C. Tadhunter

AGN feedback: when, how, and how much?

Despite that general importance for understanding the evolution of massive galaxies, we still understand relatively little about AGN-driven outflows and the impact they have on their host galaxies. Concentrating on samples radio-loud AGN, I will review the following aspects: the triggering and timing of AGN activity; the link between AGN and starbursts; the observational evidence for AGN outflows; and the energetic significance of AGN-induced outflows compared with those driven by starbursts.

AGN outflows: how, when, and how much?

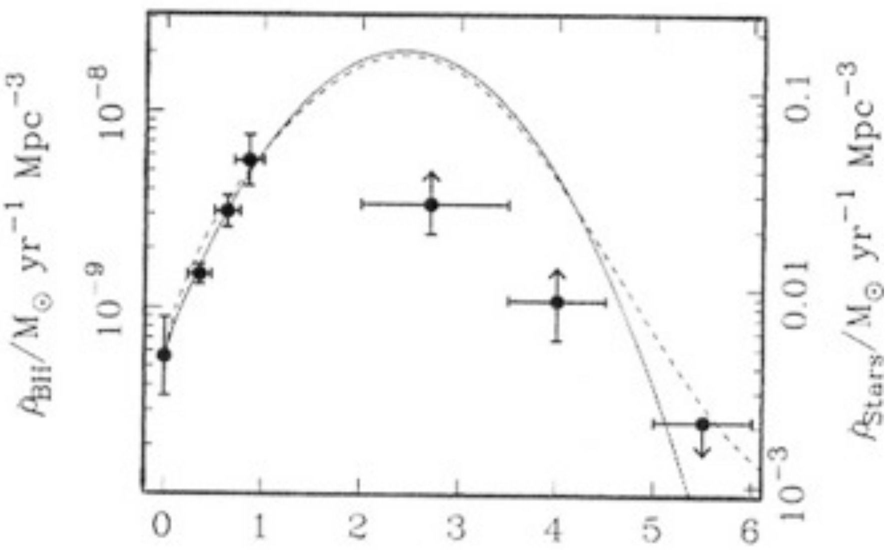
Clive Tadhunter

University of Sheffield

Collaborators: J. Holt, K. Inskip,
R. Gonzalez Delgado,
D.Batcheldor, R. Morganti,
M. Villar Martin, D. Dicken,
J. Rodriguez Zaurin

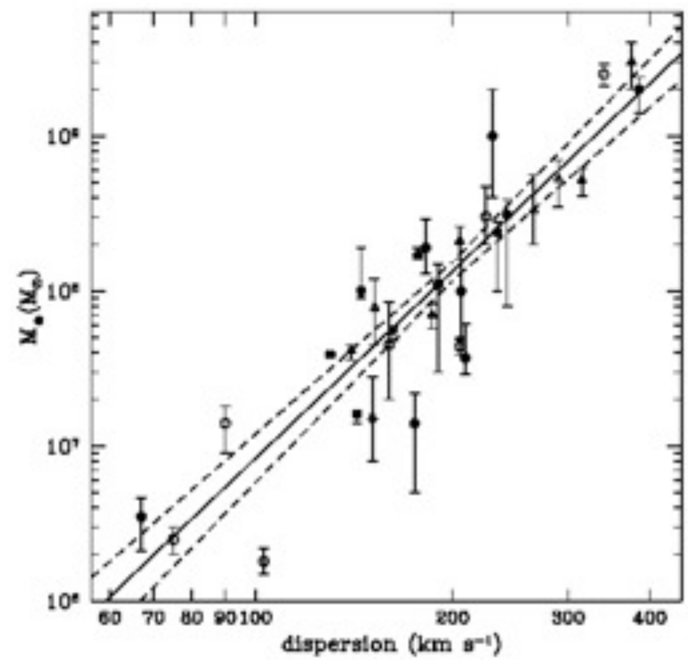
Activity and galaxy evolution

Evolution of activity and star formation



Dunlop & Peacock 1990, Madau 1987

Black hole vs. galaxy bulge properties



Tremaine et al. (2002)

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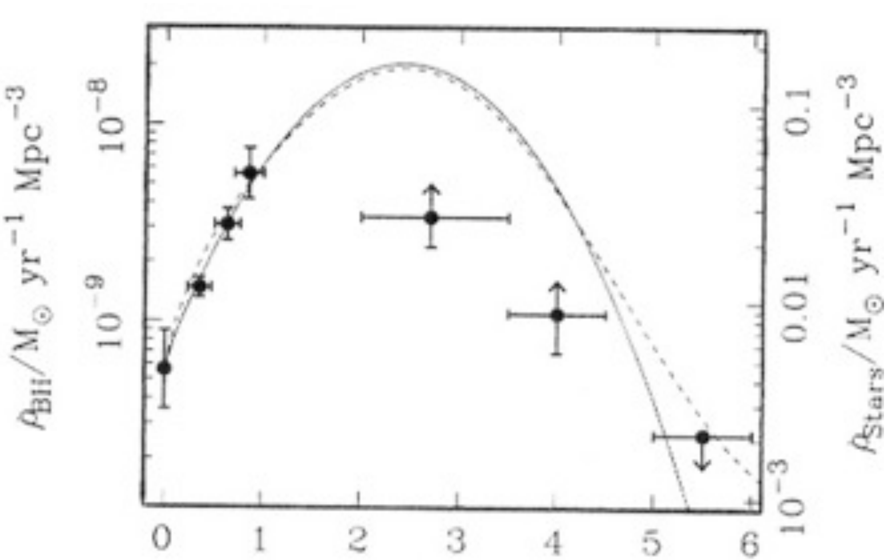

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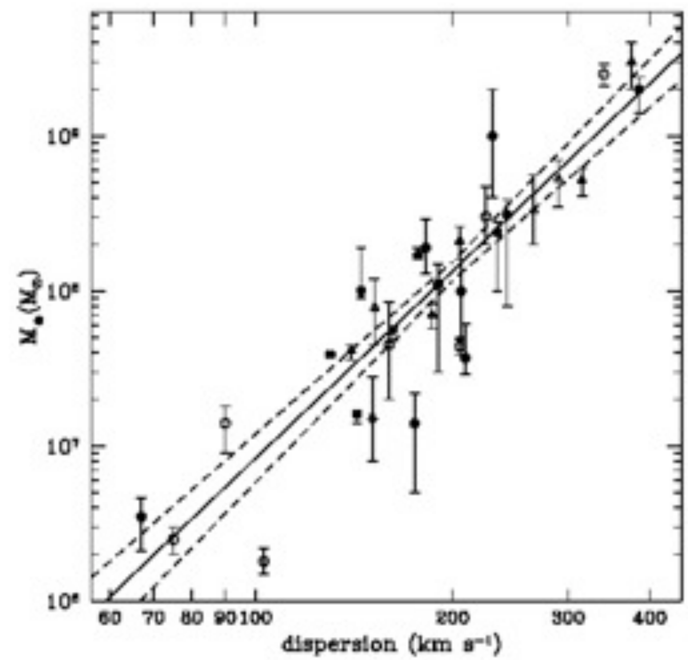

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Triggering?

Activity and galaxy evolution

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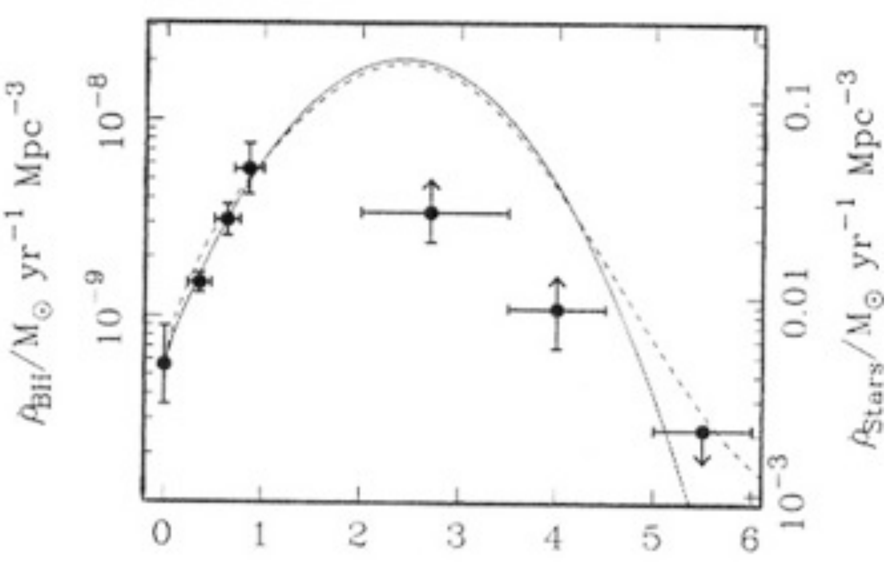

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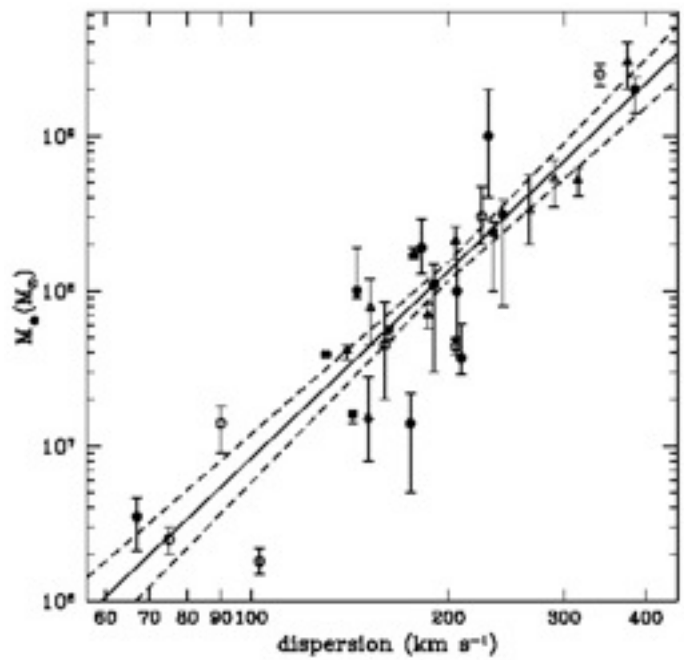
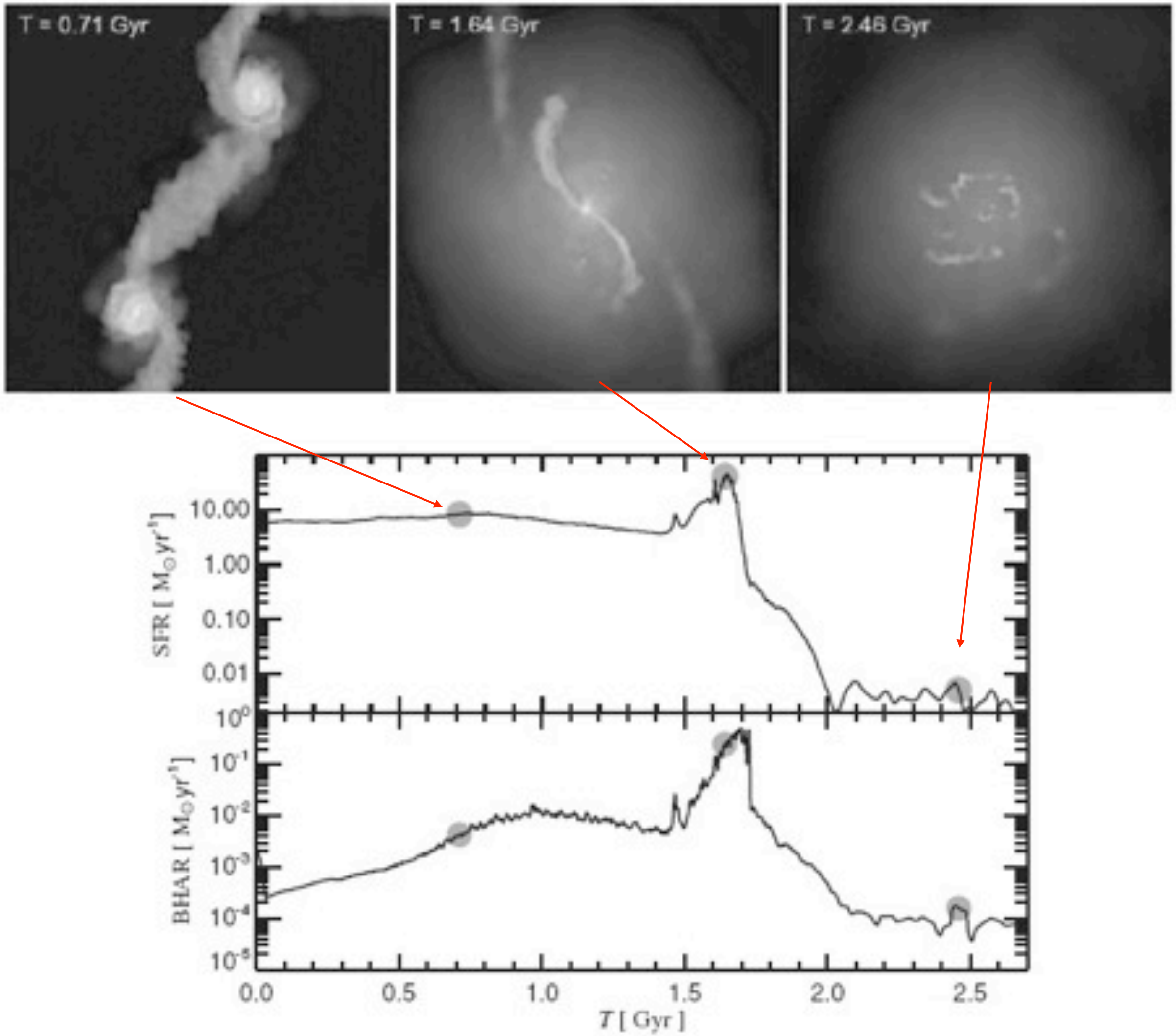


Tremaine et al. (2002)

Triggering?

Feedback?

Star formation in major gas-rich mergers



Springel et al. (2005)

Uncertainties with hydrodynamical simulations

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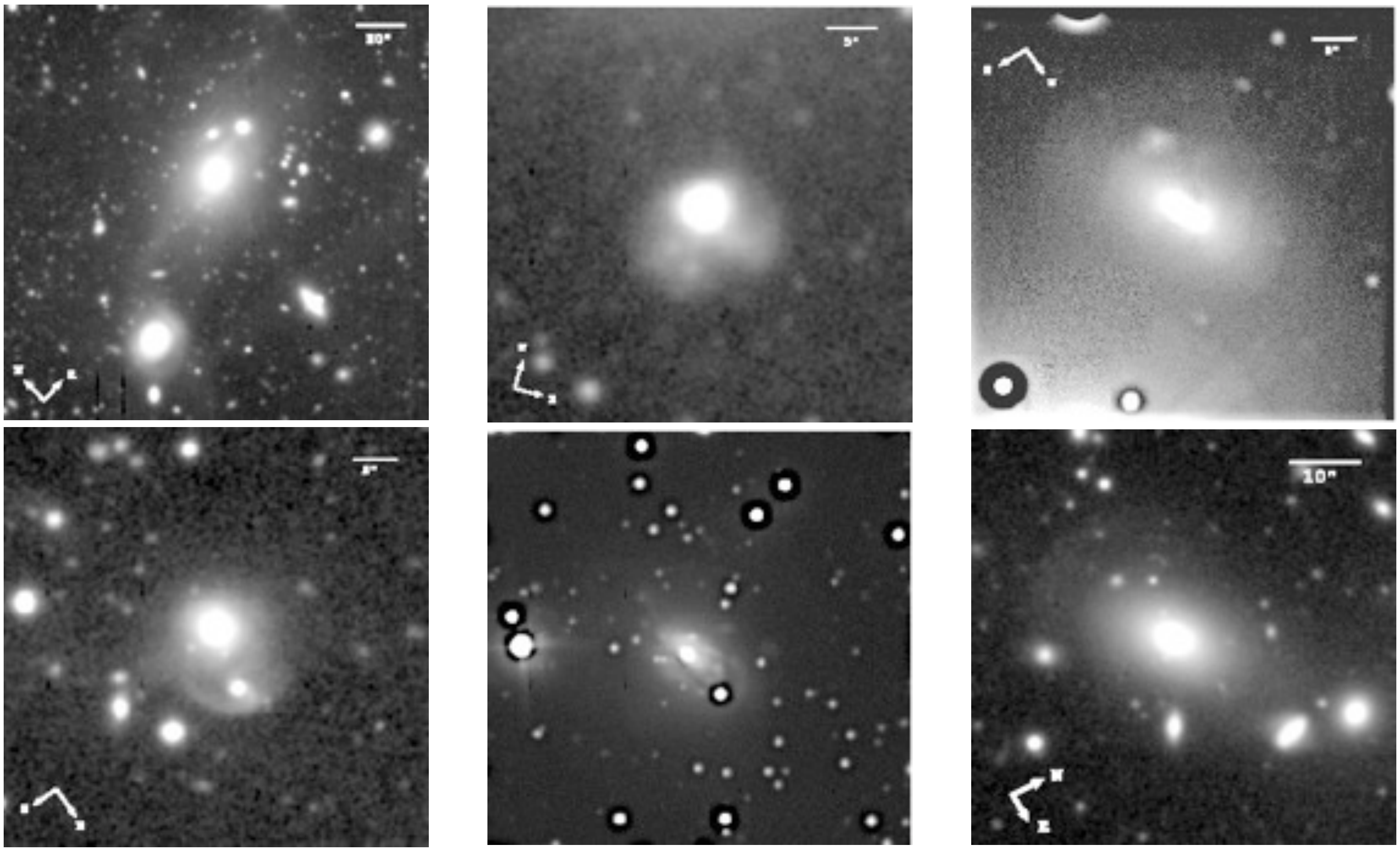
- Resolution: the resolutions of most of the simulations relatively poor (~100pc); they do not cover key aspects of AGN physics
- The proportion of the available accretion energy that goes into the quasar ouflows (the "coupling efficiency": $\sim 0.005 - 0.1 P_{acc}$)

AGN feedback: key questions

- How and when are AGN triggered in the course of galaxy evolution?
- Are AGN and starbursts always triggered concurrently?
- What is the observational evidence for AGN-induced outflows?
- How energetically significant are AGN-induced outflows?

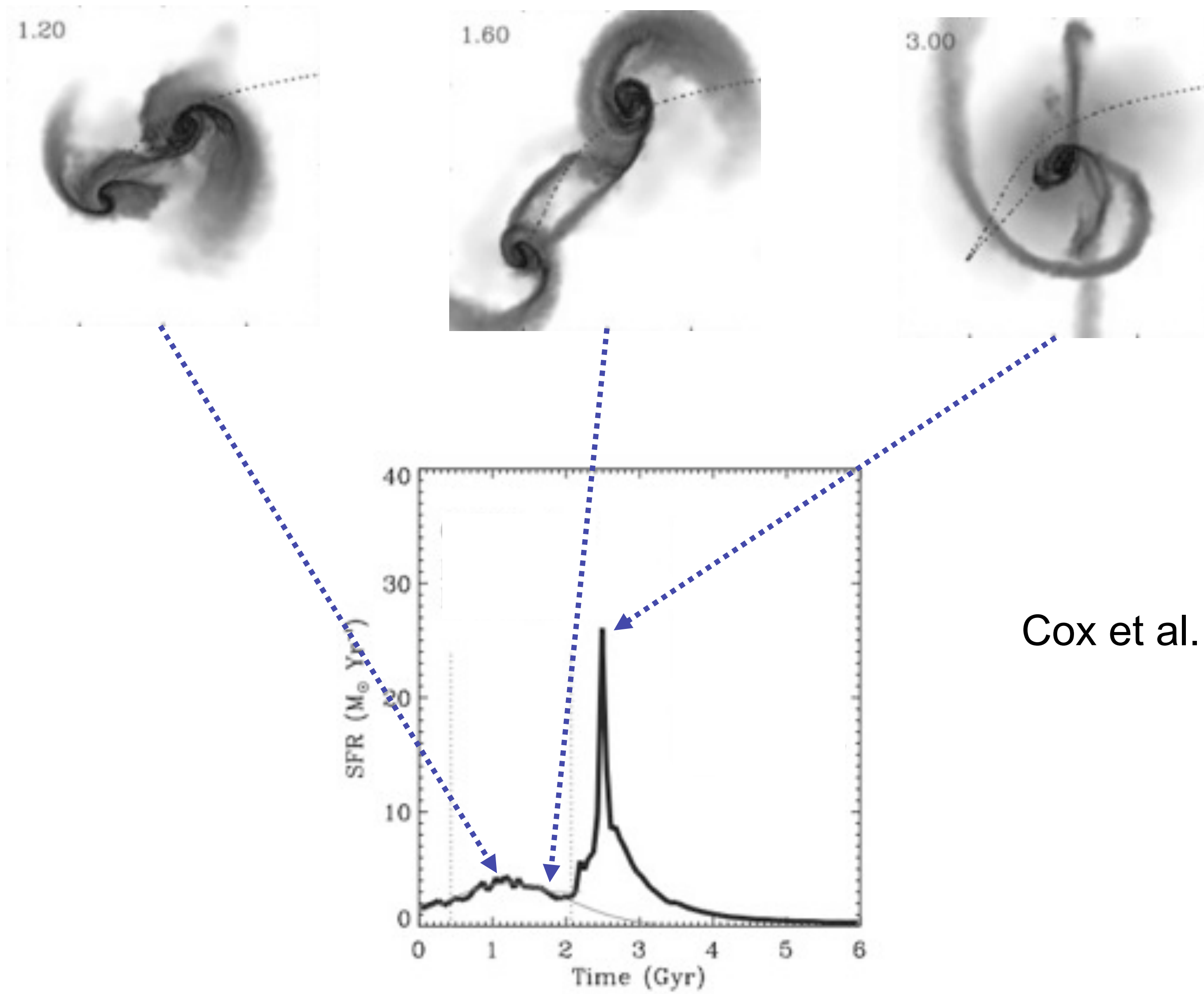
Triggering AGN: how and when?

Deep Gemini imaging of the 2Jy sample



The diversity of morphologies observed in powerful radio galaxies suggests that AGN can be triggered at a variety of stages in galaxy interactions (Ramos Almeida et al. 2010).

