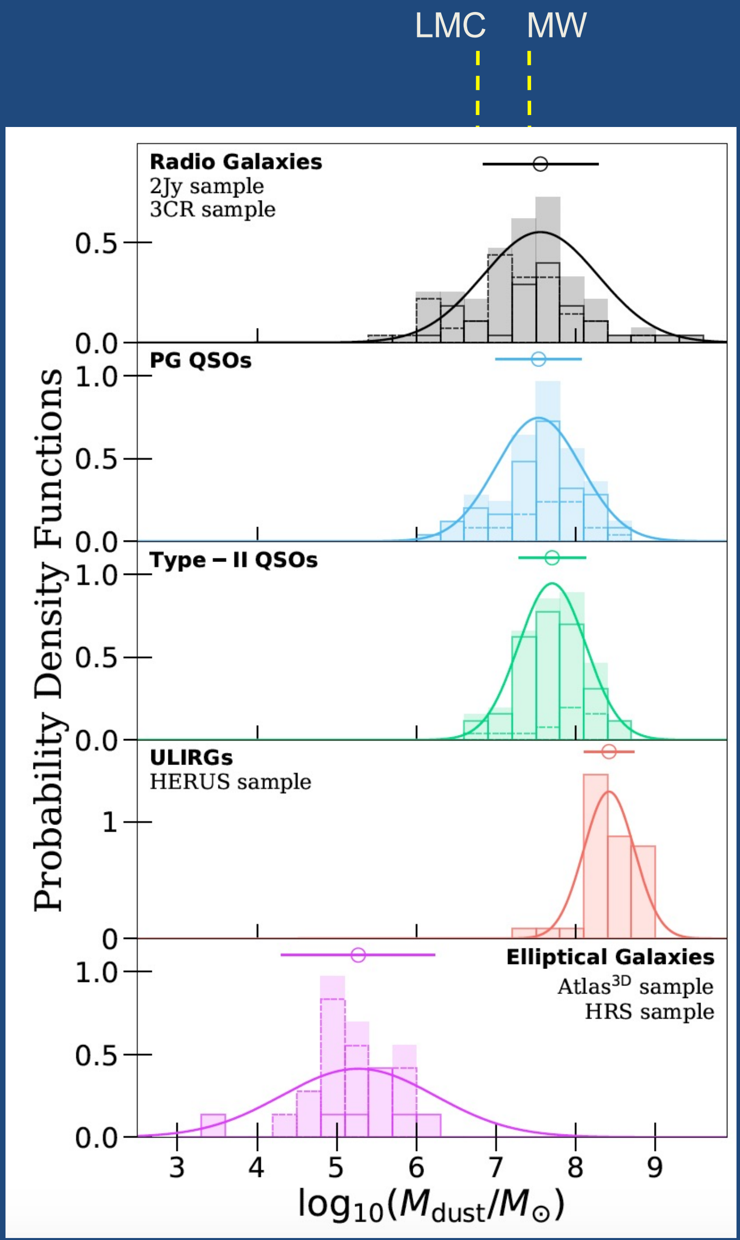


Bower et al. (2006)