Triggering starbursts in major galaxy mergers



Cox et al. (2008)

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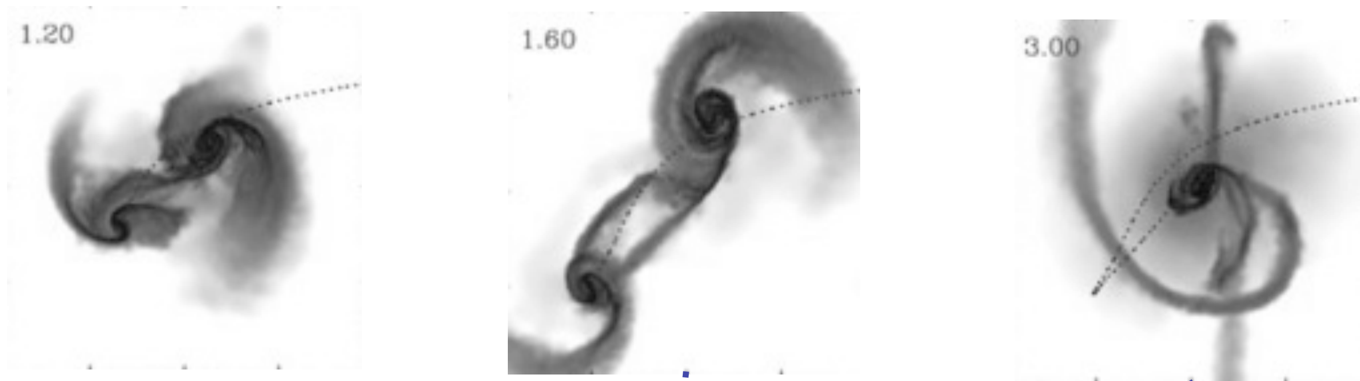

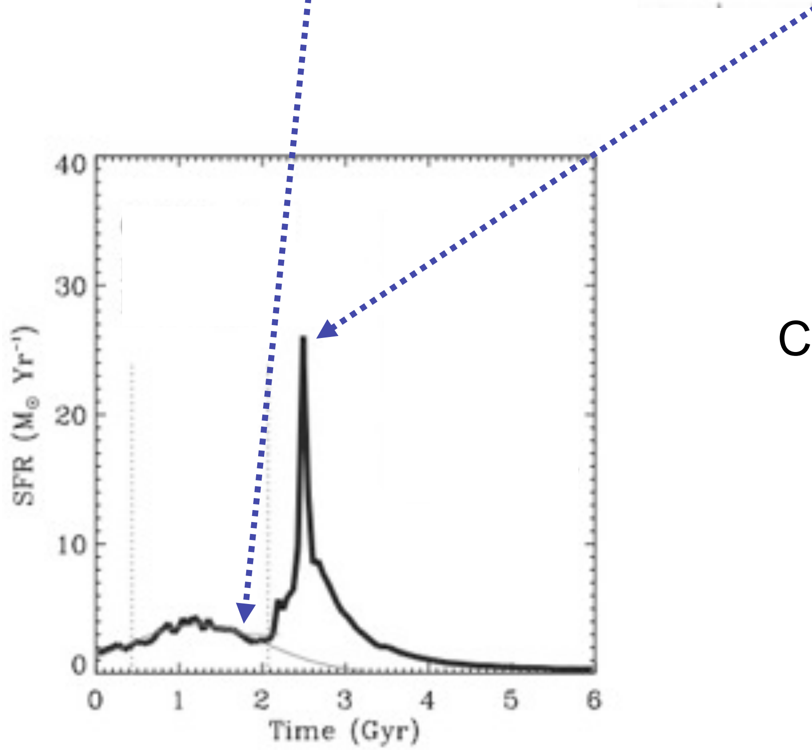

Cox et al. (2008)

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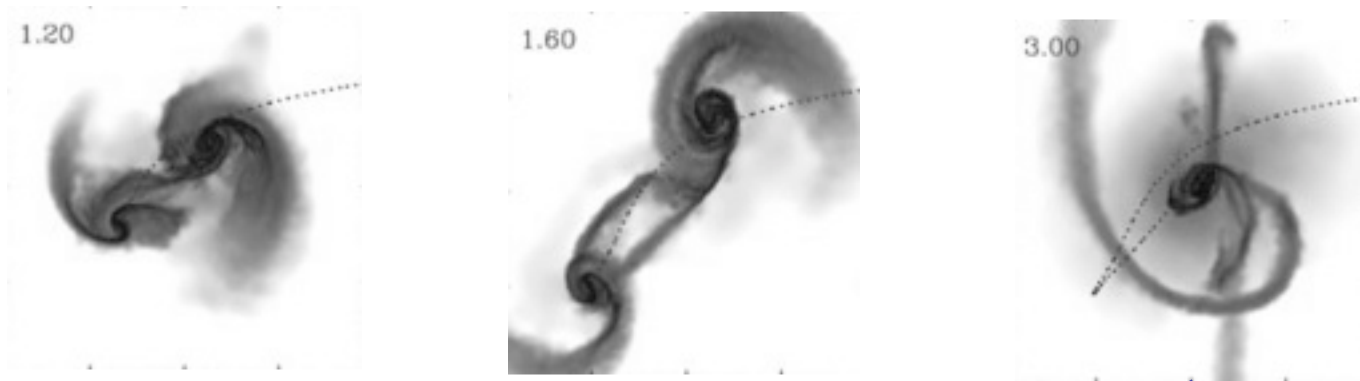

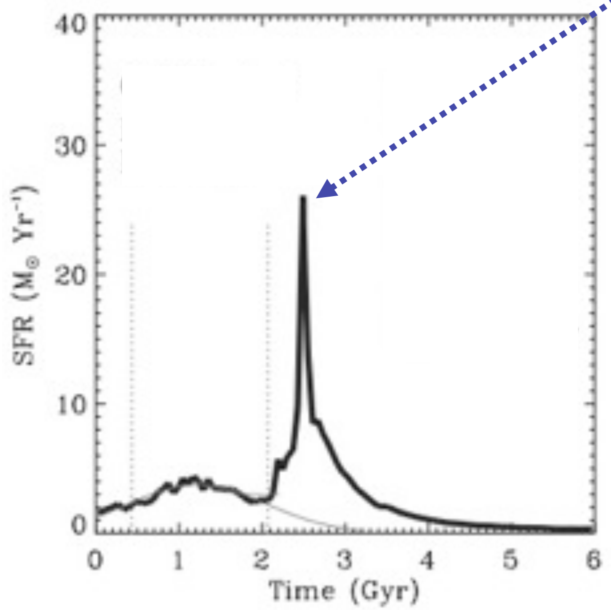

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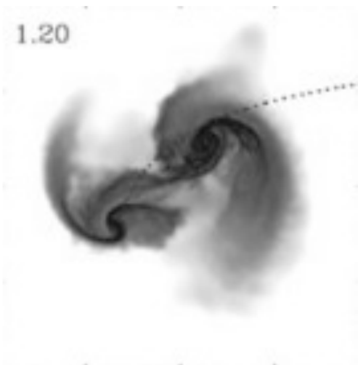
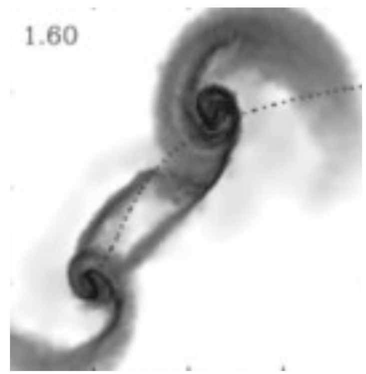
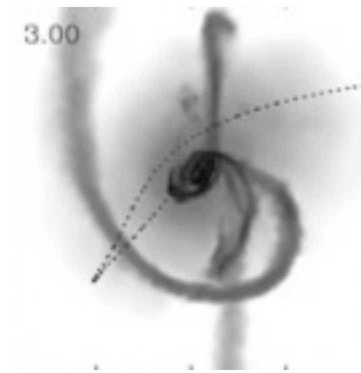
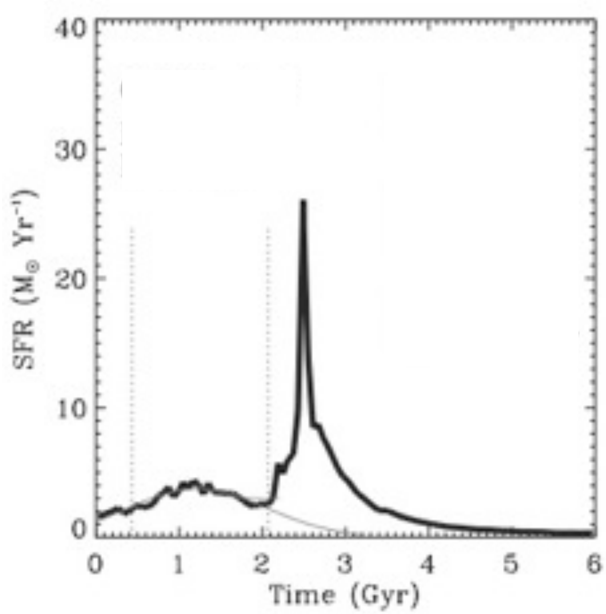
Triggering starbursts in major galaxy mergers









Cox et al. (2008)

Starbursts in radio galaxies: occurrence

- Starburst rate from optical spectroscopy:
  - 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)
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- Far-IR continuum excess+MFIR colours+PAH:
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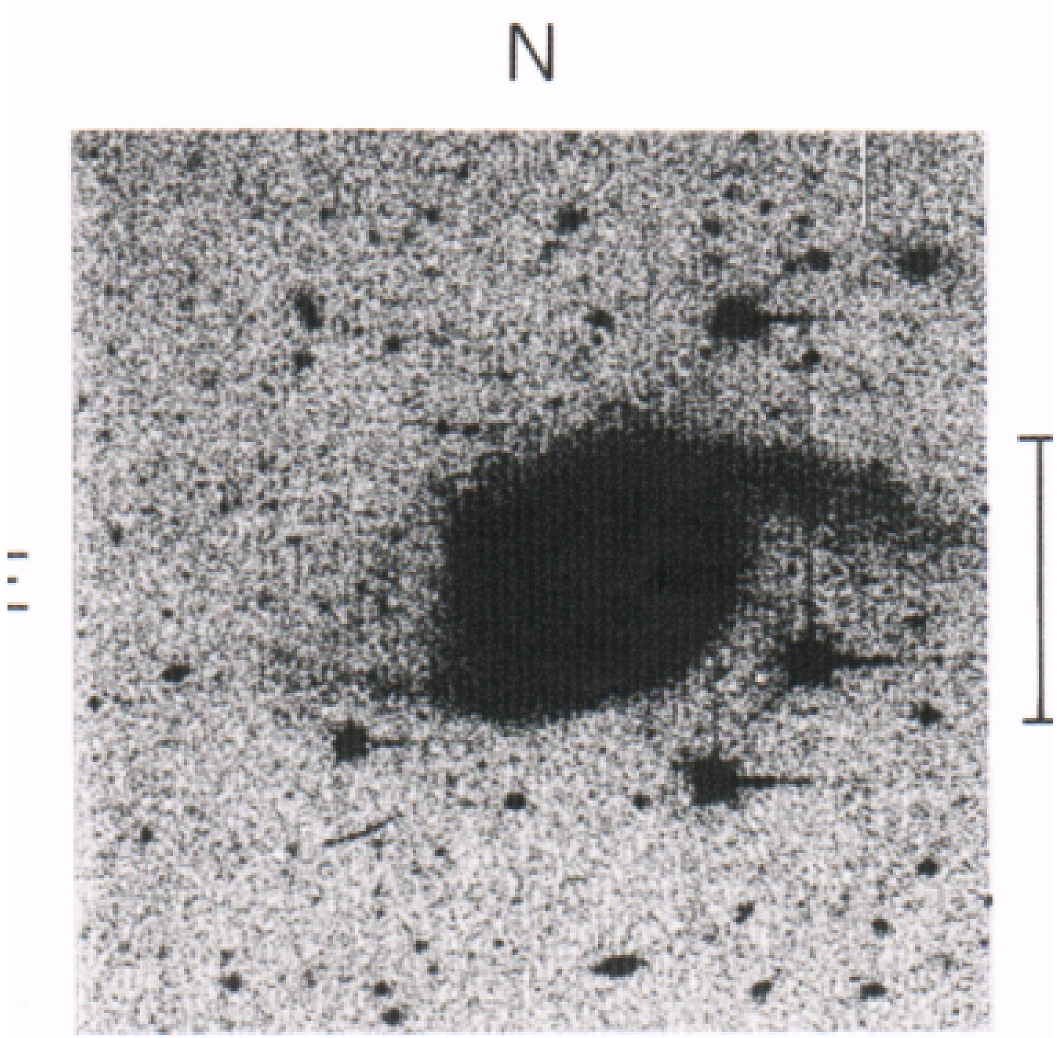
The lack of major starburst components in the majority of powerful radio galaxies (> 65%) demonstrates that, while the activity may be triggered in galaxy interactions, in most cases it is not triggered at the peaks of major, gas-rich mergers.

The post-starburst radio galaxy 3C305

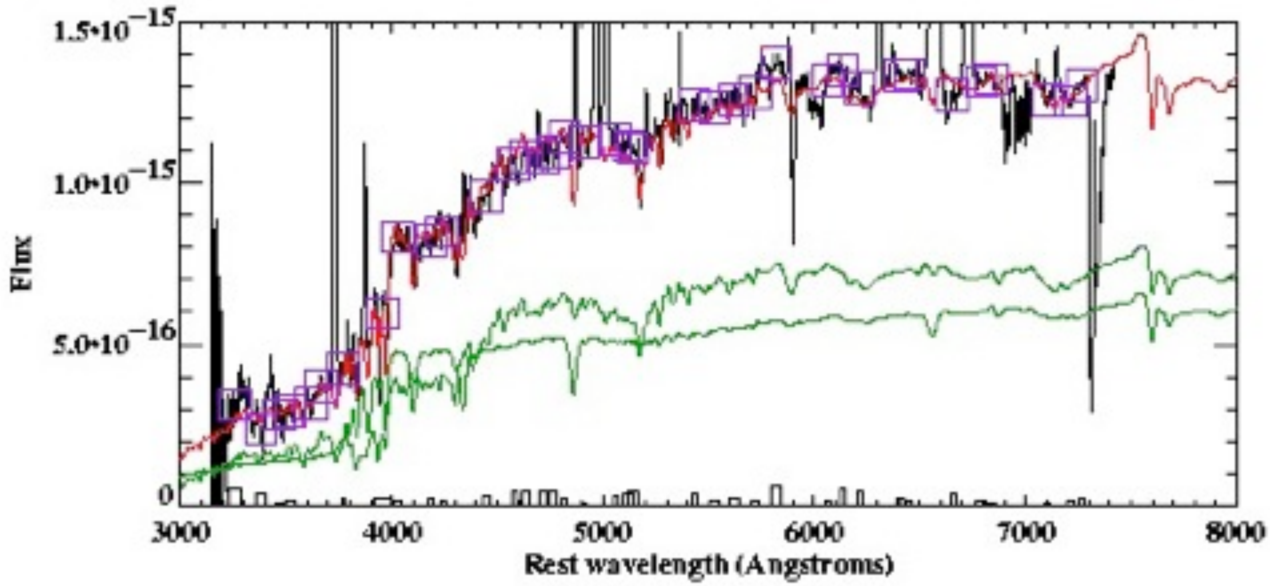


3C 305

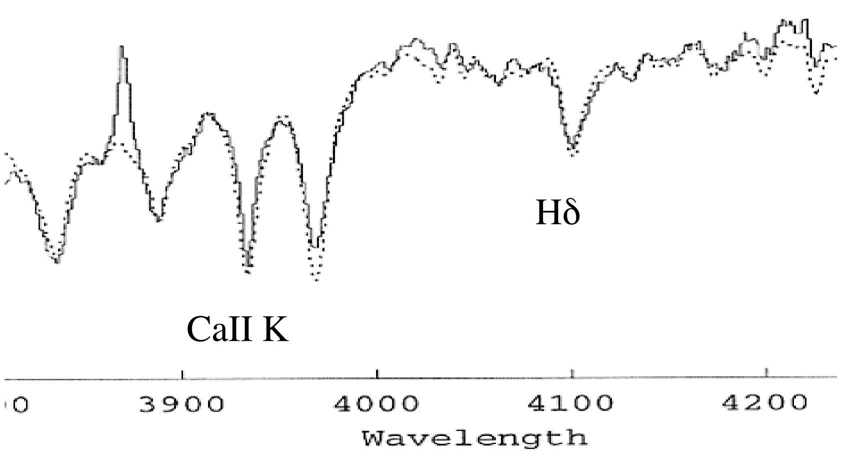
The post-starburst radio galaxy 3C305

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

The post-starburst radio galaxy 3C305



WHT/ISIS

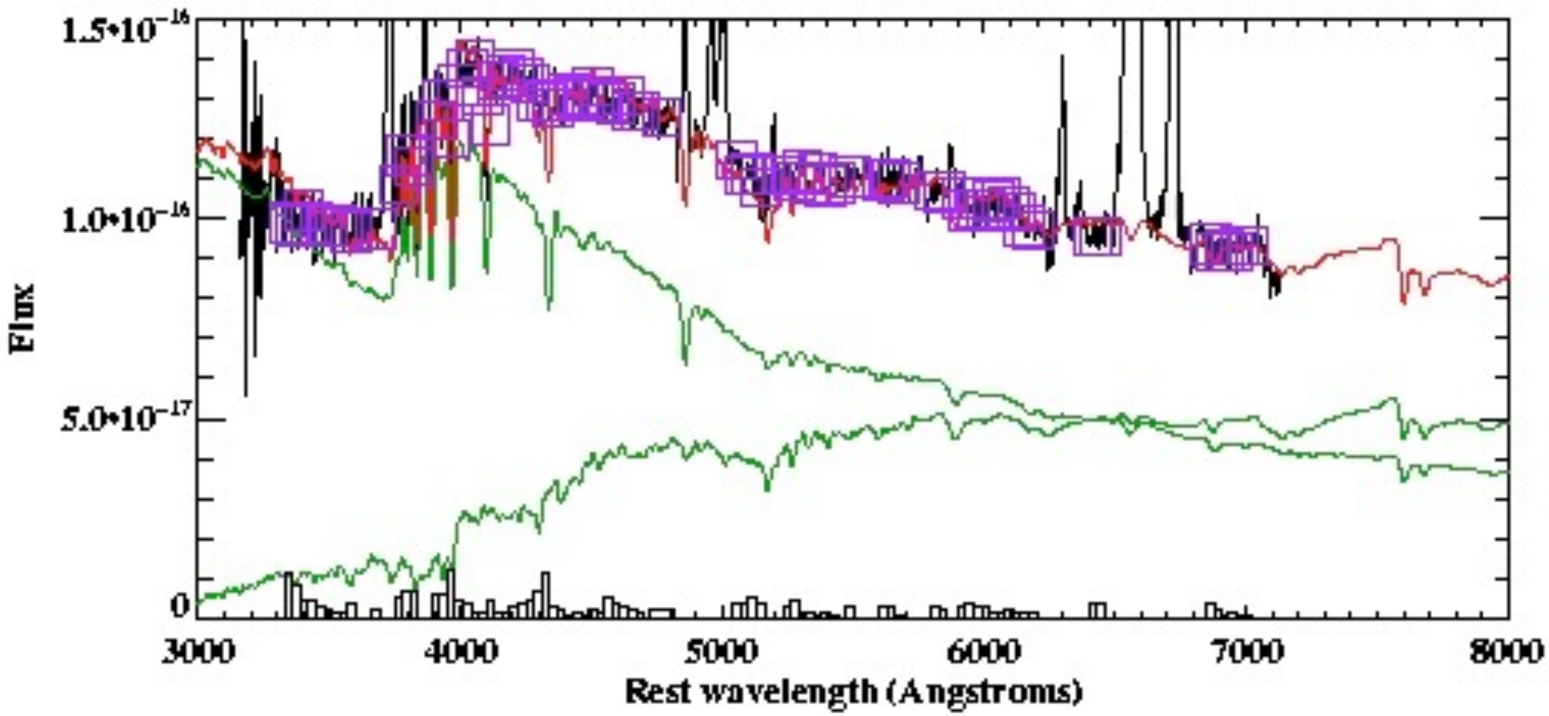


Starburst Properties
Age: 0.4 - 0.9 Gyr
E(B-V)=0.4 - 0.8 mag
Mass:1.5+/-0.5x10^{10} M_{sun}
(16 - 40% of total stellar mass)

Bruzual & Charlot(1996) models
Salpeter IMF (0.1-125 M_{sun})

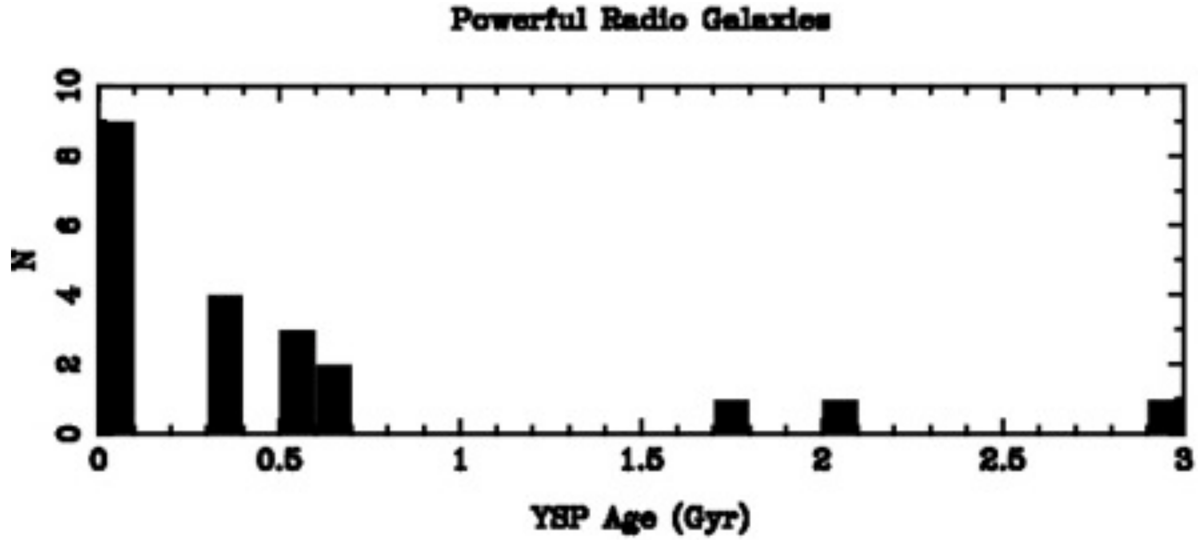
Starburst dominated objects: the ULIRG 3C459

3C459 (z=0.22) NTT+EMMI

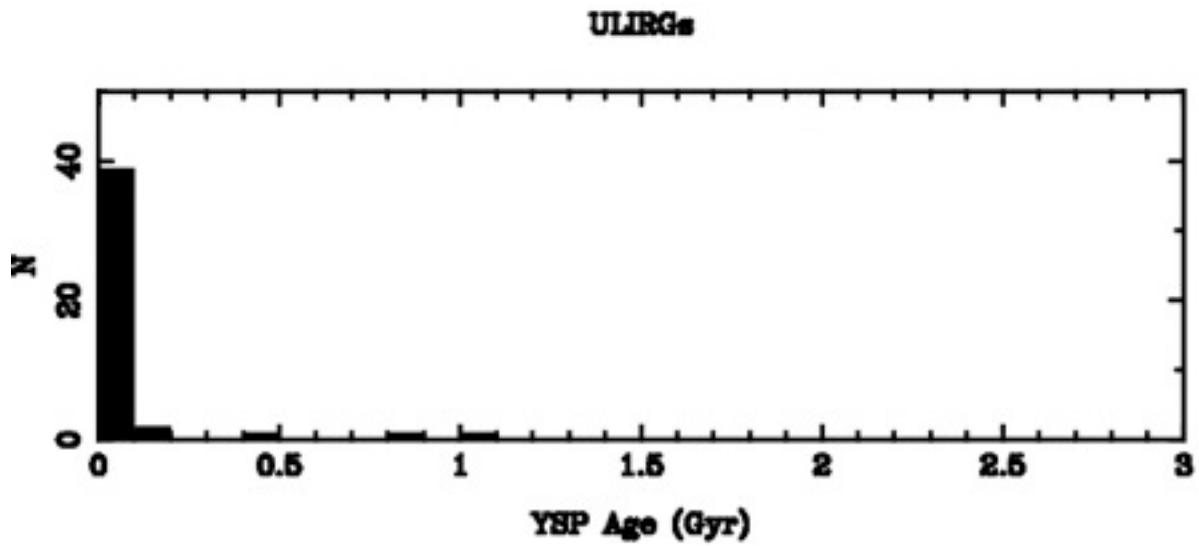


YSP Properties
Age: 0.05 Gyr
Mass:4x10^{9} M_{sun}
(>5% of total stellar mass in slit)

The Ages of the YSP in ULIRG and PRG

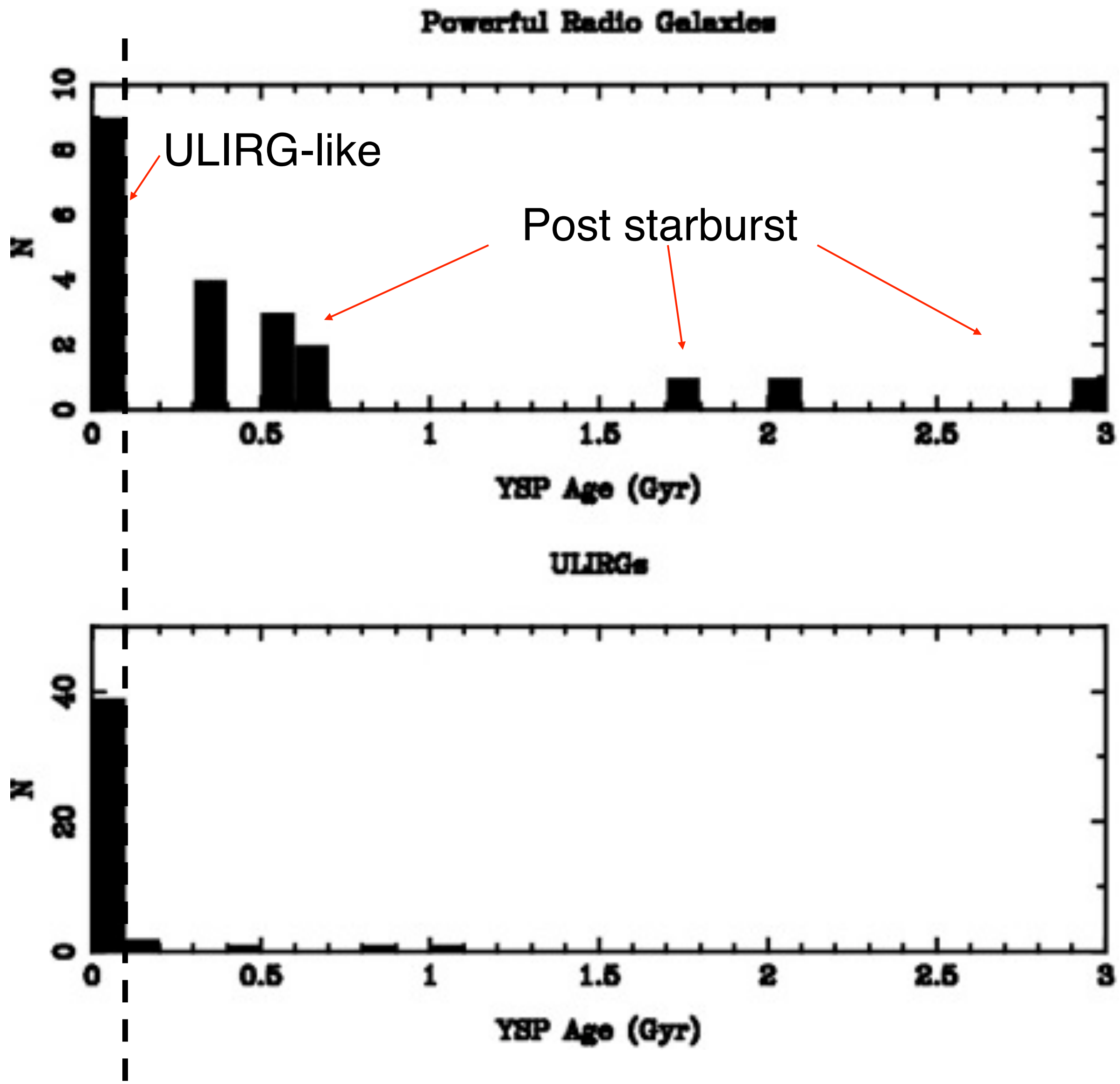


Tadhunter et al. (2005)
Holt et al. (2006,2007)
Wills et al. (2008)
Tadhunter et al. (2010)



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

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. (2010)