Herschel dust mass results

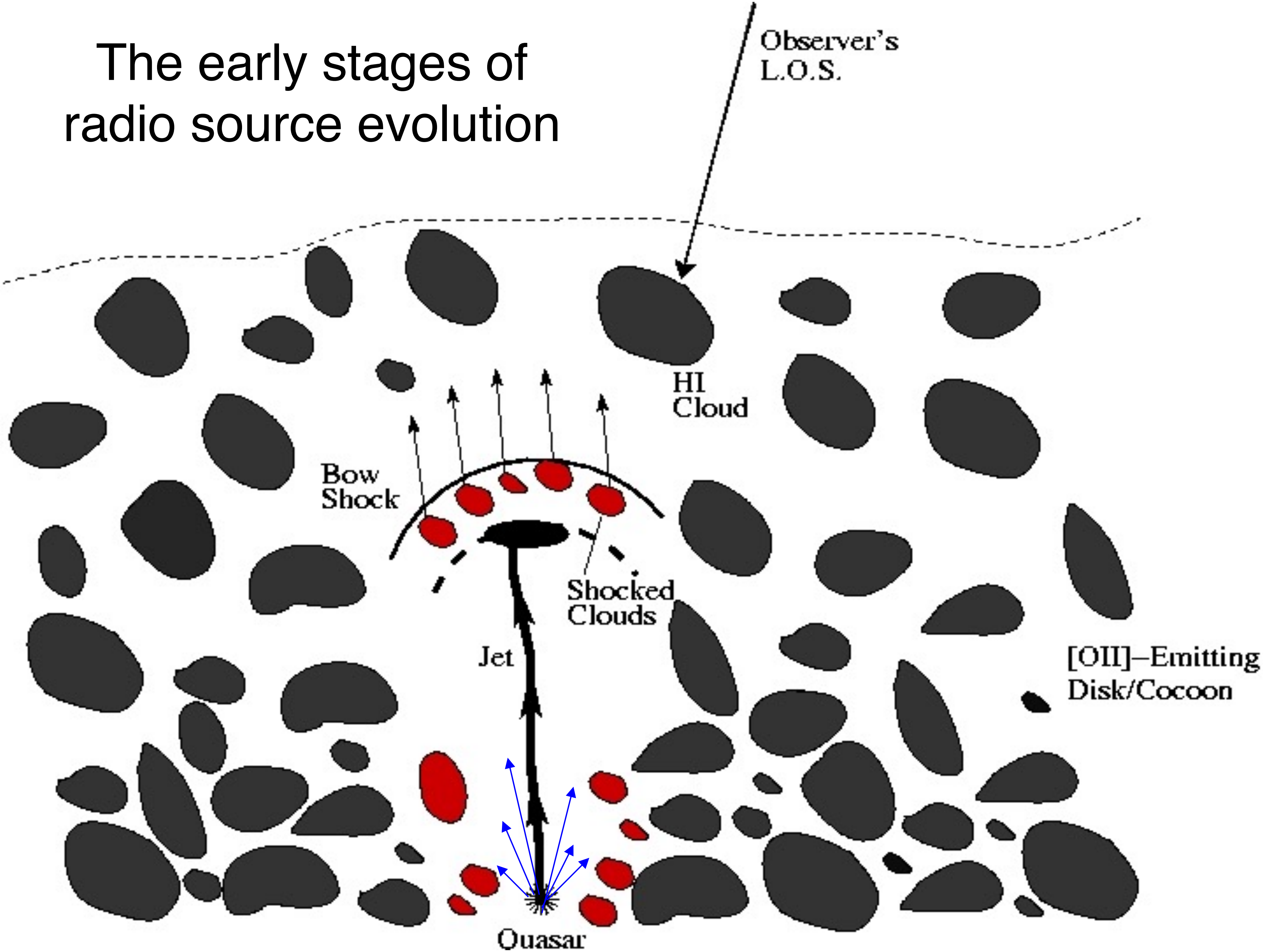
- Typical quasar dust masses ~10x lower than ULIRGs, but >100x higher than elliptical galaxies
- <15% of elliptical galaxies have $M_{dust} > 10^6\ M_{\odot}$

→ In most cases triggering mergers are relatively minor (although ~10-20% of SLRG consistent with more major mergers)