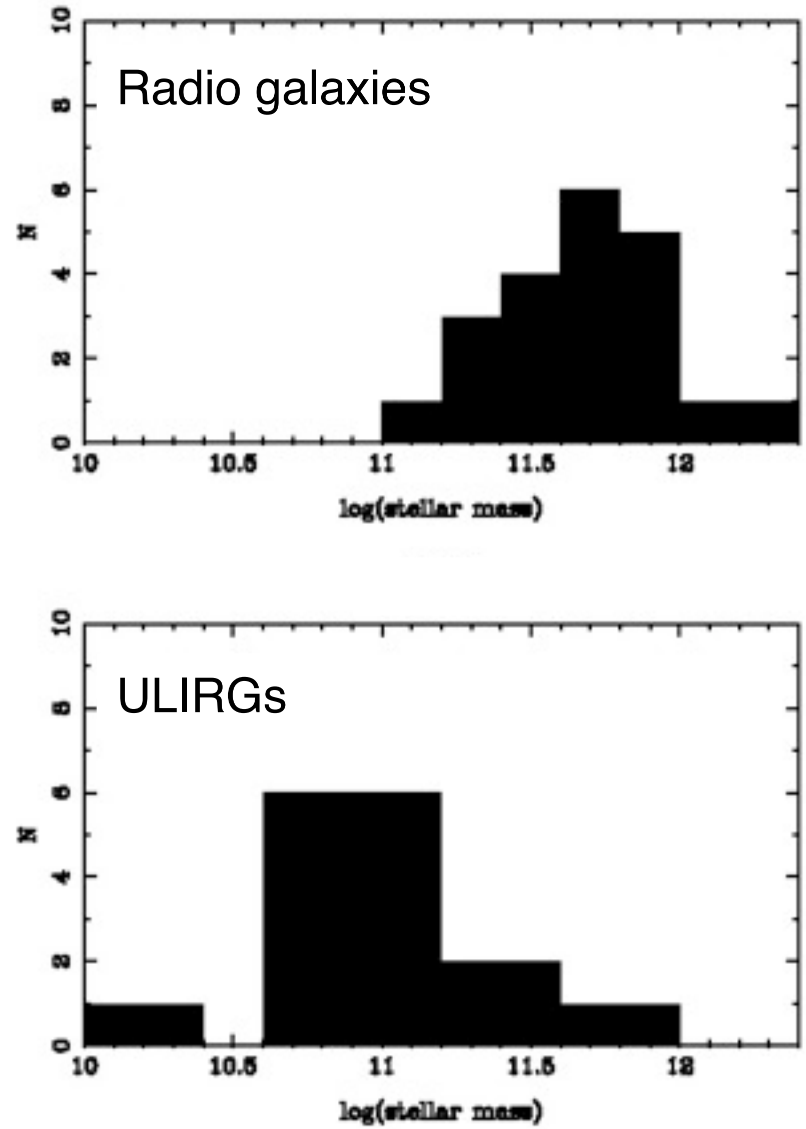
Rodriguez-Zaurin et al. (2007,2008,2009,2010)

Typical maximum age of radio source

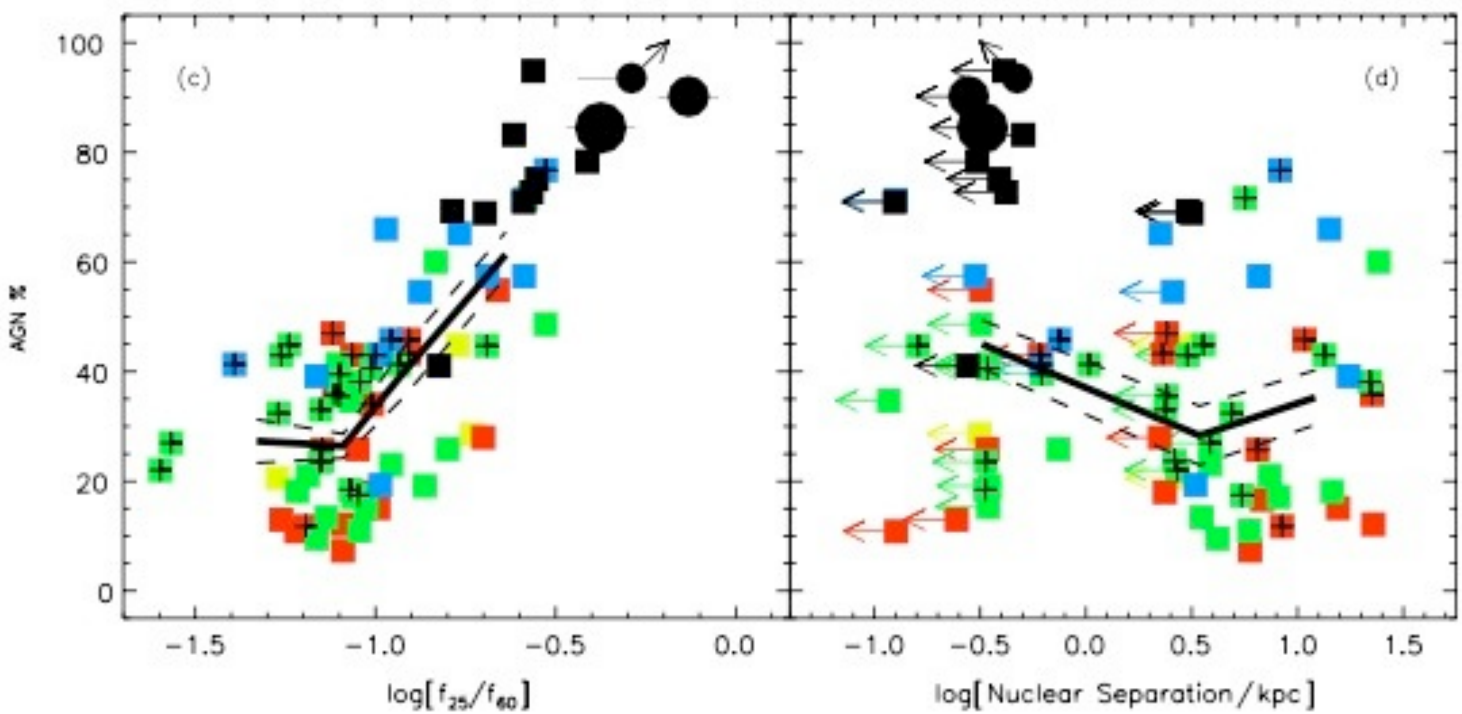
Stellar masses of starburst radio galaxies

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

(Masses based
an models that assume
a significant old stellar
population)



The AGN contribution in ULIRGs



Veilleux et al. (2009)

Despite being observed close to the peaks of major galaxy mergers, many ULIRGs do not show energetically dominant AGN components. This further suggests an intermittent gas supply.

Triggering radio-loud AGN: summary

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This diversity is likely to reflect the fact that sufficient fuel can be delivered to the nuclear regions at several stages during galaxy interactions of various types.

Feedback mechanisms

Powerful radio galaxies: energetics

- Radiation

Quasar luminosity: 10^{44} — 10^{47} erg s^{-1}
Luminosity integrated over lifetime: 10^{57} — 10^{62} erg

- Jets

Jet power: 10^{43} — 10^{47} erg s^{-1}
Jet power integrated over lifetime: 10^{57} — 10^{62} erg

- Winds

Total wind power: ~0.005 - 0.1P_{ac}?
Wind power over lifetime: 10^{56} — 10^{61} erg?

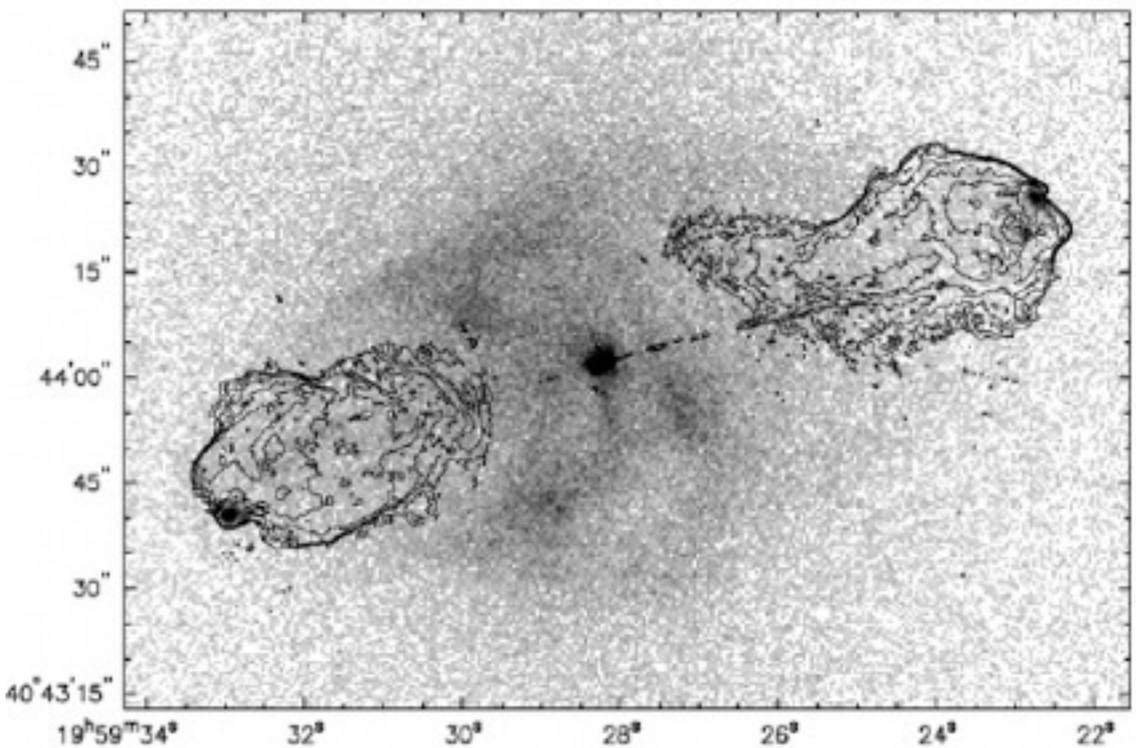
Comparison:
Luminosity of hot ISM in a cluster: 10^{44} — 10^{45} erg s^{-1}
Grav. binding energy of gas in spiral: 10^{58} — 10^{60} erg

Relativistic outflows (“radio mode”)

Cygnus A: impact of jets on hot ICM

Chandra X-ray image (Wilson et al. 2006)

Cygnus A: impact of jets on hot ICM



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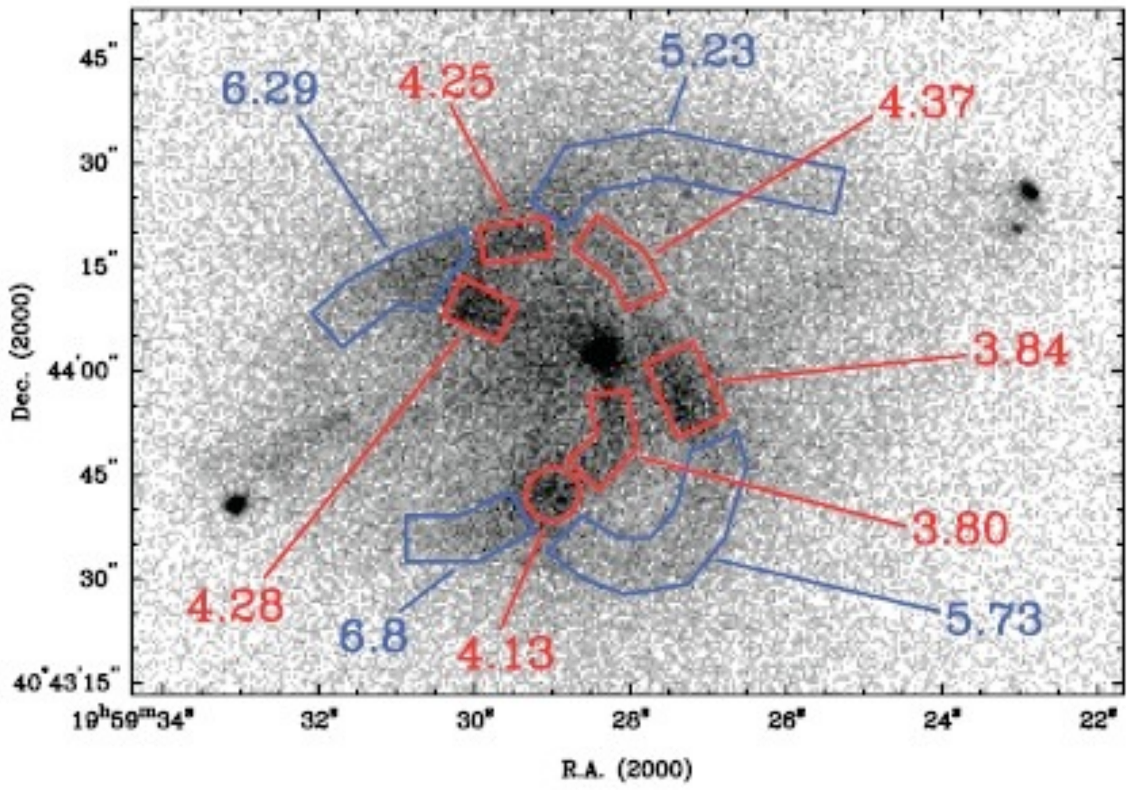

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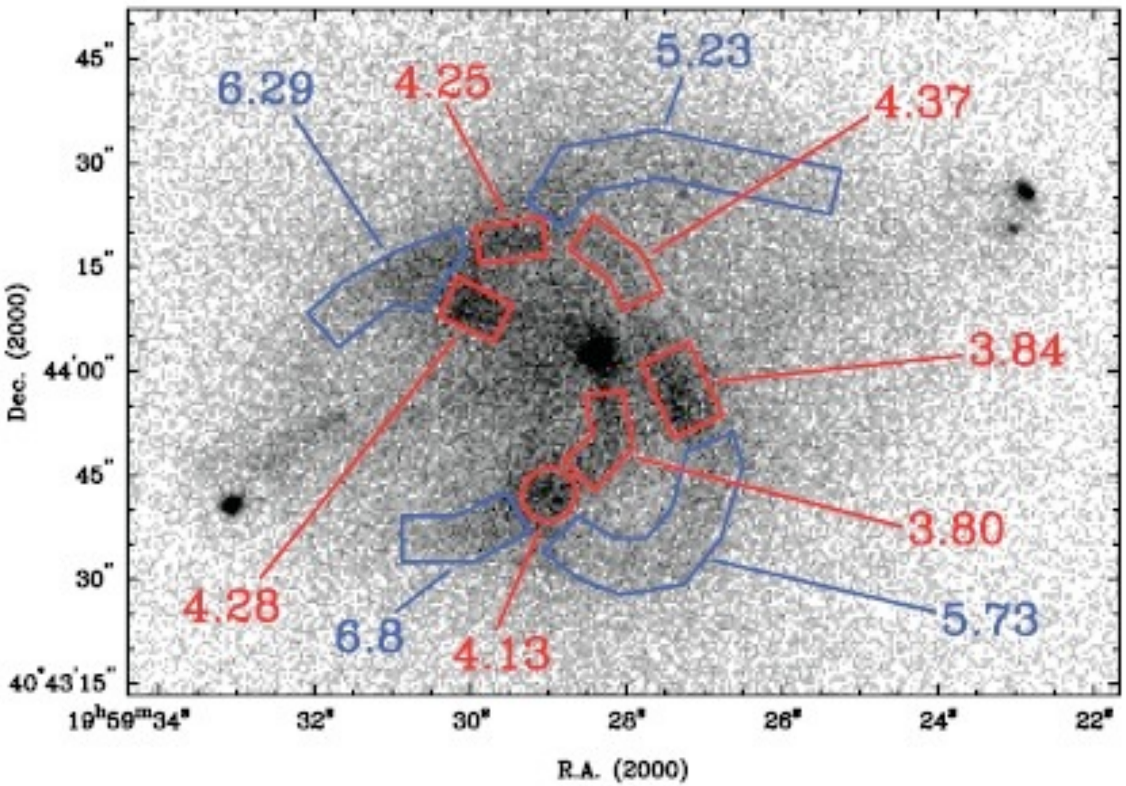
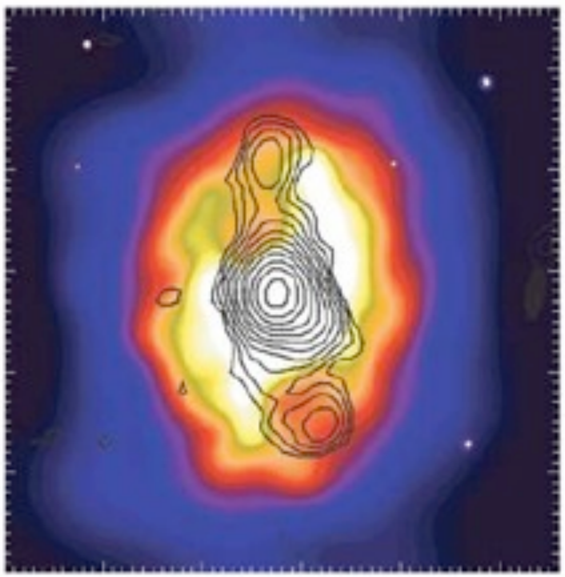


Chandra X-ray image (Wilson et al. 2006)

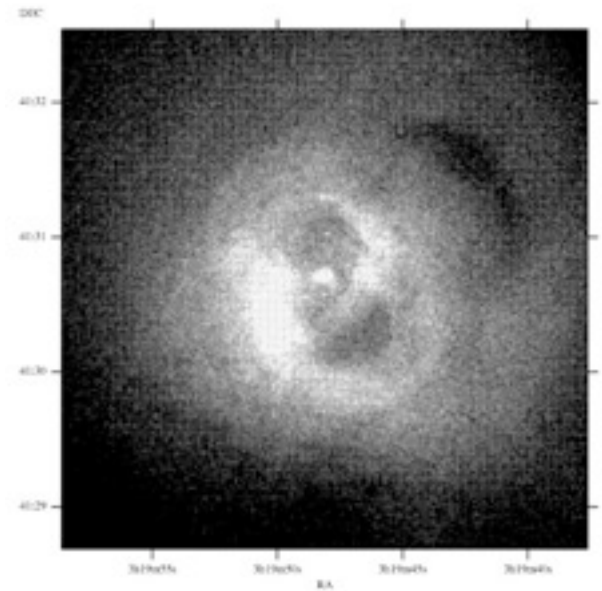
$$\dot{M} \sim 10^4 M_{sun} yr^{-1} \quad \dot{E} \sim 4 \times 10^{45} erg/s$$

$$\dot{E}/L_{edd} \sim 10^{-2}$$

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



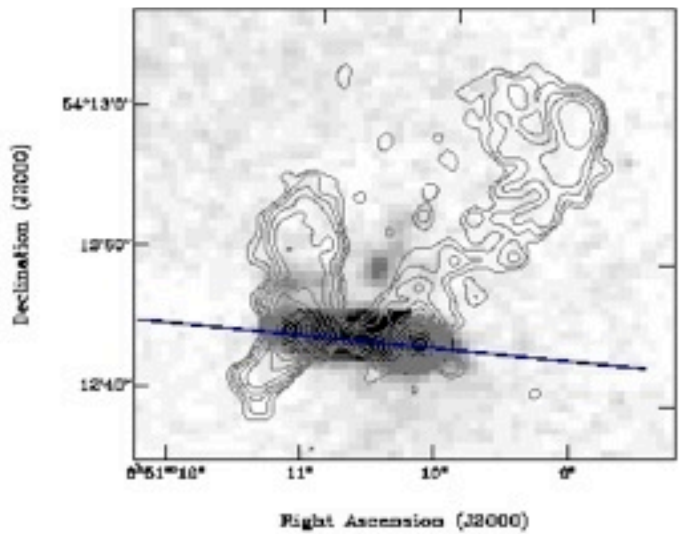
MS0735.6+7421
McNamara et al. (2005)



Perseus A
Fabian et al. (2003)

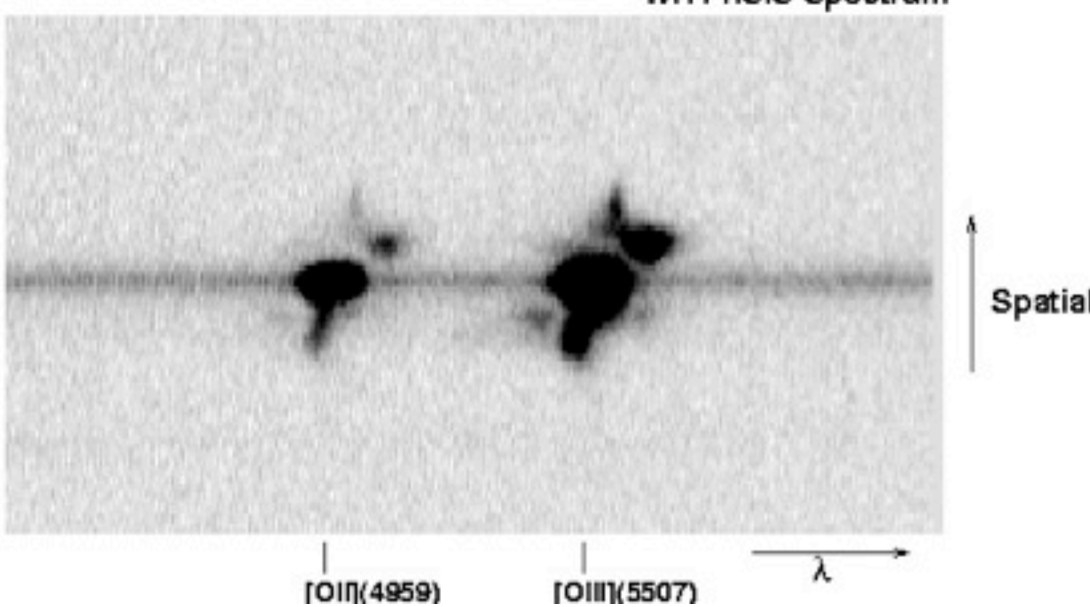
Energies associated with the X-ray cavities and shocks: ~10^{59} - 10^{62} erg

A massive outflow associated with the jet-cloud interactions in 3C171 (z=0.231)



Halpha TTF Image with 6cm Radio Overlayed

WHT+ISIS Spectrum



Clarke et al. 1998
WHT+ISIS

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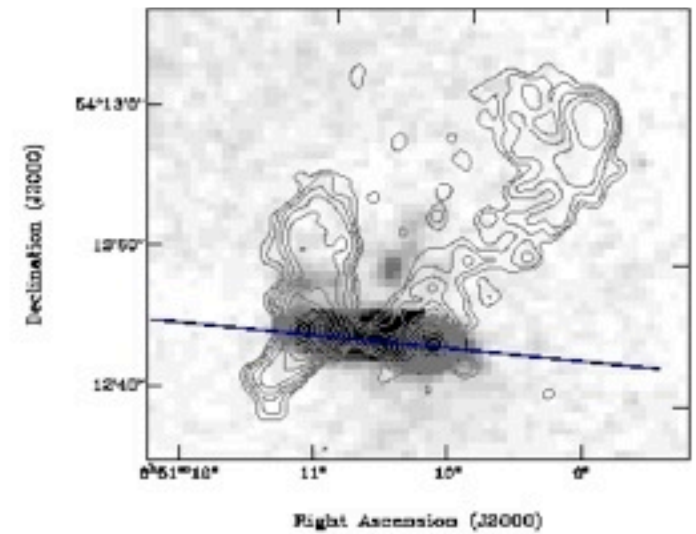


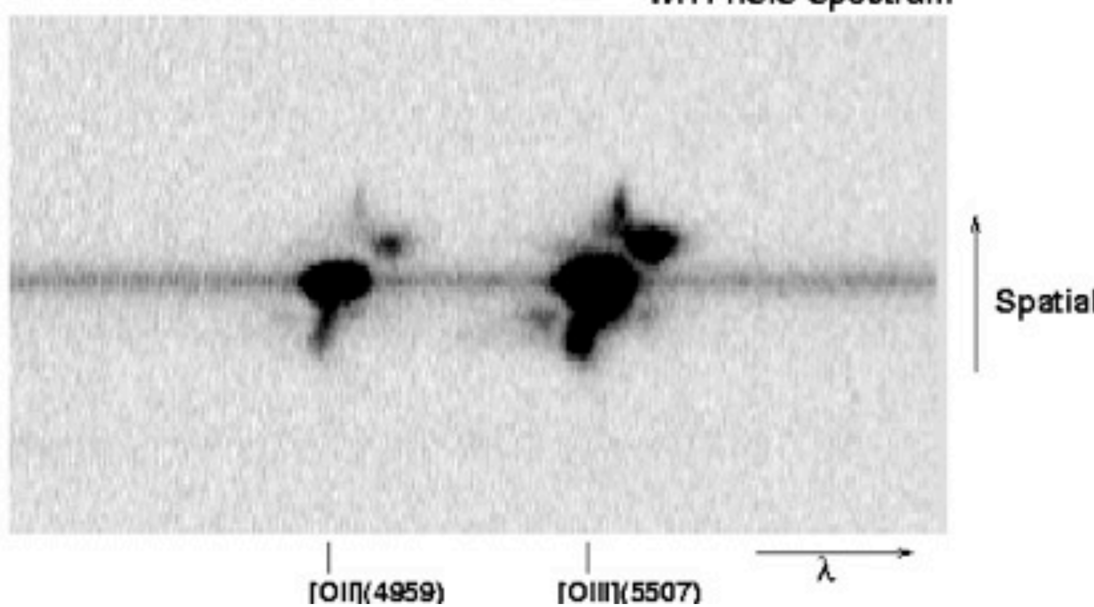
Halpha TTF Image with 6cm Radio Overlayed

$$\dot{M} \sim 500 - 1000 M_{sun} yr^{-1}$$

$$\dot{E} \sim 10^{44} erg/s$$

$$\dot{E}/L_{edd} \sim 10^{-3}$$

WHT+ISIS Spectrum



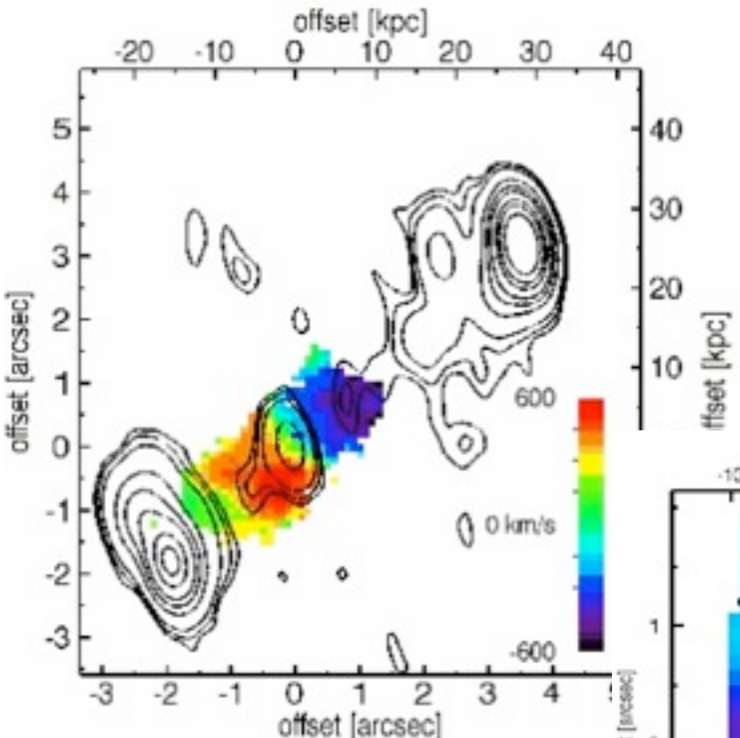
Clarke et al. 1998
WHT+ISIS

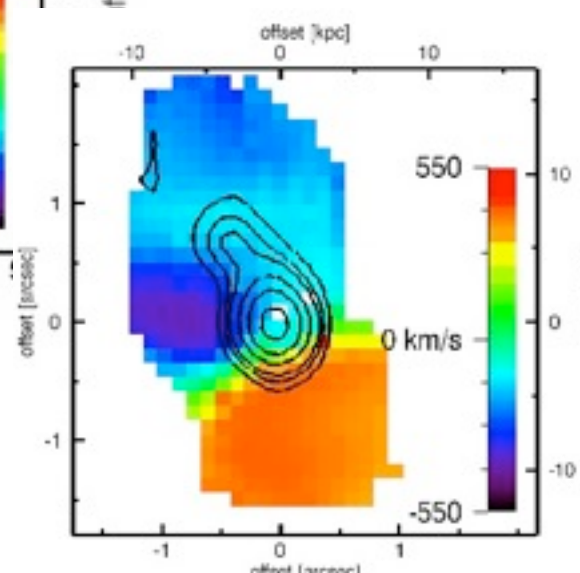
Outflows in high redshift radio galaxies (z~2)

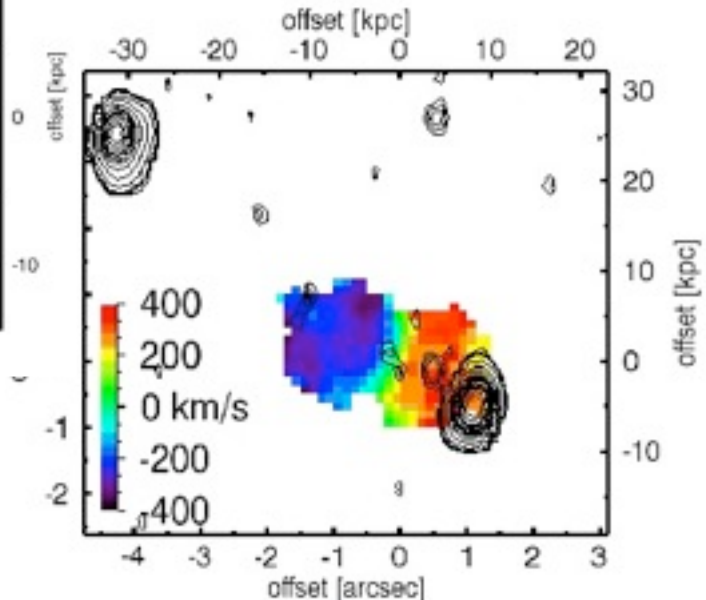
$$300 < \dot{M} < 1000\ M_{sun} yr^{-1}$$

$$10^{44} < \dot{E} < 10^{46}\ erg\, s^{-1}$$

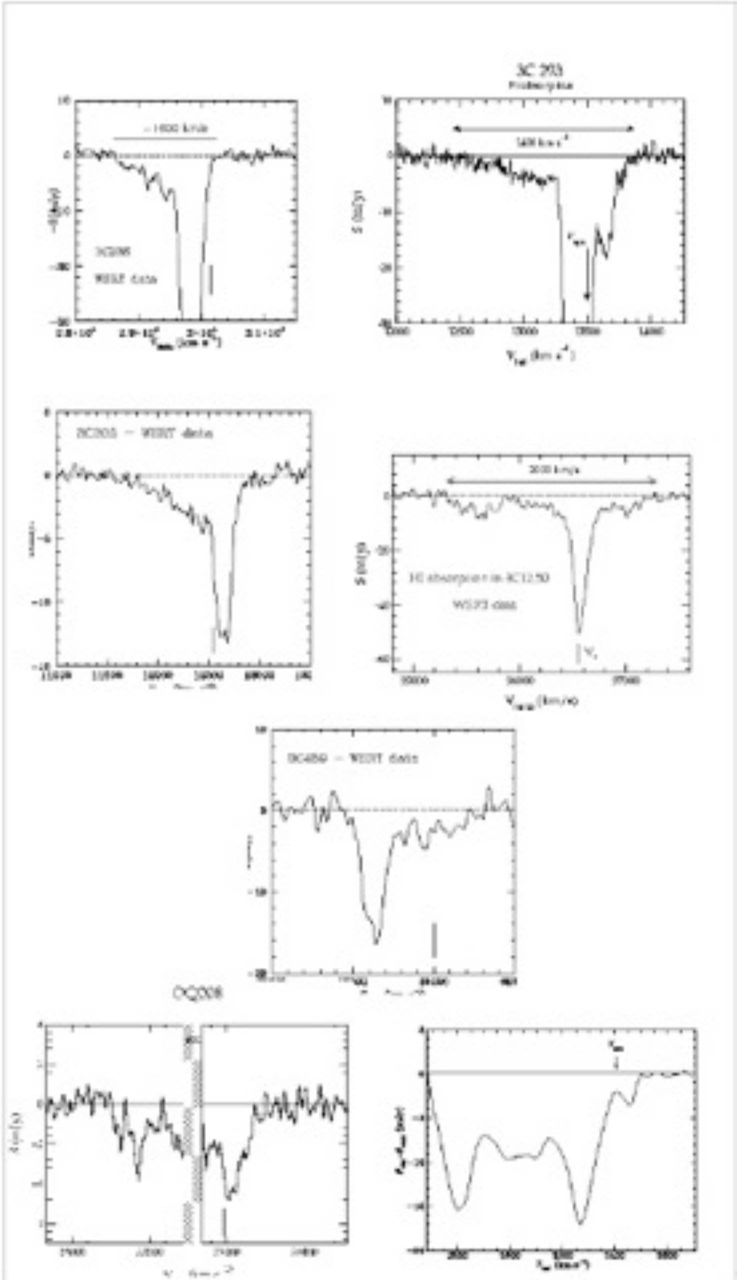
$$0.001 < \dot{E}/L_{edd} < 0.1$$







Nesvadba et al. (2006, 2008)



HI (21cm) Outflows in Nearby Radio Galaxies

- Broad blueshifted wings extending up to -2,000 km/s

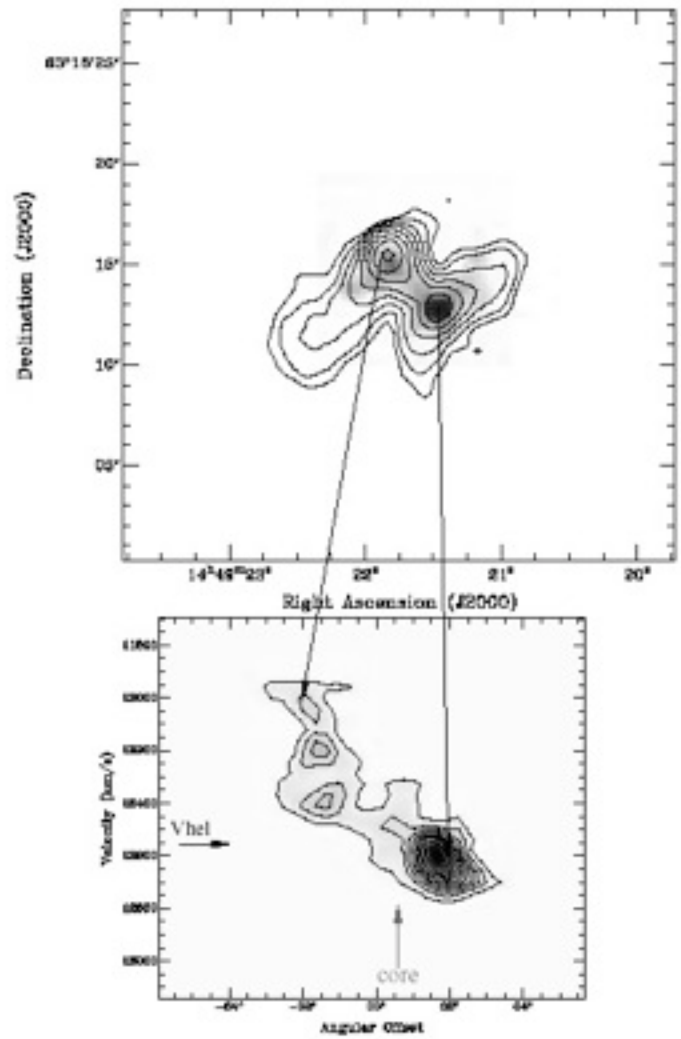
- Significant mass outflow rates:

$$\dot{M} \sim 1.2 - 56 M_{sun} yr^{-1}$$

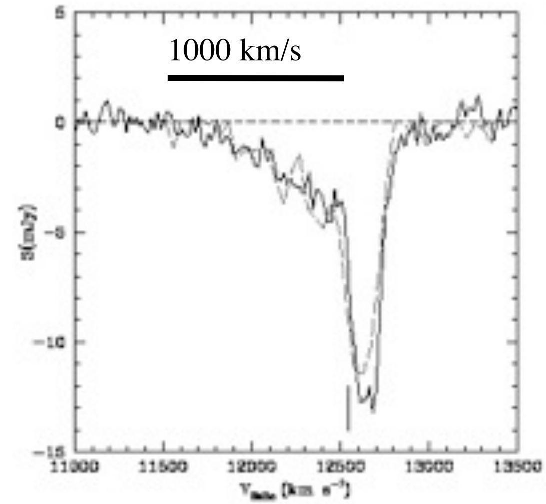
- There is clear observational evidence that the neutral outflows are jet-driven.

Morganti et al. (2005b), WRST with broadband capability

Fast HI 21cm outflow in 3C305: evidence for jet acceleration



VLA HI Absorption Map



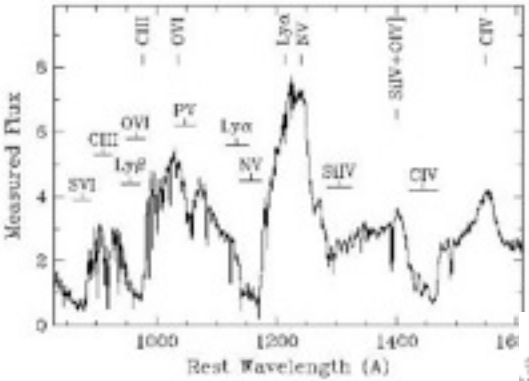
WRST - Integrated Profile

Morganti et al. (2005a), WRST+VLA

Near-nuclear outflows (“quasar mode”)

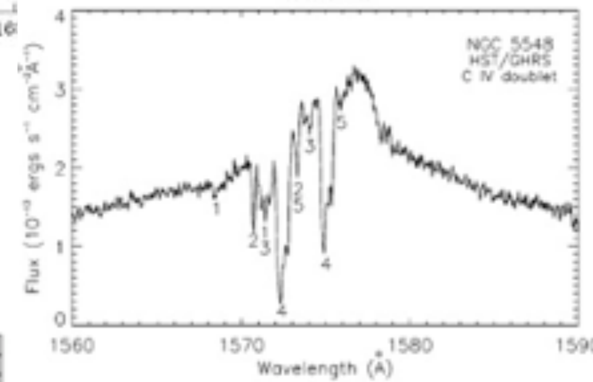
The observational evidence for near-nuclear outflows in AGN

Clear evidence for outflows in a large fraction of the local AGN population



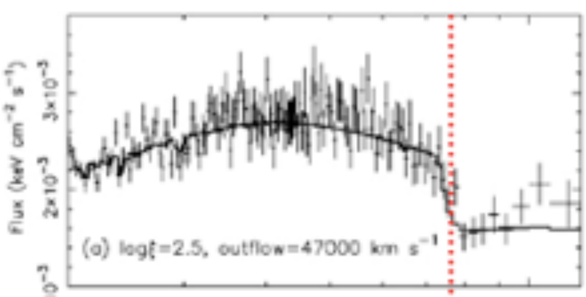
Broad absorption line systems (BALs)

$5 \times 10^3 < \Delta V < 3 \times 10^4 \; km\, s^{-1}$



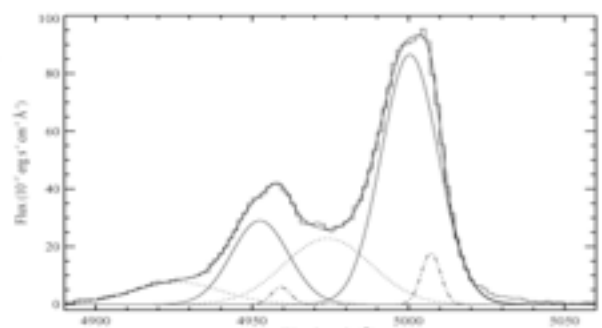
Blueshifted narrow absorption lines (UV/X-ray)

$100 < \Delta V < 2{,}000 \; km\, s^{-1}$



High velocity absorption edges (X-ray)

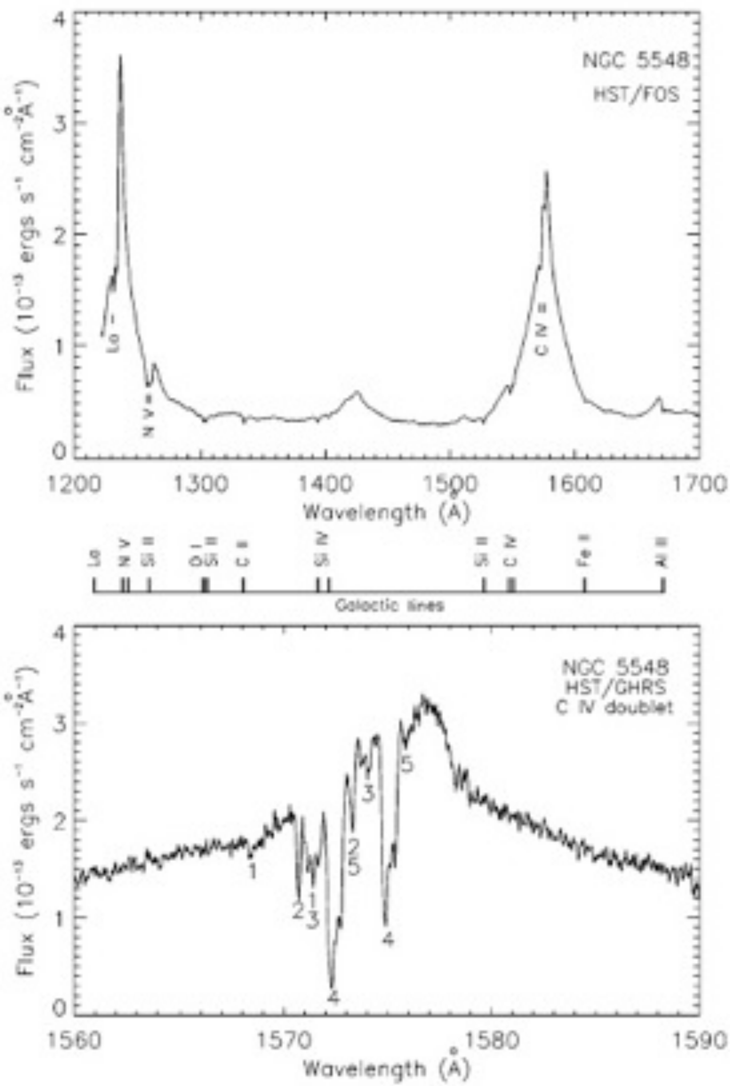
$\Delta V > 15{,}000 \; km\, s^{-1}$



Blueshifted narrow emission lines (optical/IR)

$100 < \Delta V < 2{,}000 \; km\, s^{-1}$

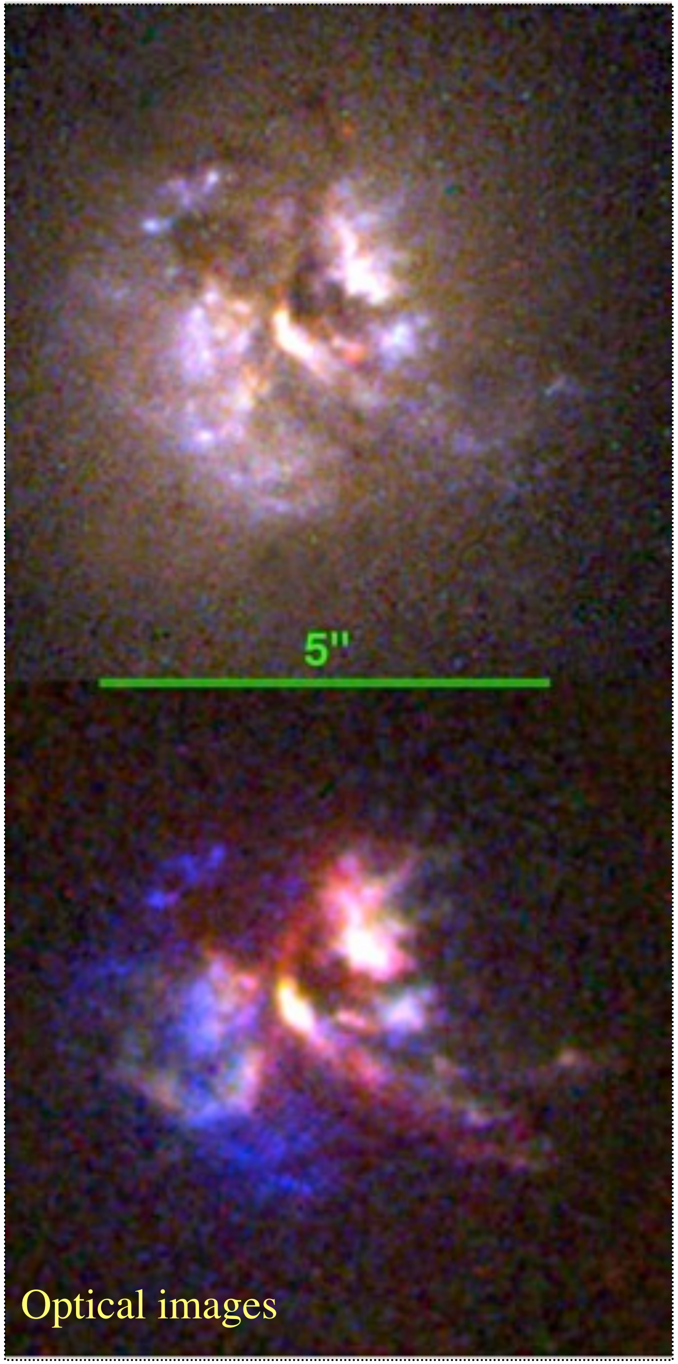
Narrow absorption line systems in AGN



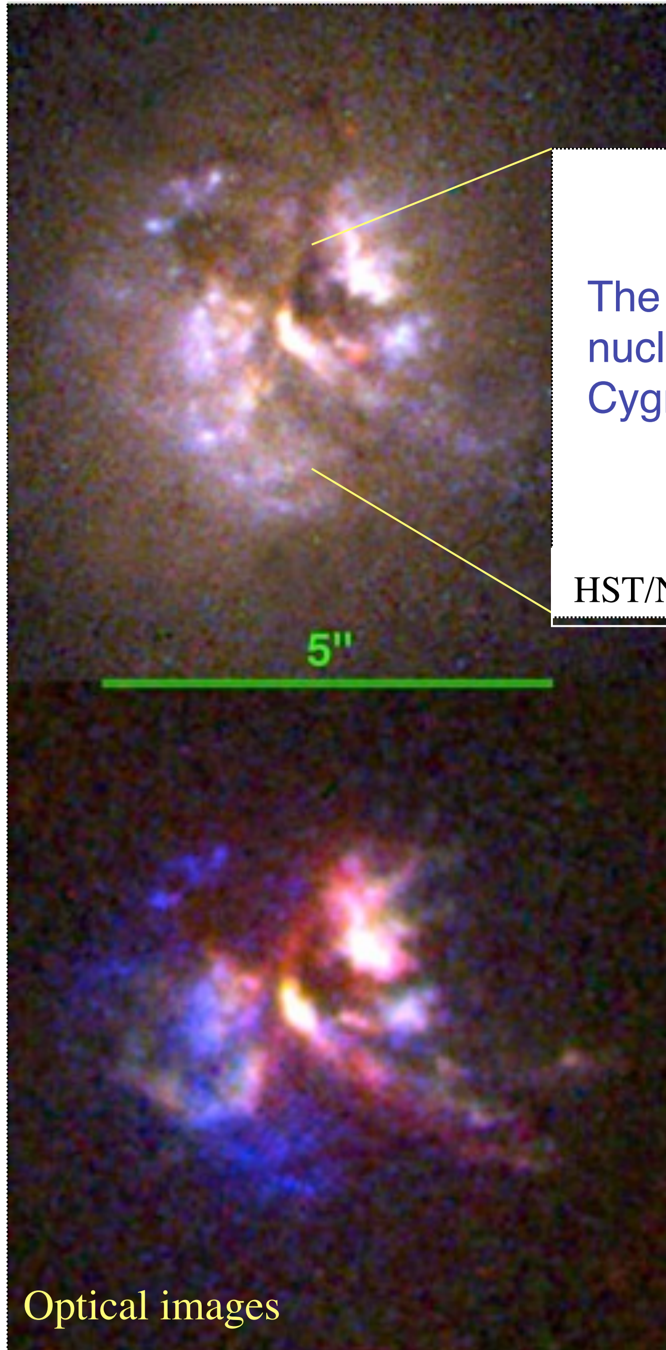
- Detected in UV/X-ray spectra of ~60% of nearby type 1 AGN
- Absorbing gas has a high ionization state
- Absorption features strongly blueshifted ($-2100 < \Delta V < 0$ km s^{-1})
  ➔ high ionization *outflows* close to the central AGN
- Radial scale: ~1 - 25pc
- Mass outflow rates relatively modest: $\dot{M} < 1\ M_{sun} yr^{-1}$
  (but large uncertainties in radii, geometries, physical conditions of absorption line systems)

e.g. Crenshaw et al. (2003)