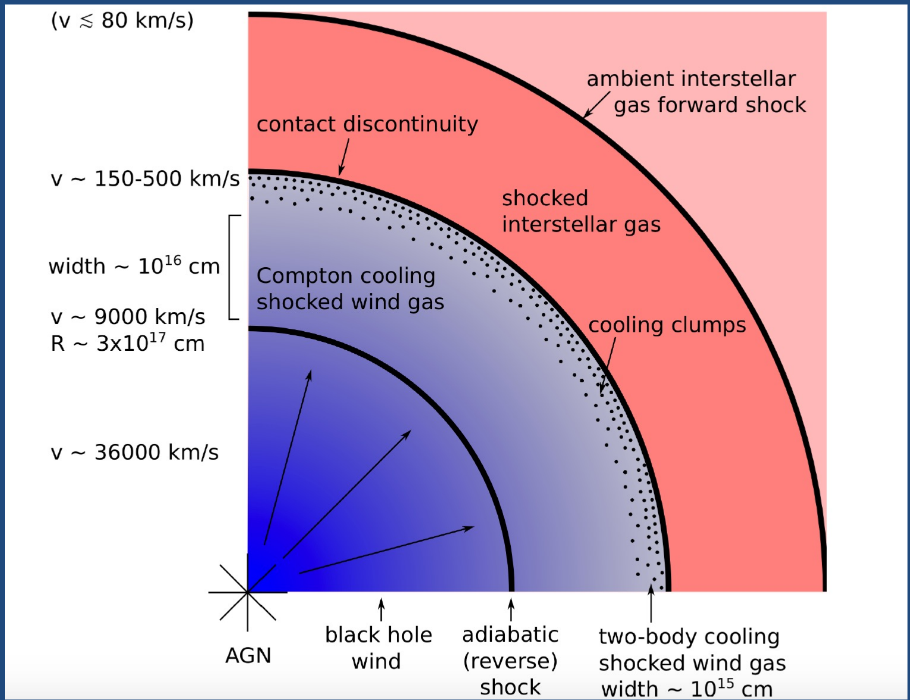
Tadhunter et al. (2014)
Bernhard et al. (2021)

The early stages of radio source evolution

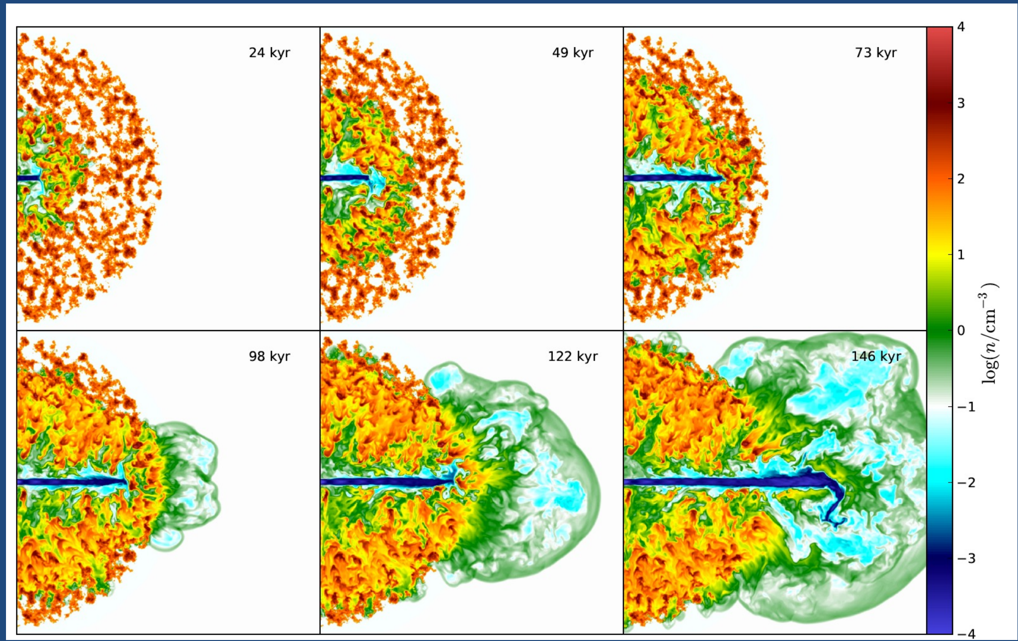


AGN feedback acting on the cooler gas components in host galaxies

King and Pounds (2015)