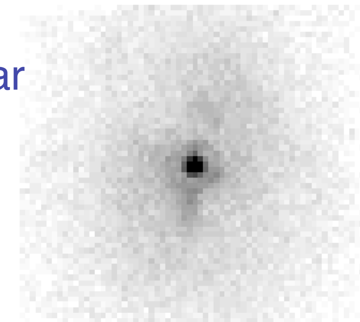
Cygnus A viewed by HST



Cygnus A viewed by HST



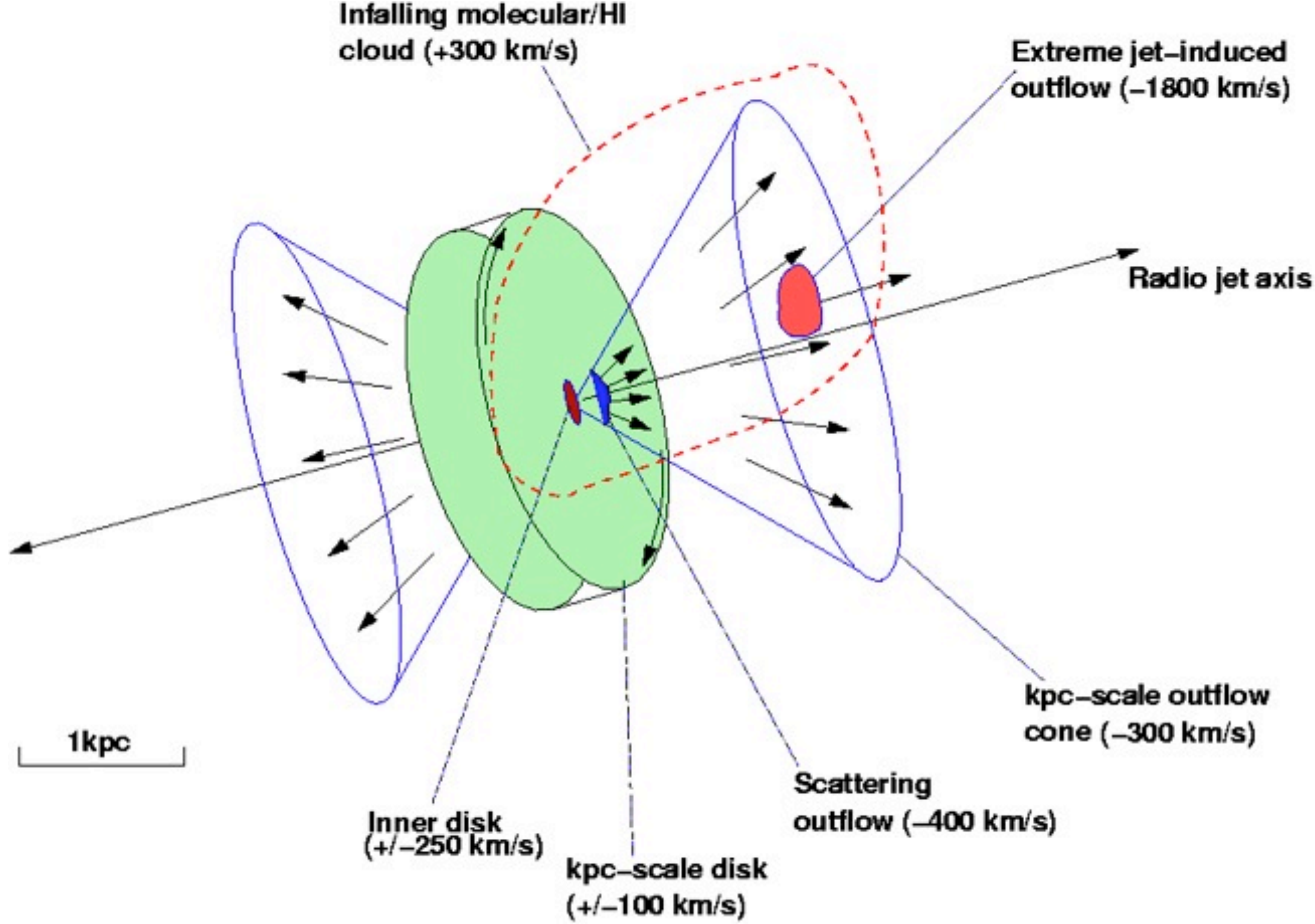
The quasar nucleus in Cygnus A



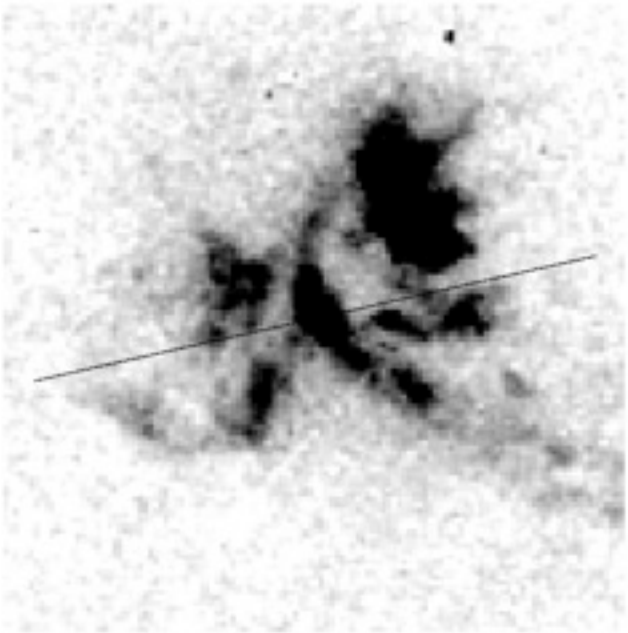
HST/NICMOS infrared 2.2μm image

Tadhunter et al. (1999)

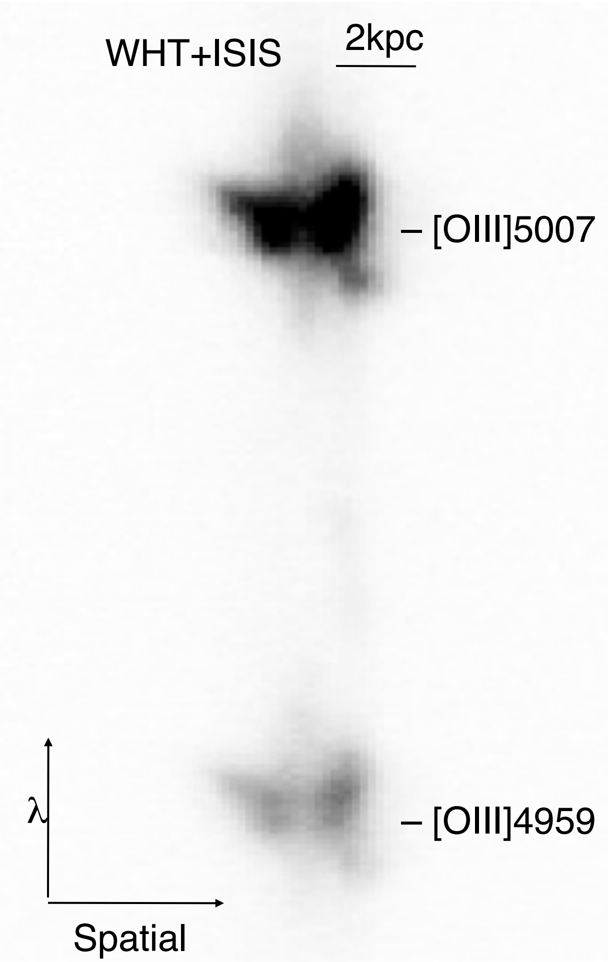
Kinematic components in Cygnus A



Outflows on a 1-3kpc scale in Cygnus A

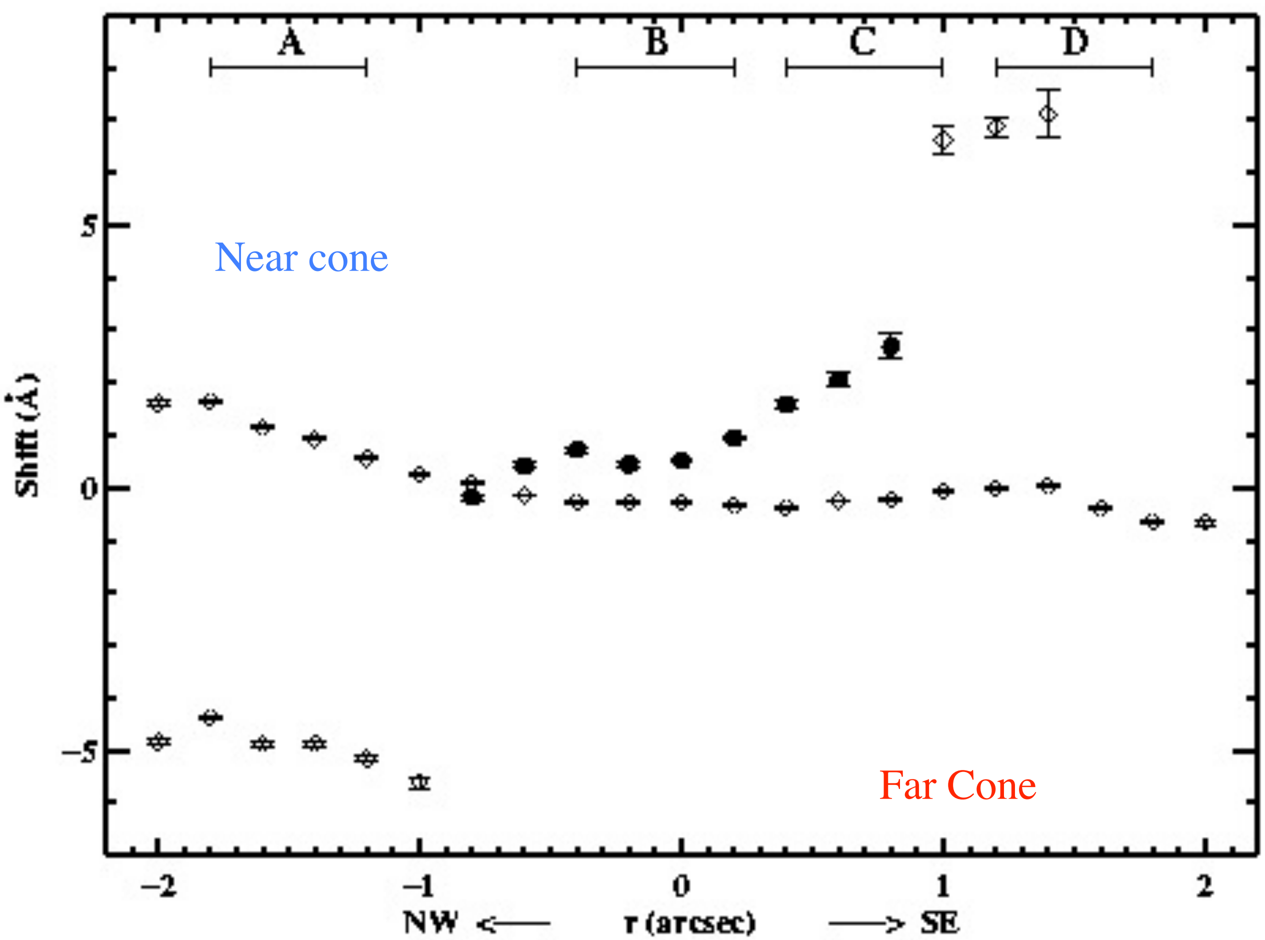


HST emission line image ([OIII])
Jackson et al. 1998



Taylor et al. (2003)

Outflows on a 1-3kpc scale in Cygnus A



Taylor et al. (2003)

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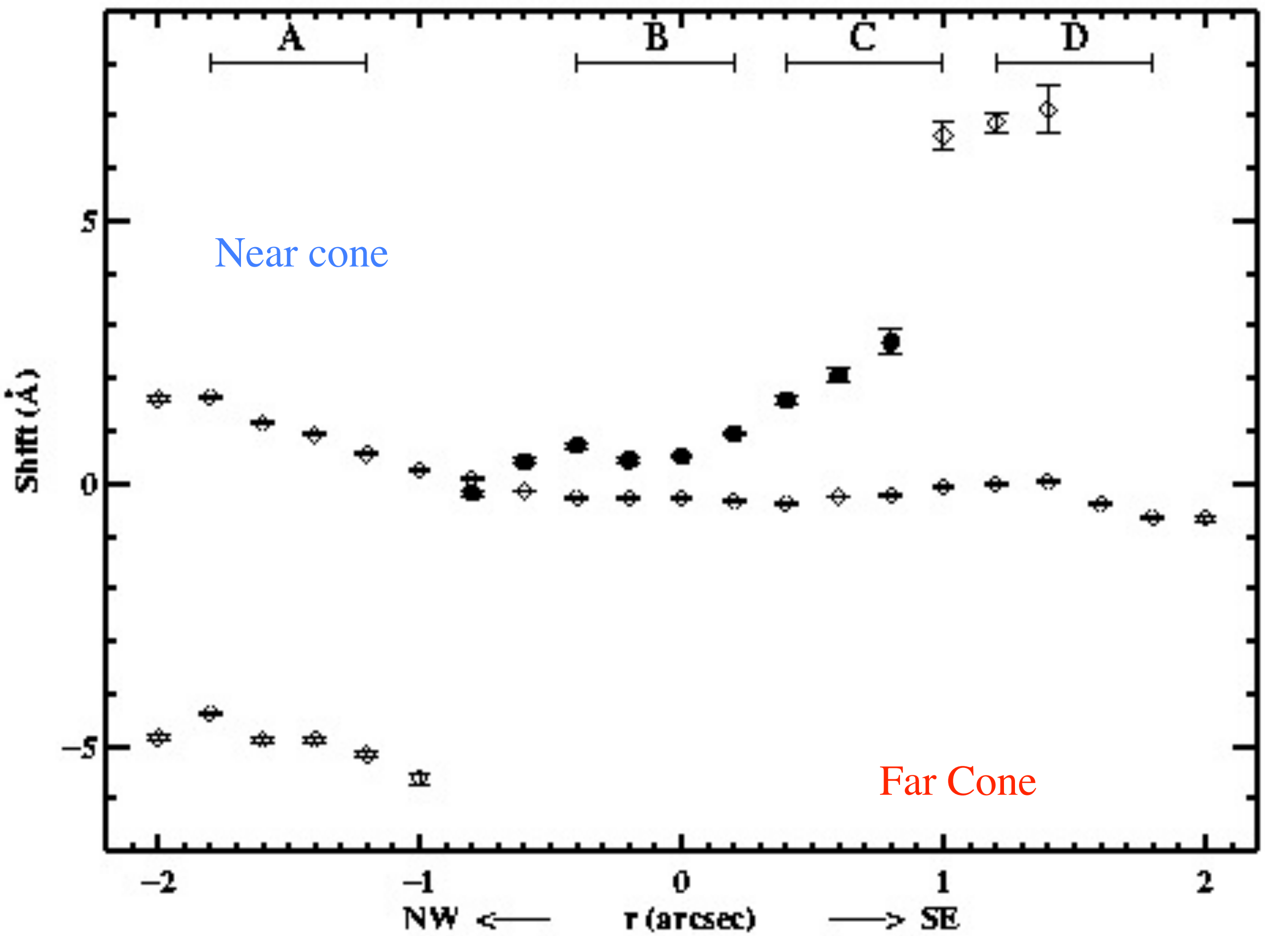


$$\dot{M} = \Omega r^2 v_{out} n_e f m_H \sim 5 - 10 M_{sun} yr^{-1}$$

$$(n_e = 10^2 cm^{-3}, f \sim 5 \times 10^{-4})$$

Taylor et al. (2003)

Cygnus A: energetics

Jet and radiative power:

- Eddington luminosity: 3.3x10^{47} erg s^{-1}
- Radiative bolometric luminosity: (0.5--2.0)x10^{46} erg s^{-1}
- Moderate Eddington ratio: $L_{bol}/L_{edd} < 0.06$
- Jet power: ~(0.3-30)x10^{46} erg s^{-1}

Outflows:

- Power in expanding cocoon (X-ray): 4x10^{45} erg s^{-1}
- Power in emission line outflow (NLR): 2.3x10^{41} erg s^{-1} $(L_{kin}/L_{edd} < 10^{-6})$

Warm outflows in Seyfert-like ULIRGs

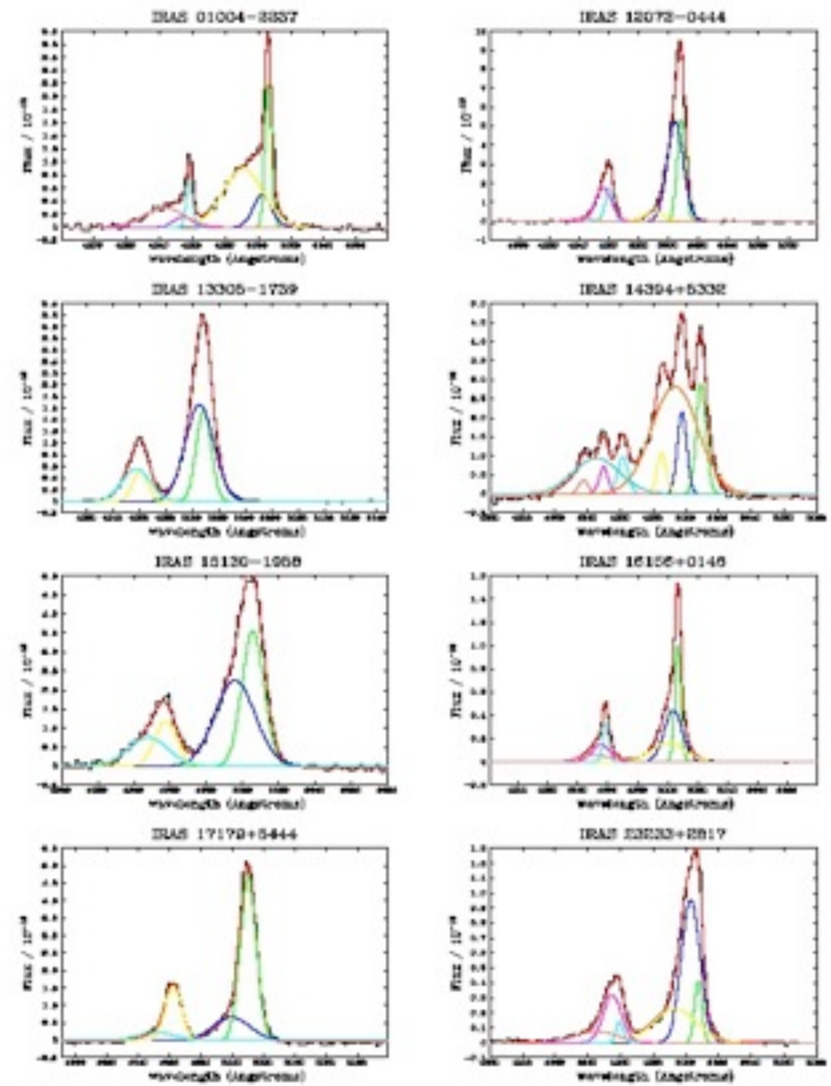


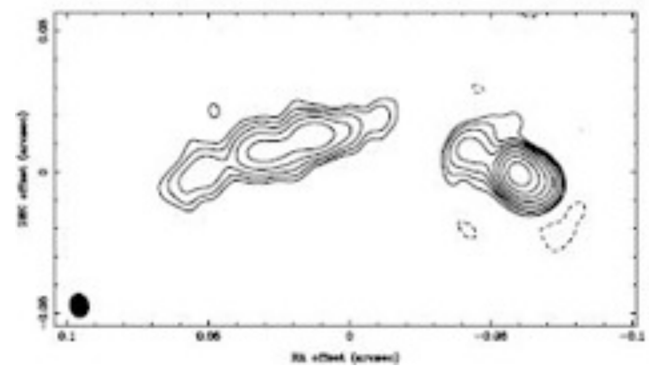
Fig. 1.

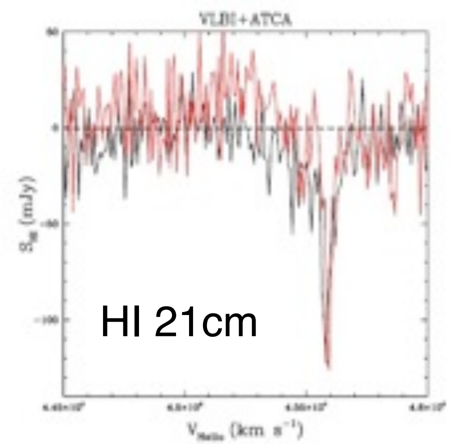
Strongly blueshifted emission lines are common in nearby ULIRGs with optical Seyfert nuclei.

Spoon et al. (2007, 2009)
Rodriguez Zaurin et al. (2010)

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

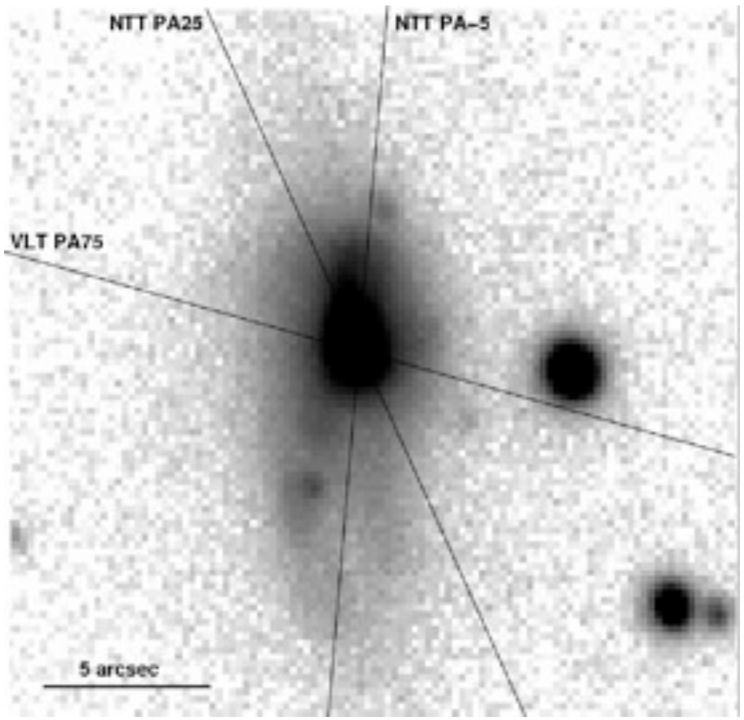
- Flat radio spectrum
- One-sided VLBI jet (radius ~420pc)
- Variability
- ULIRG -- as luminous as 3C273 in mid-IR
- Significant HI 21cm absorption

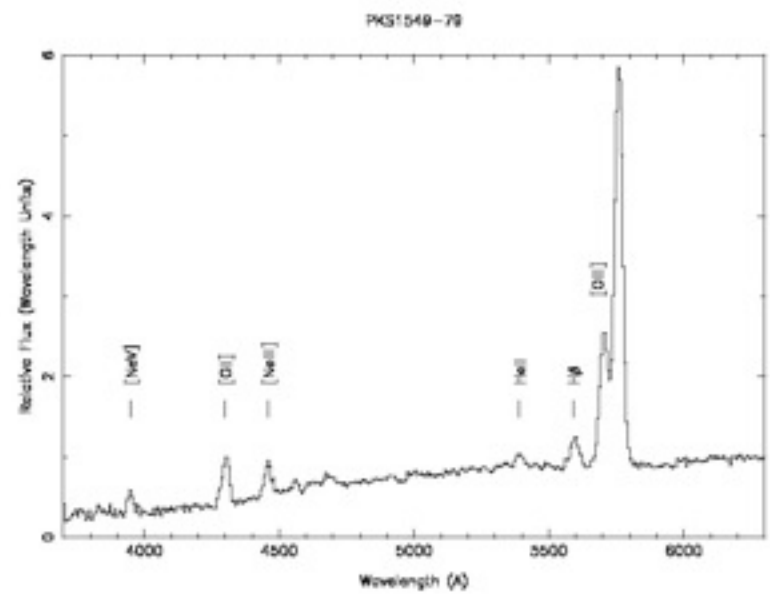




Holt et al. (2006)

Emission line kinematics in PKS1549-79

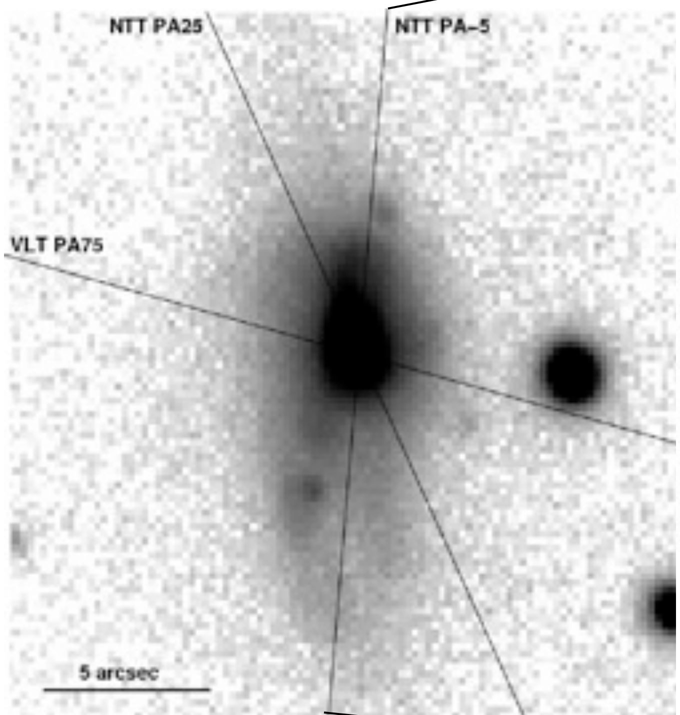




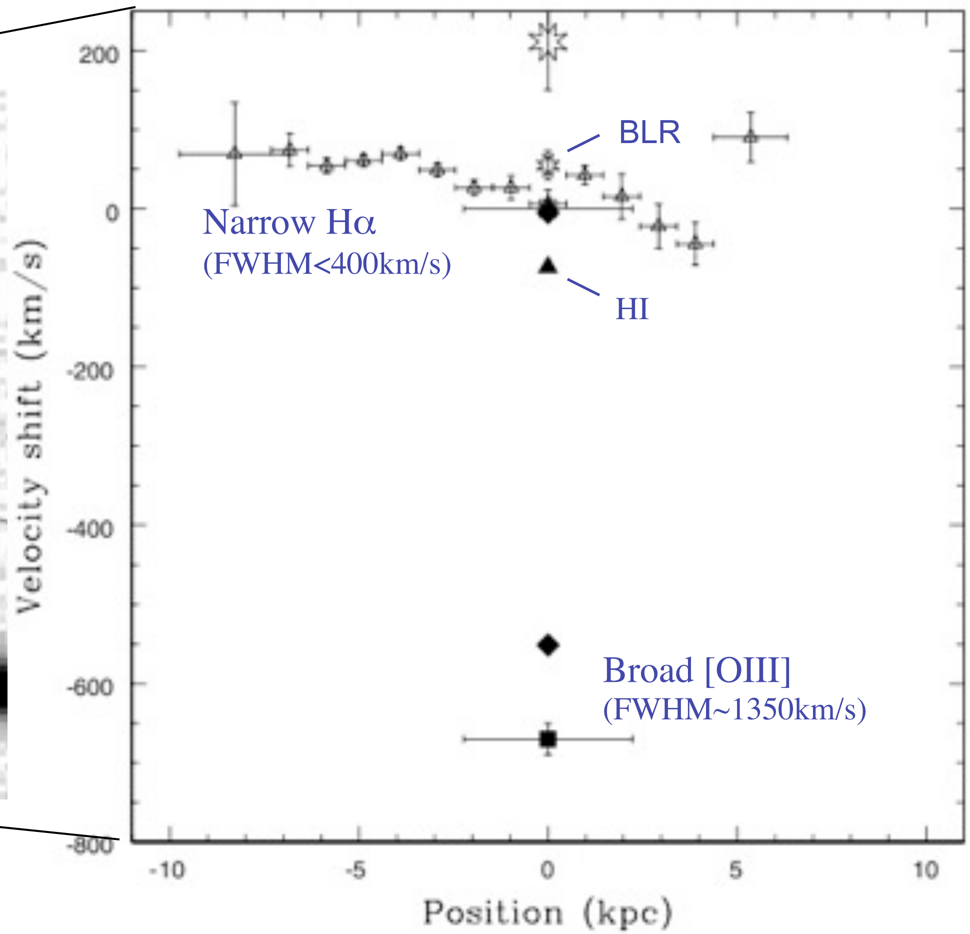
Nuclear spectrum

VLT+FORS1
Gunn r

Emission line kinematics in PKS1549-79

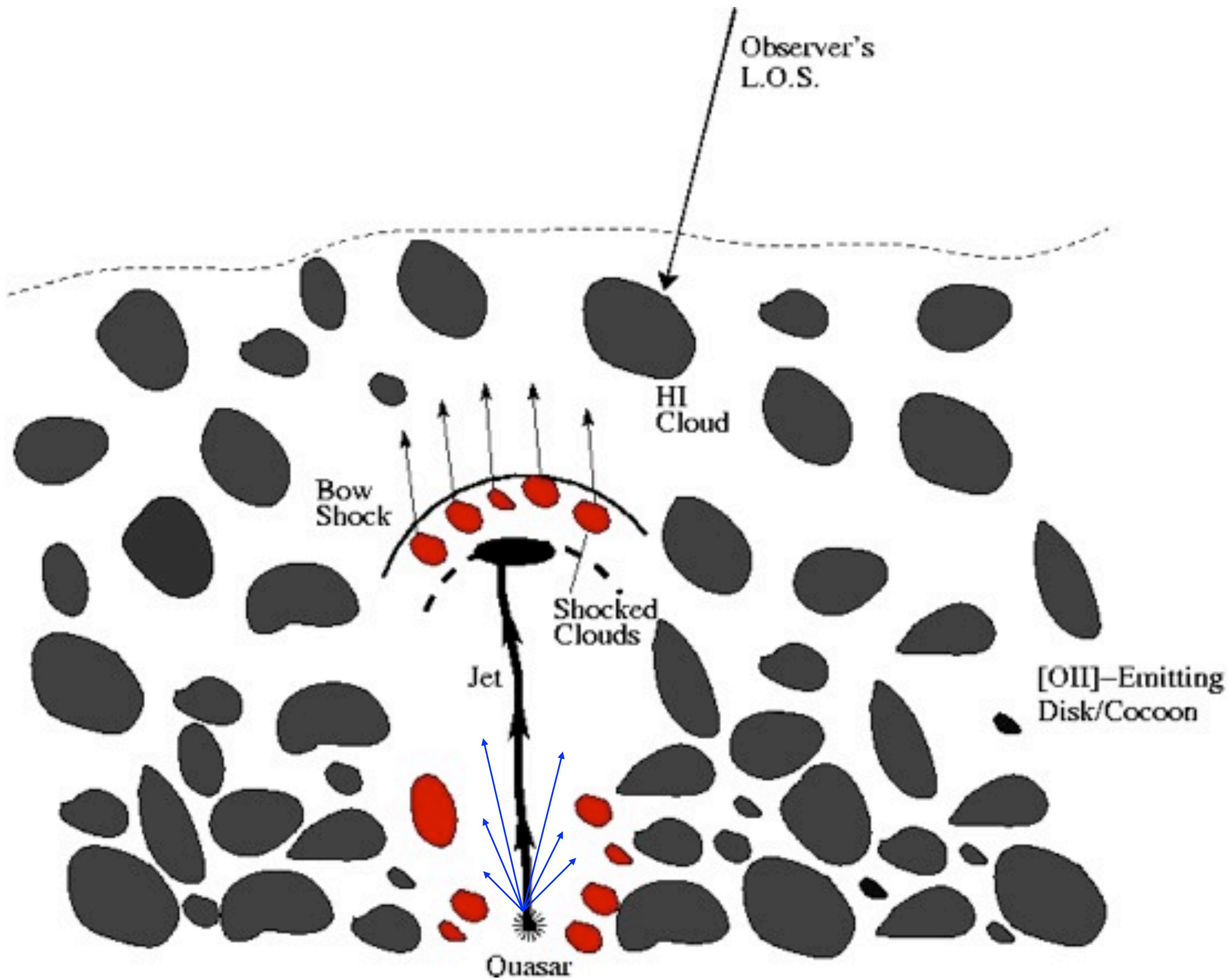


VLT+FORS1
Gunn r



VLT+FORS2
Holt et al. (2006)

The early stages of radio source evolution



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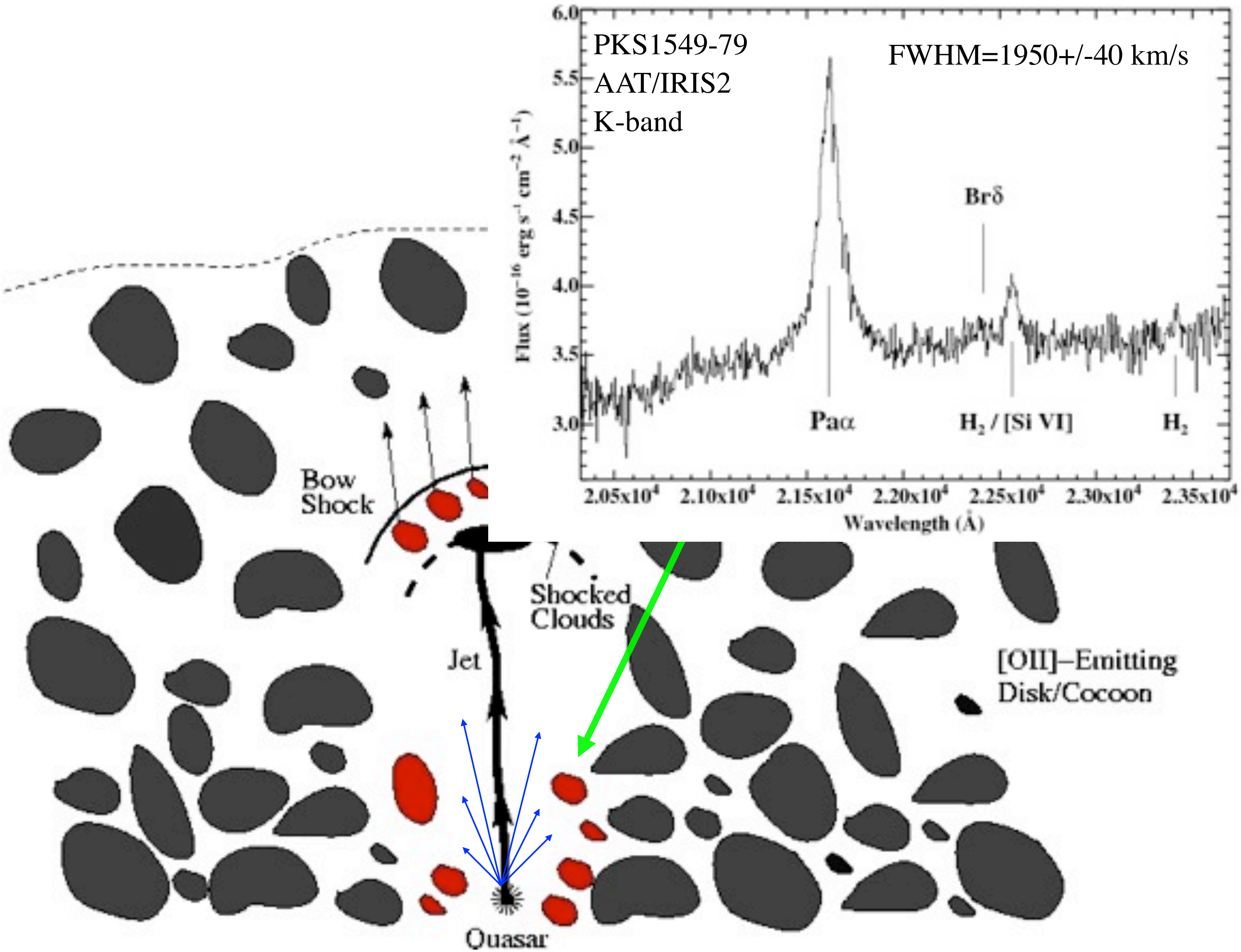
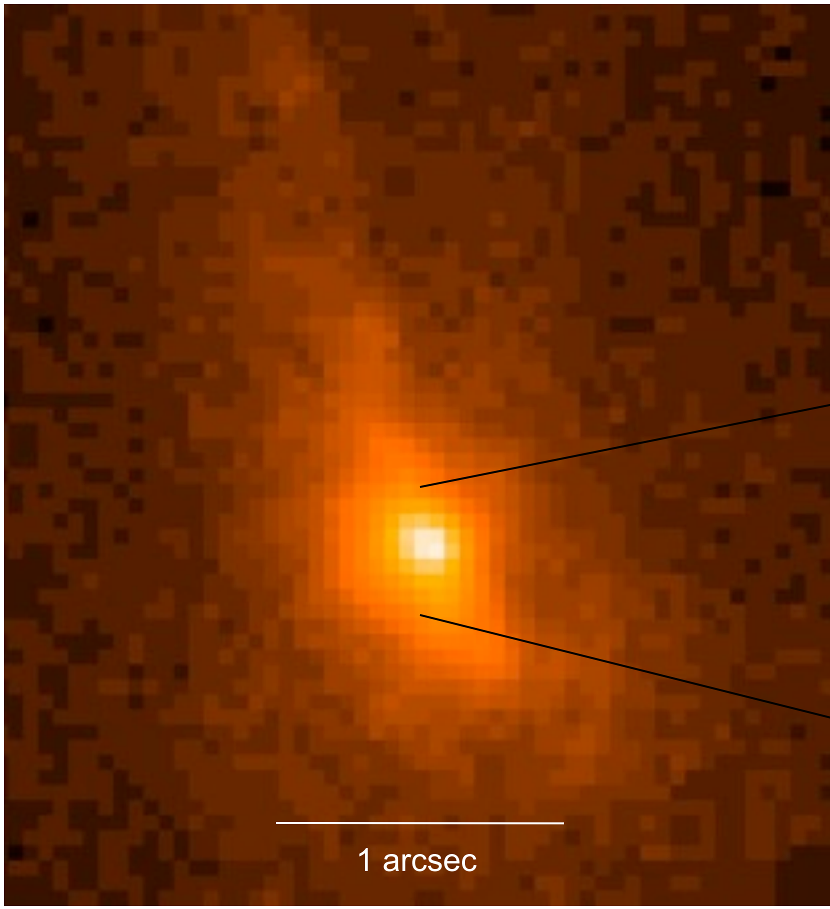
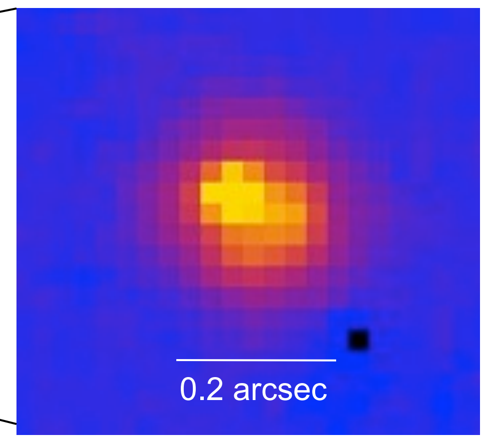


HST/ACS images of PKS1549-79



WFC continuum image (5900A)

$F_{QSR} < 10^{-17}$ erg s^{-1} cm^{-2} A^{-1}



HRC [OIII] image

Batcheldor et al. (2007)

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 many 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)

Reasons for the (apparent) lack of energetic near-nuclear outflows

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- Possible that the energetically dominant outflow component has not yet been observed because it is in a hotter or cooler phase. (Are we really observing the piston?)

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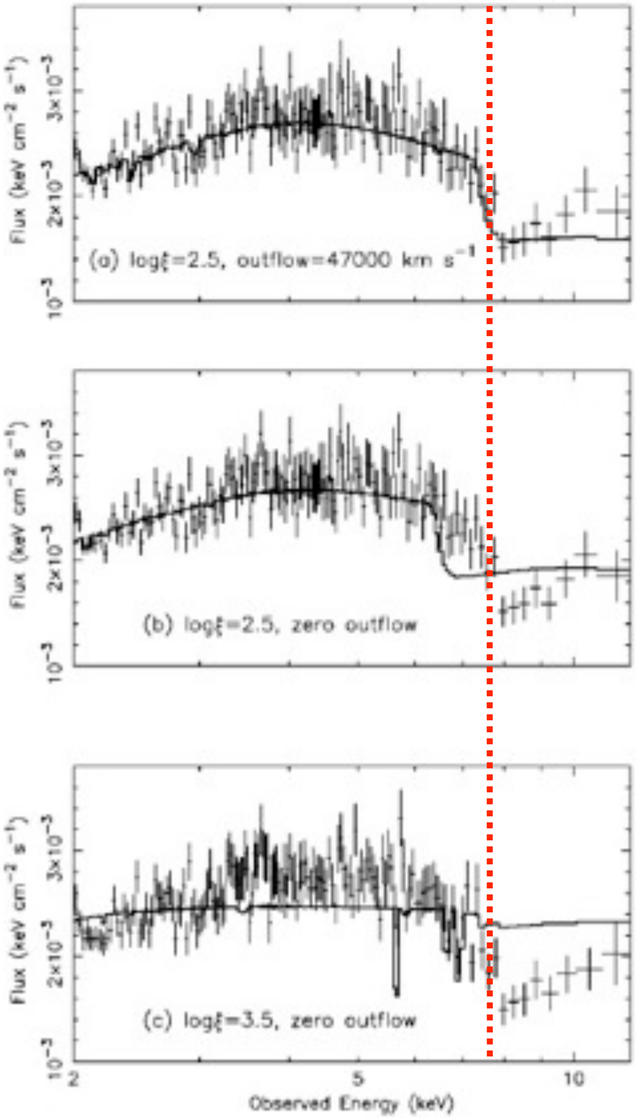
- Possible that the energetically dominant outflow component has not yet been observed because it is in a hotter or cooler phase. (Are we really observing the piston?)
- Is a large fraction of the near-nuclear outflow obscured at optical/UV wavelengths?

Massive, high ionization outflow in PDS456 (z=0.18)

Reeves et al. (2003)



- Radio quiet quasar
- X-ray absorption edge indicates a high velocity outflow ΔV~50,000 km/s

$$\dot{M} \sim 10 M_{sun} yr^{-1}$$

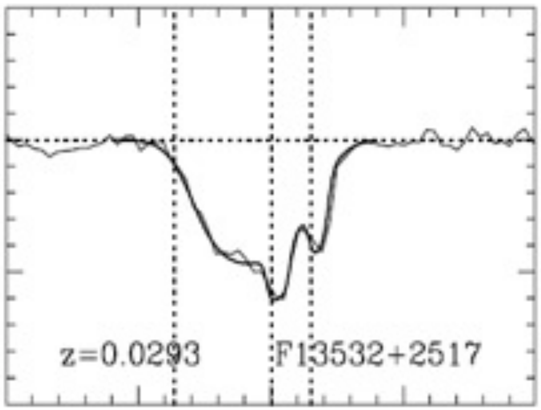
$$\dot{E} \sim 10^{46} erg/s$$

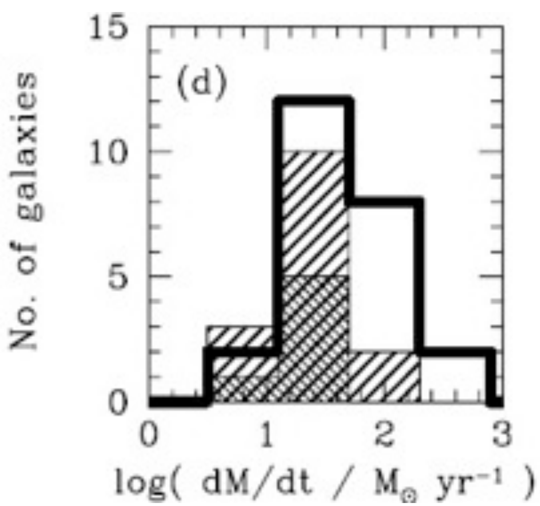
$$\dot{E}/L_{edd} \sim 0.1$$

(but large uncertainties in covering factor, geometry, radius etc..)

Outflow comparison

Neutral outflows in ULIRGs: a useful fiducial





Rupke et al. (2005a,b)

- Neutral outflows detected using NaID absorption in ~40 - 80% of nearby ULIRGs:

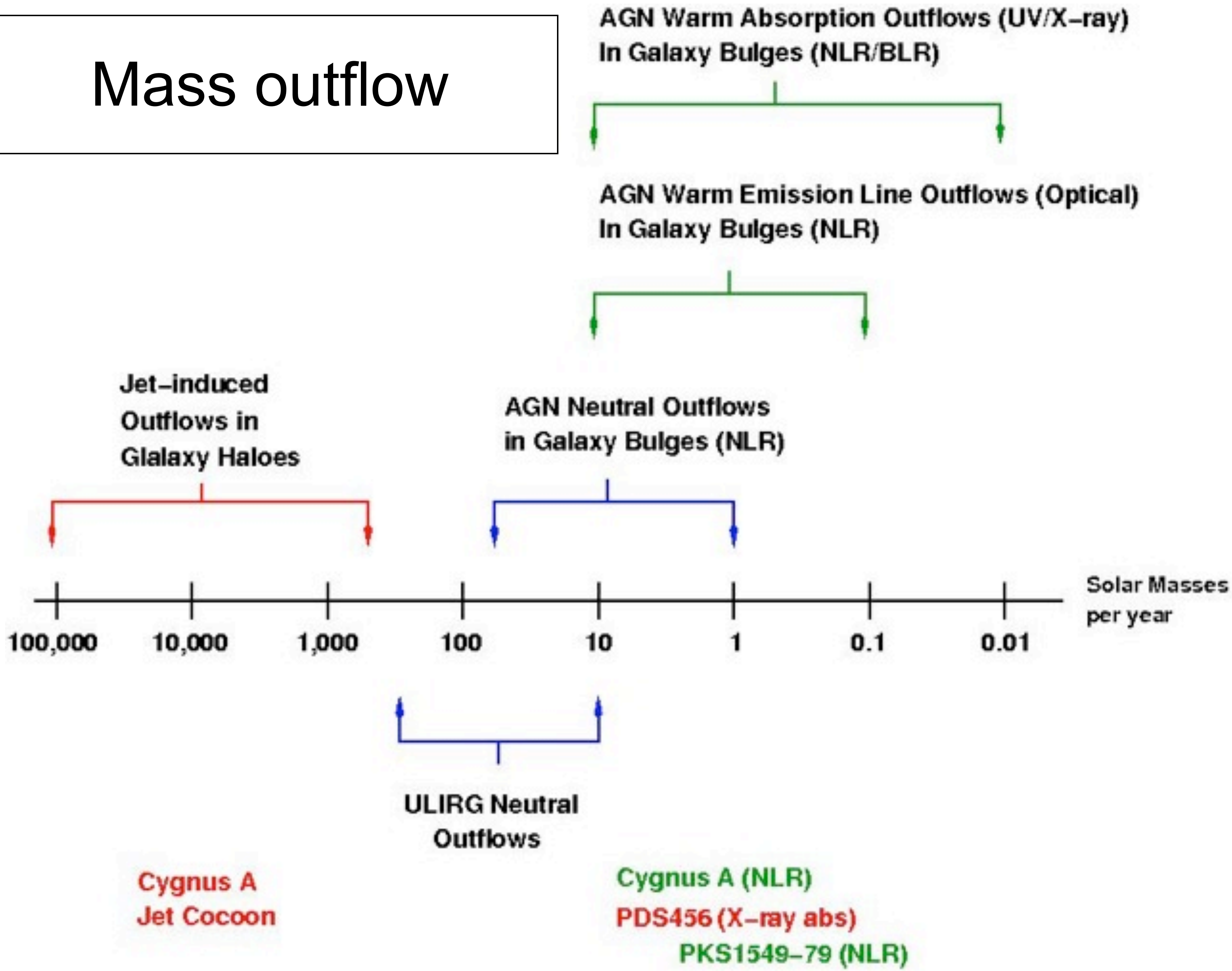
$$-1200 < \Delta v < -100 \ km\ s^{-1}$$

$$10 < \dot{M} < 300 \ M_{sun} yr^{-1}$$

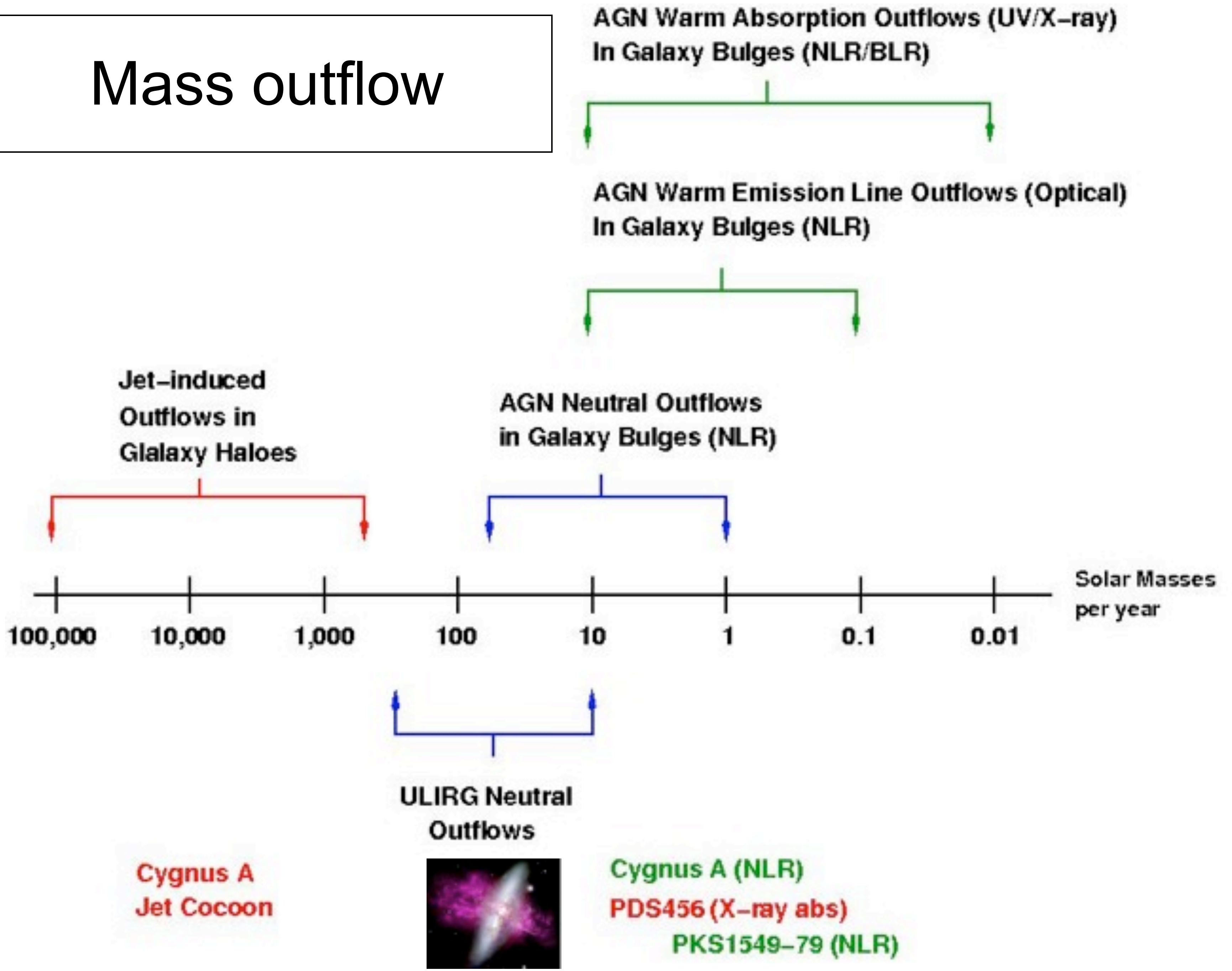
$$10^{40} < \dot{E} < 6 \times 10^{43} \ erg\ s^{-1}$$

- But no significant differences are found between the neutral outflows detected in ULIRGs with and without powerful Seyfert nuclei…