Wagner et al. (2014), Mukherjee et al. (2018)



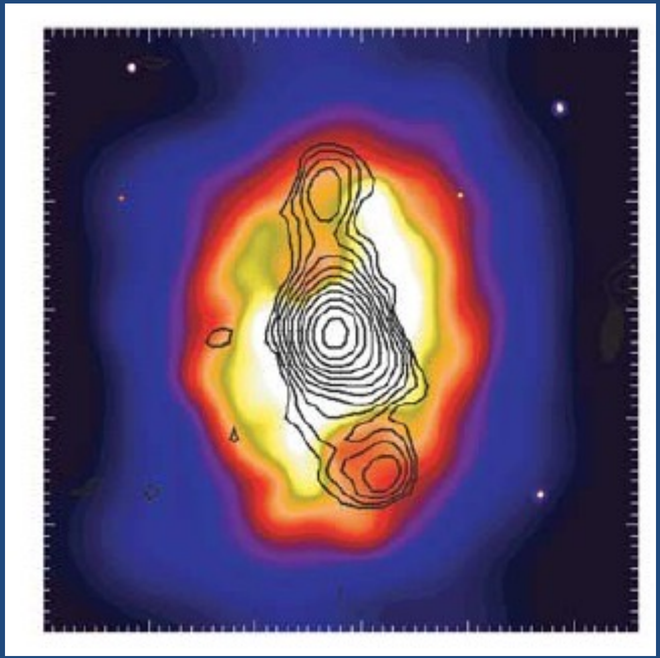
Quasar wind

e.g. ULIRGs with AGN nuclei

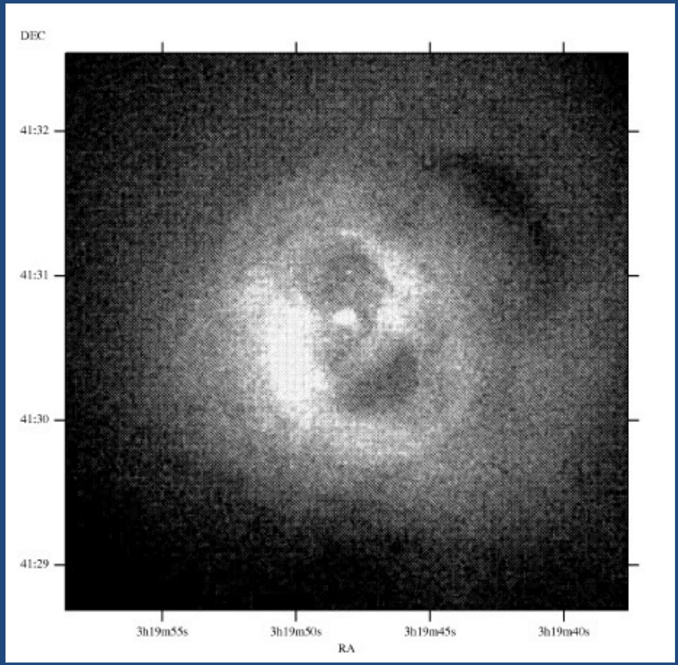
Jet-induced feedback

e.g. CSS/GPS sources (D<15 kpc)
– jet breakout phase

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

Different types of AGN feedback

- Radio mode:
  - heating the hot ISM of host galaxies, groups and clusters and preventing it from cooling (0.01 – 1 Mpc);
  - driving shocks into the cool ISM of the host galaxies and thereby heating and ejecting it (0.01 – 30 kpc).
- Quasar mode:
  - radiation pressure from AGN drives a hot wind close to the nucleus. The hot wind then shocks the ISM on larger scales, heating it and ejecting it from the galaxy (0.001 – 1 kpc?).