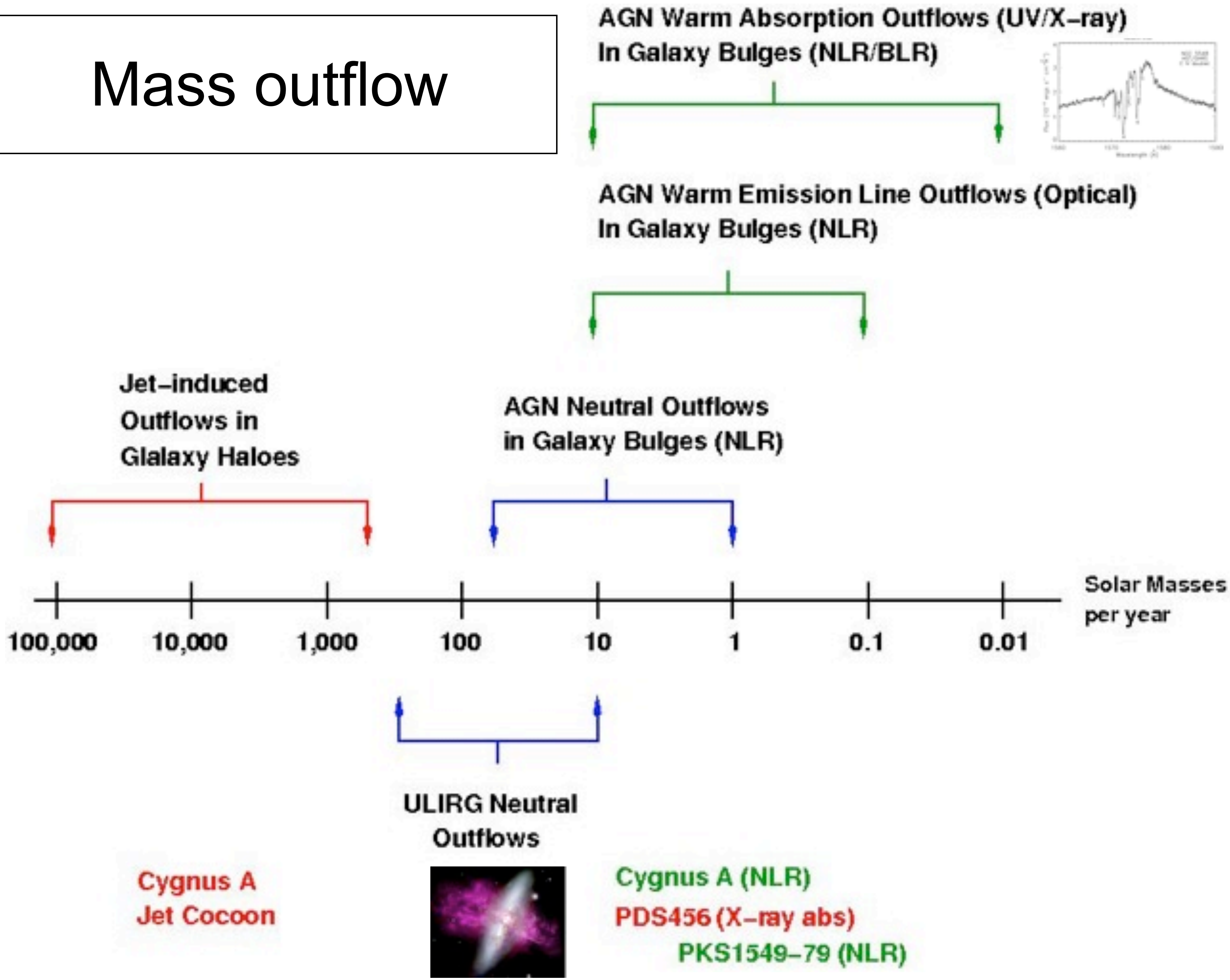
Mass outflow



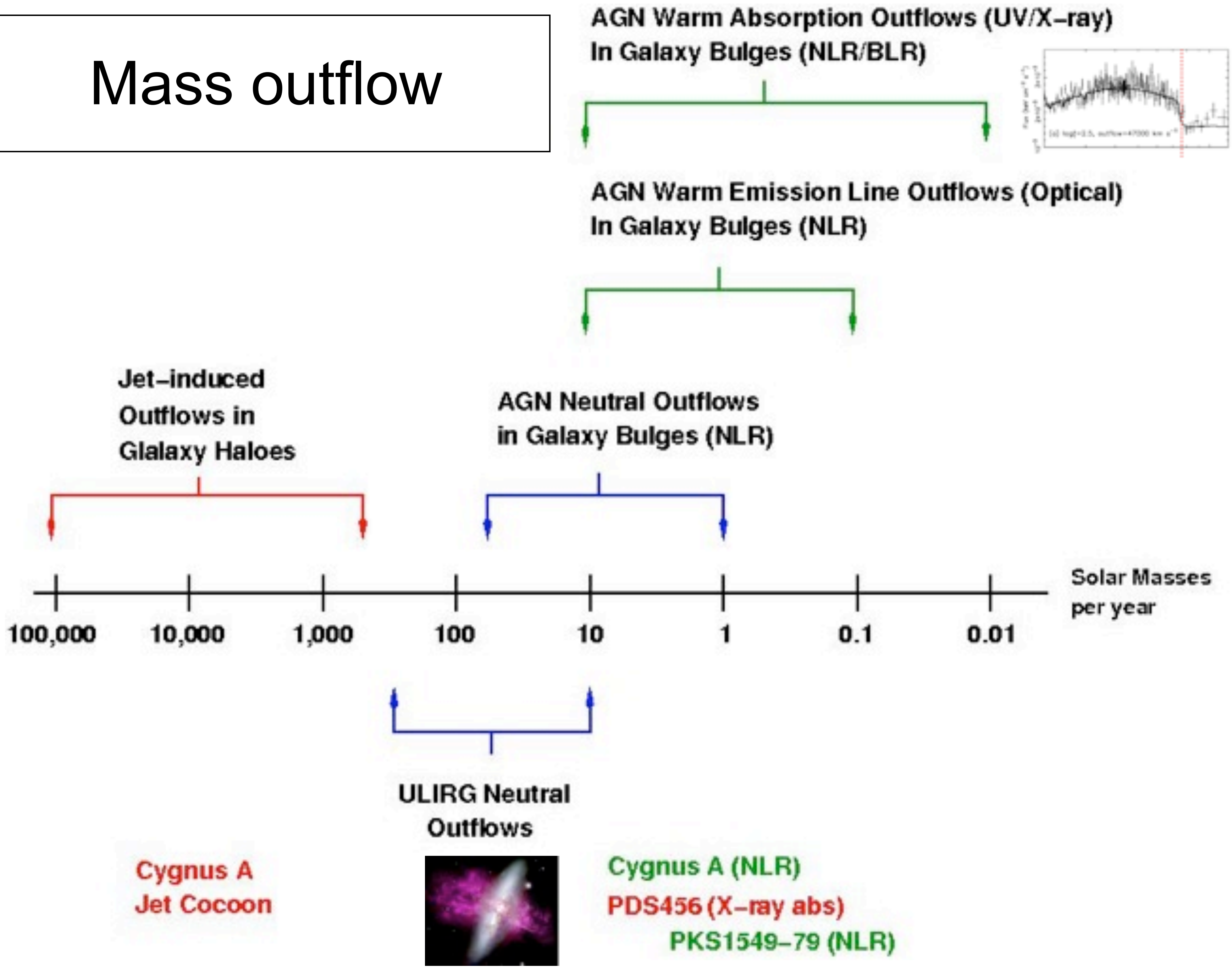
Mass outflow



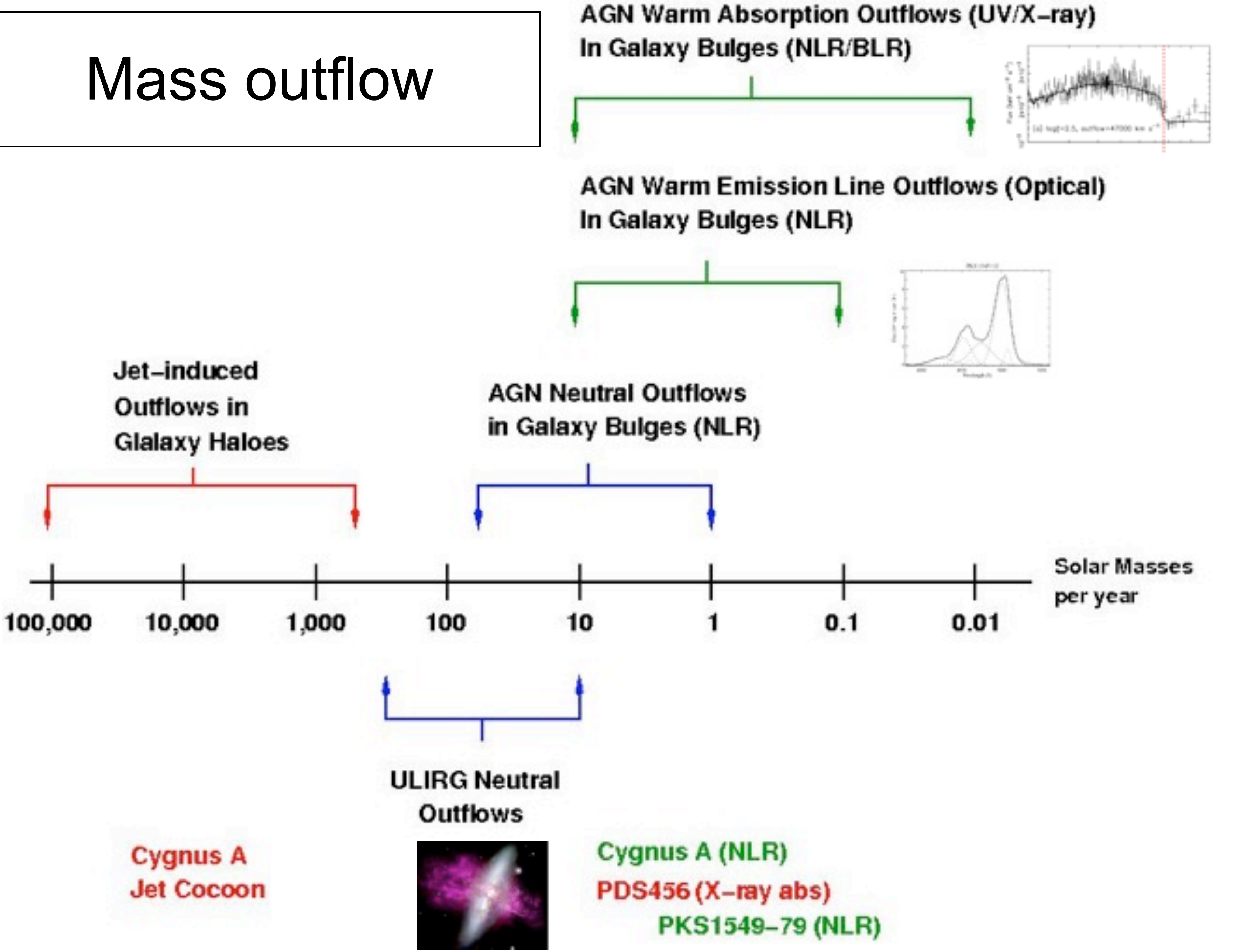
Mass outflow



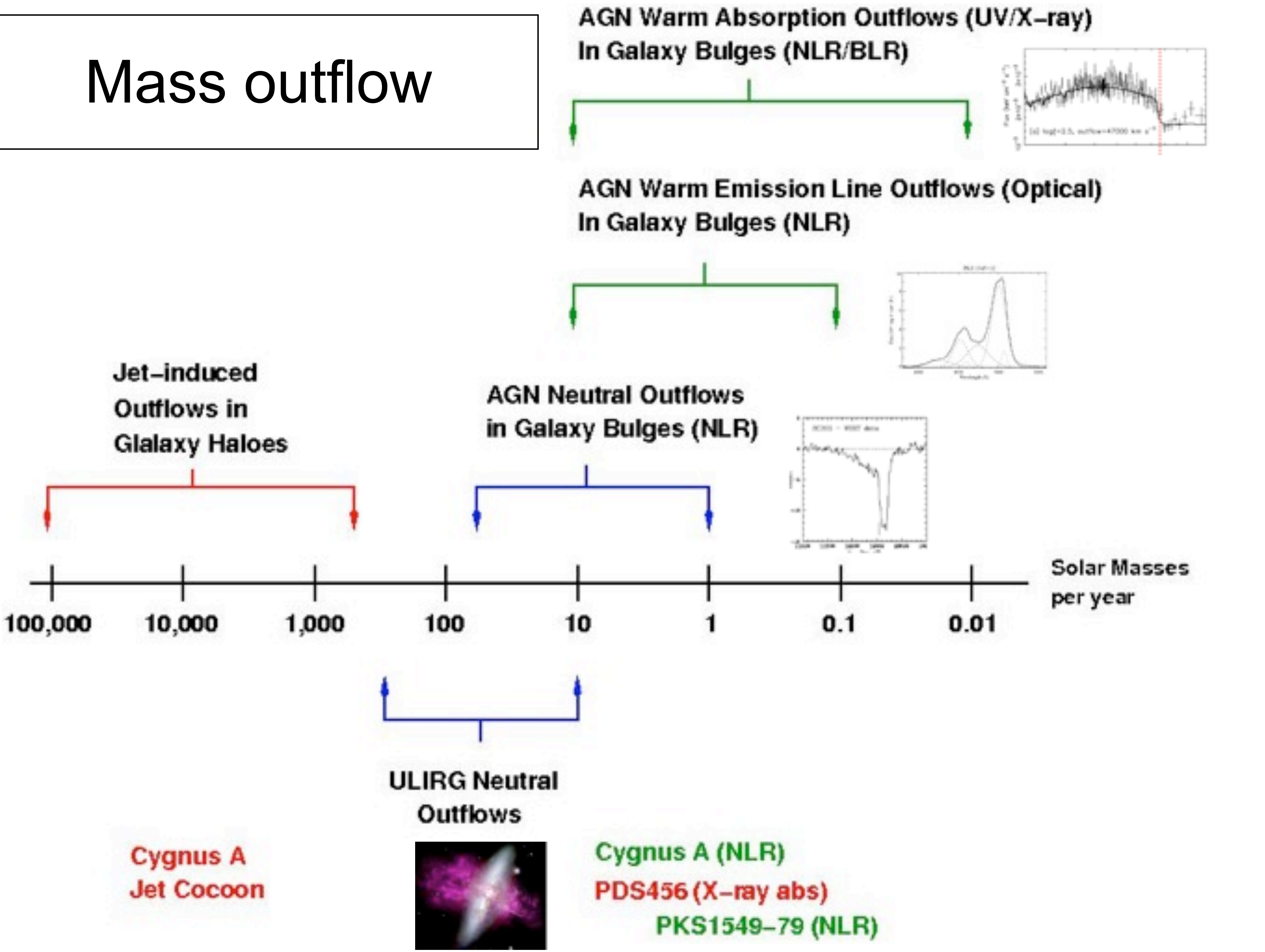
Mass outflow



Mass outflow



Mass outflow



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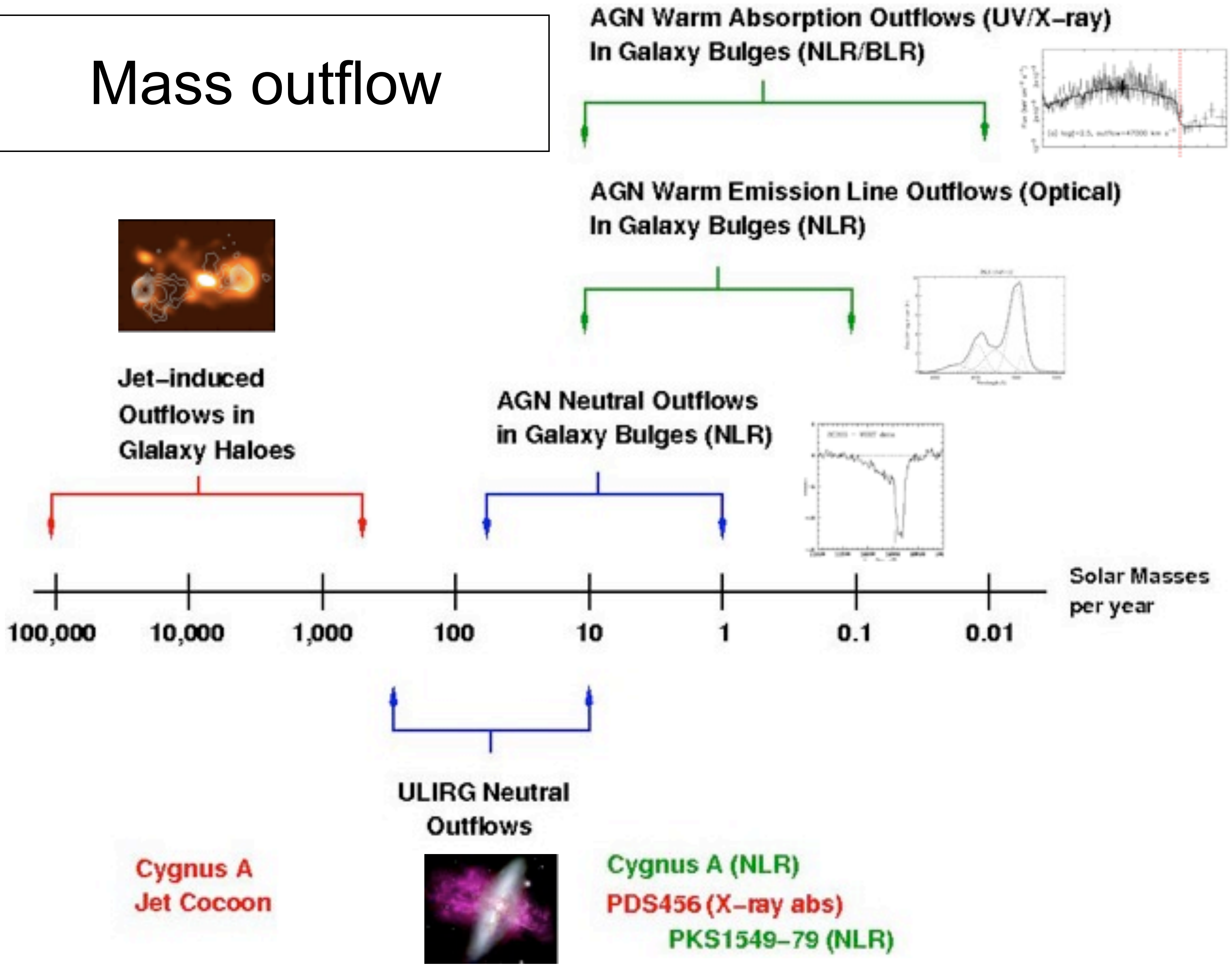
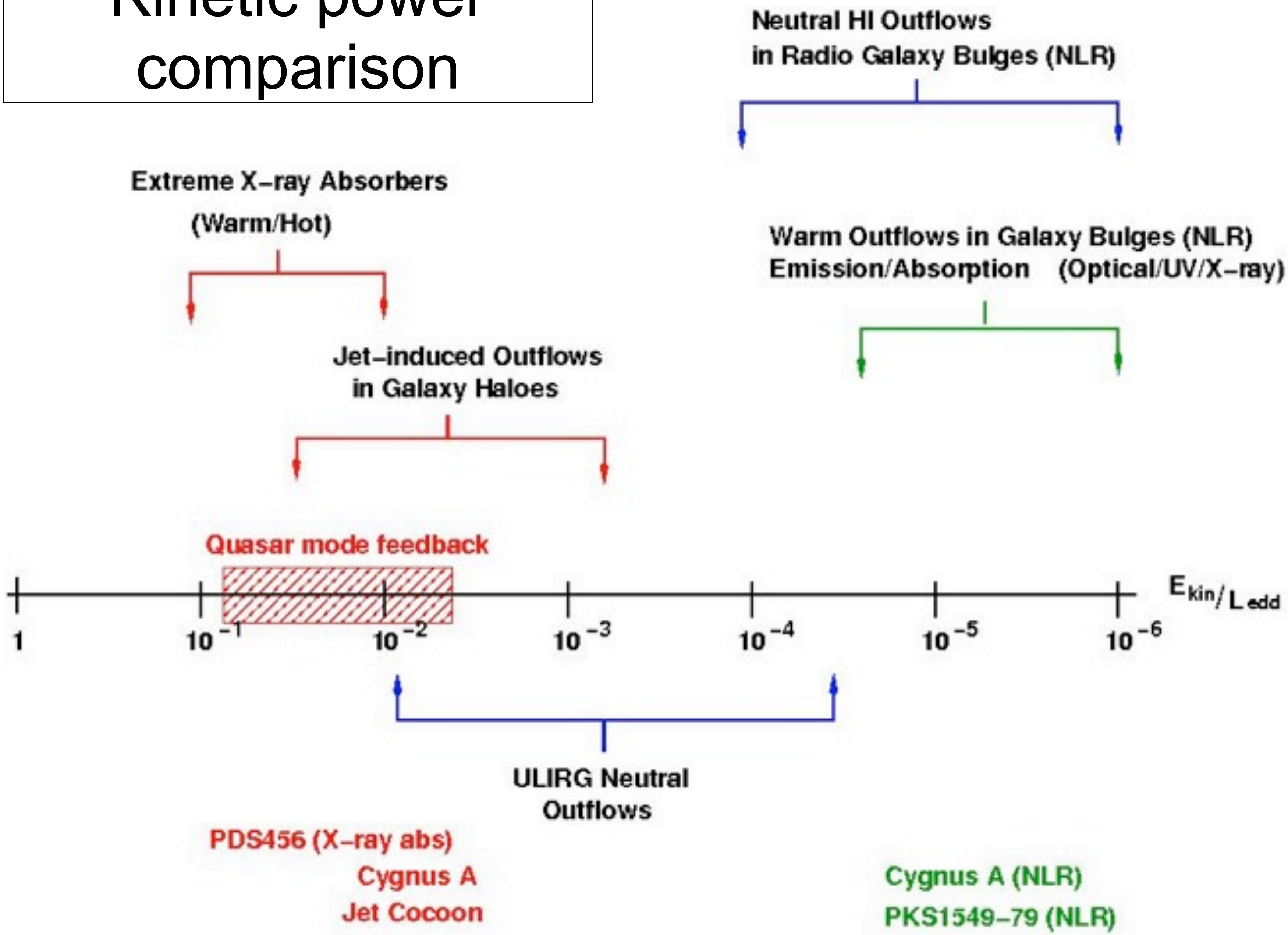


Kinetic power comparison



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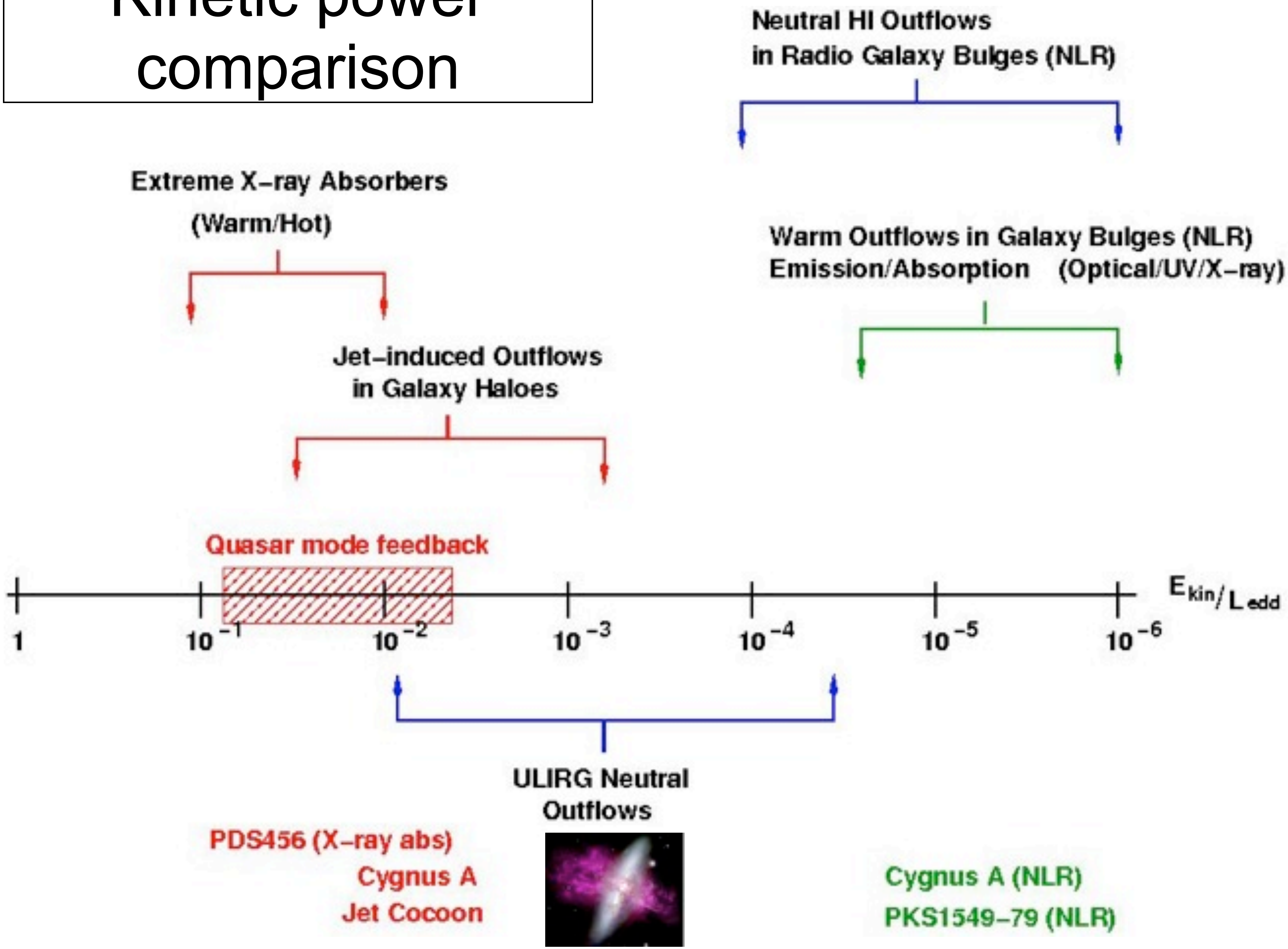

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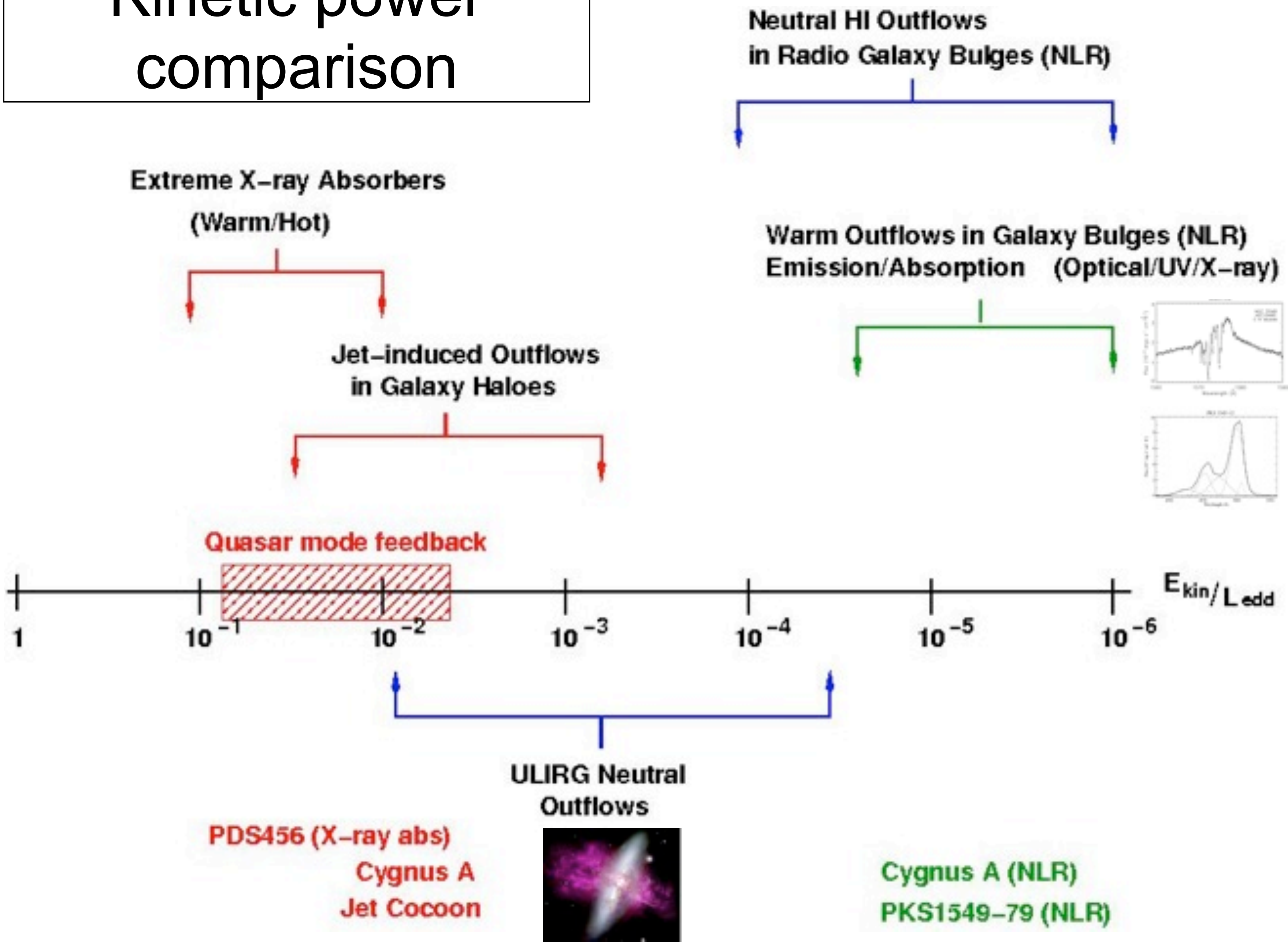

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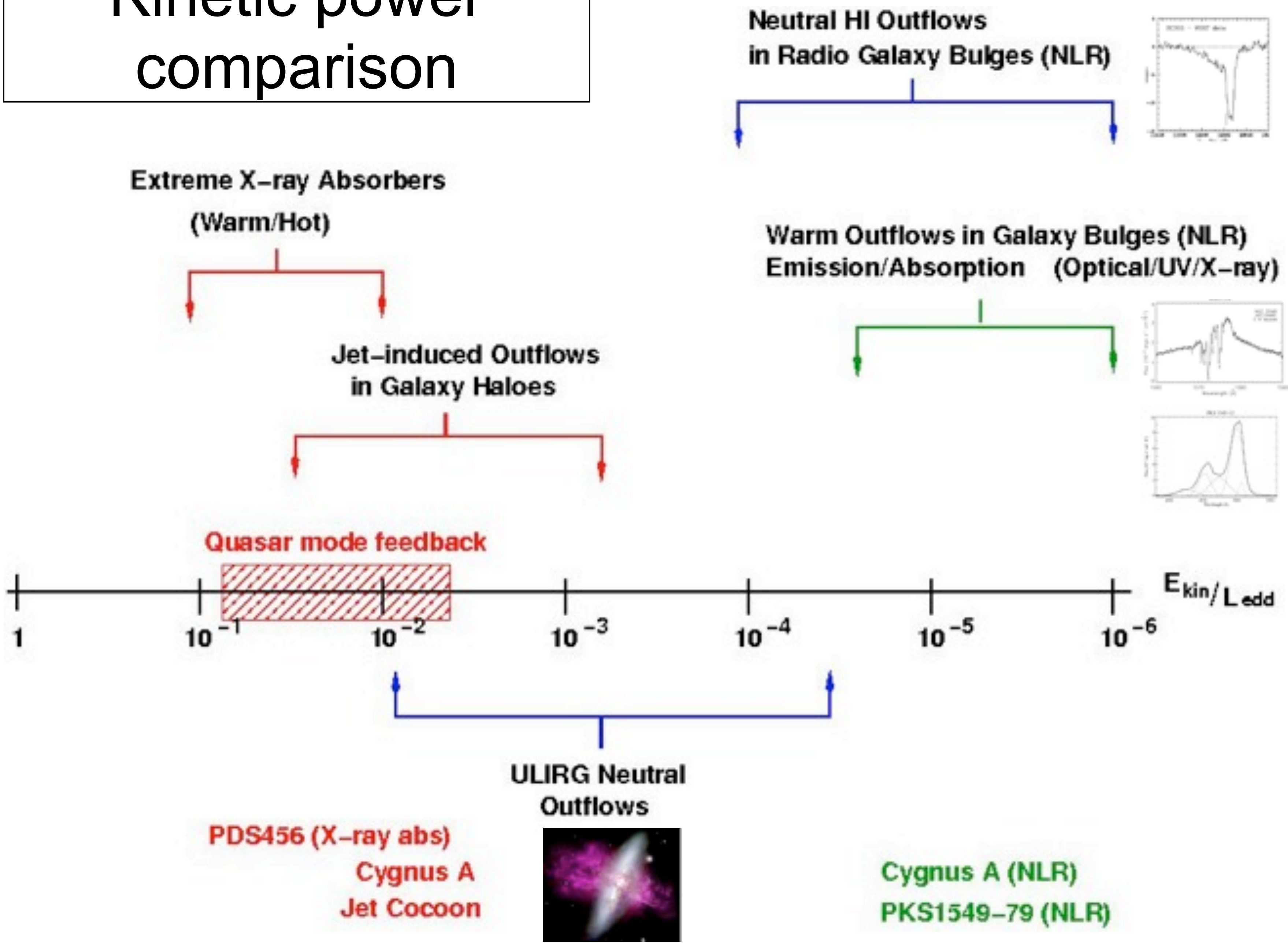

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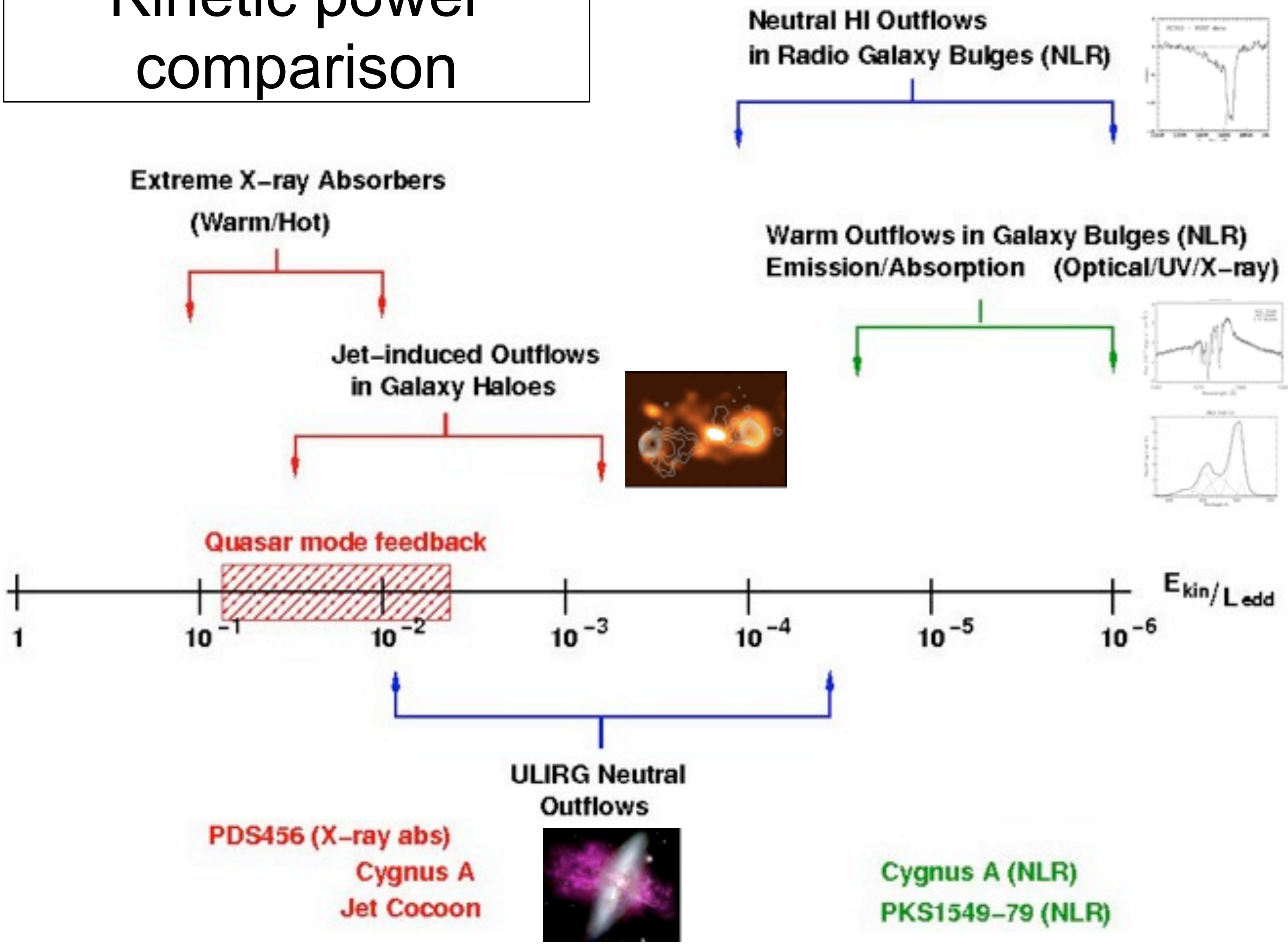

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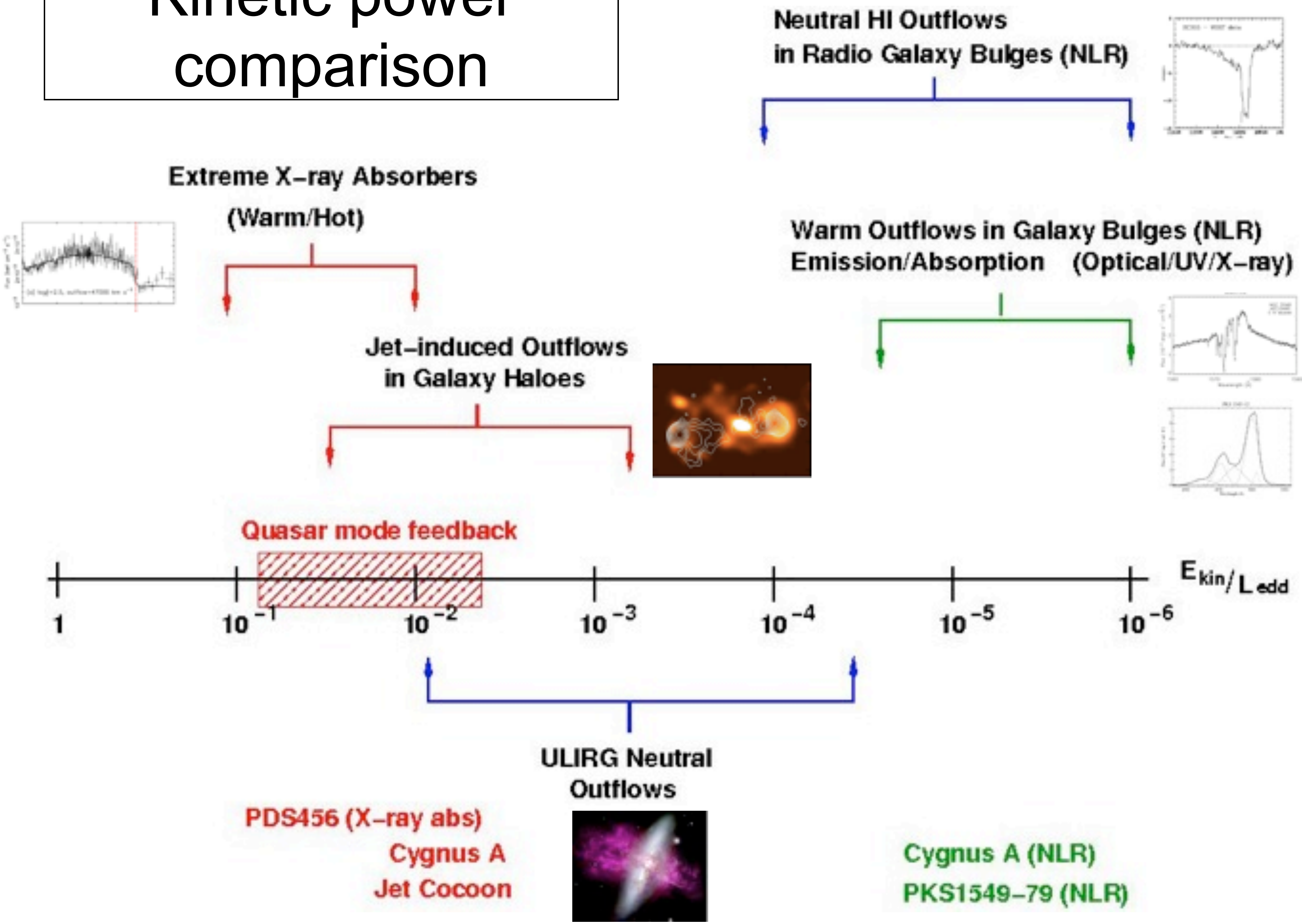

Conclusions

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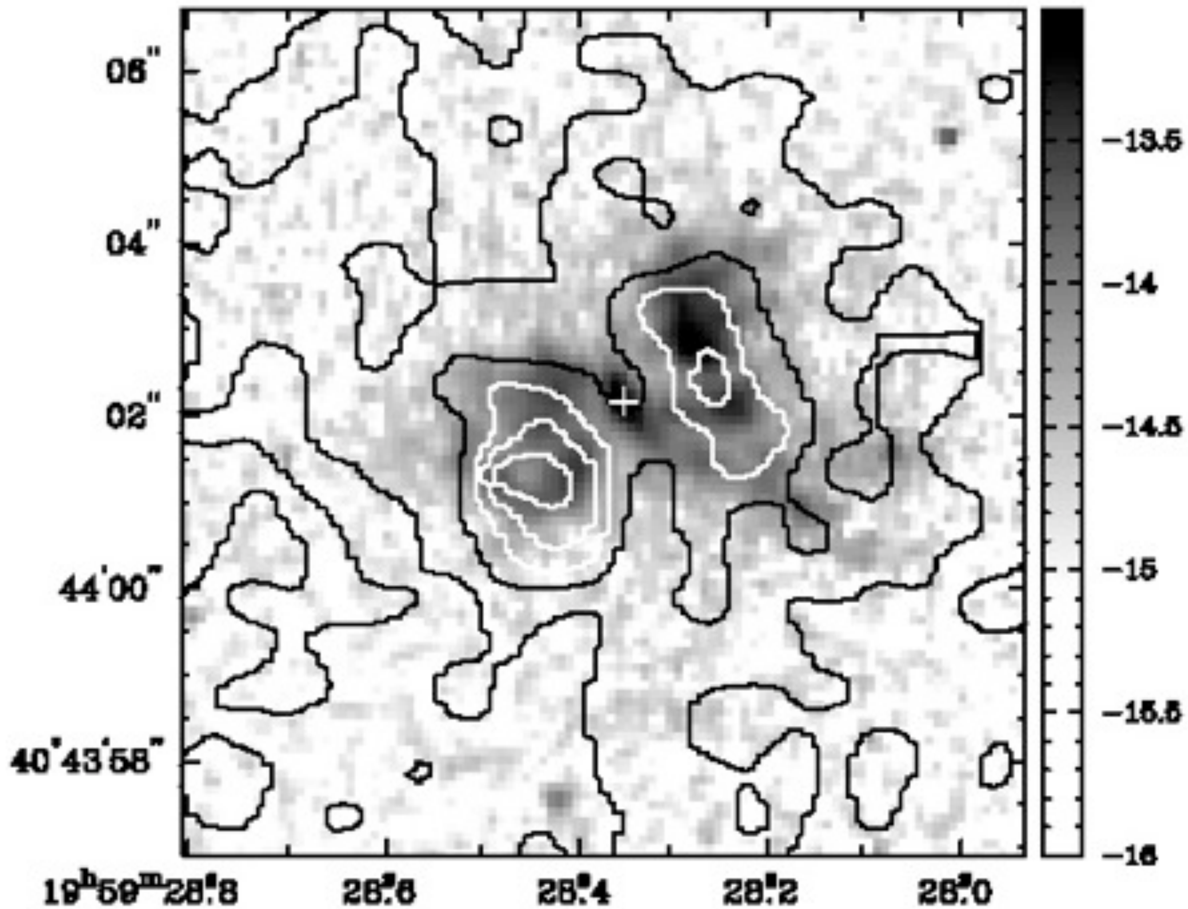
- Jet-induced outflows: have a major impact on the gas on all scales in host galaxies of AGN with powerful relativistic jets; they are likely to directly affect the star formation in the host galaxies and stop the hot ISM/ICM from cooling
- Near-nuclear AGN outflows ("quasar mode"): despite the clear observational evidence for warm and cool near-nuclear outflows in a large fraction of nearby AGN, they are often much less powerful than required by the AGN feedback models, and less powerful than starburst-induced outflows

Cygnus A Chandra results (Young et al. 2002)



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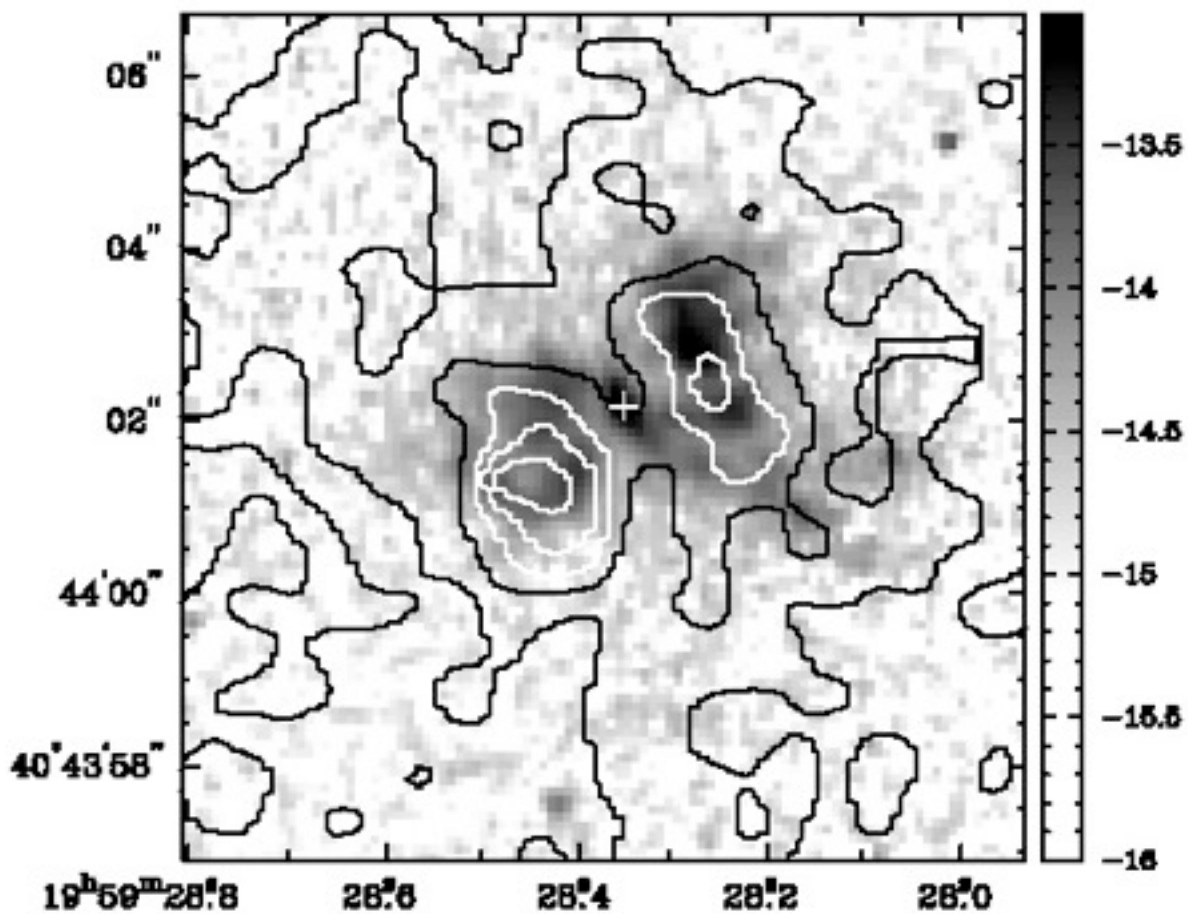
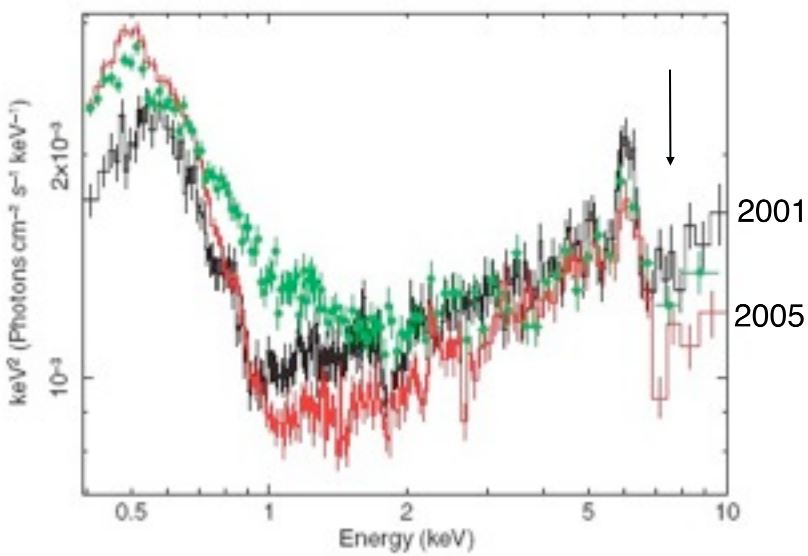


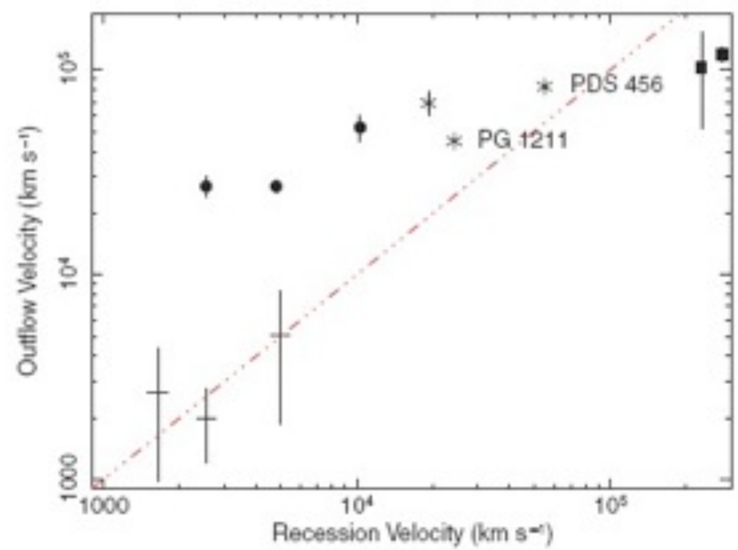
$$(n_e = 6cm^{-3}, T = 10^4 - 10^5 K)$$

$$\dot{M} \sim 240\left(\frac{\Delta v}{300km/s}\right) f^{1/2} M_{sun} yr^{-1}$$

Evidence that the X-ray detected outflows are associated with the AGN



X-ray spectra of PG1211: evidence for a variable FeK absorption feature.

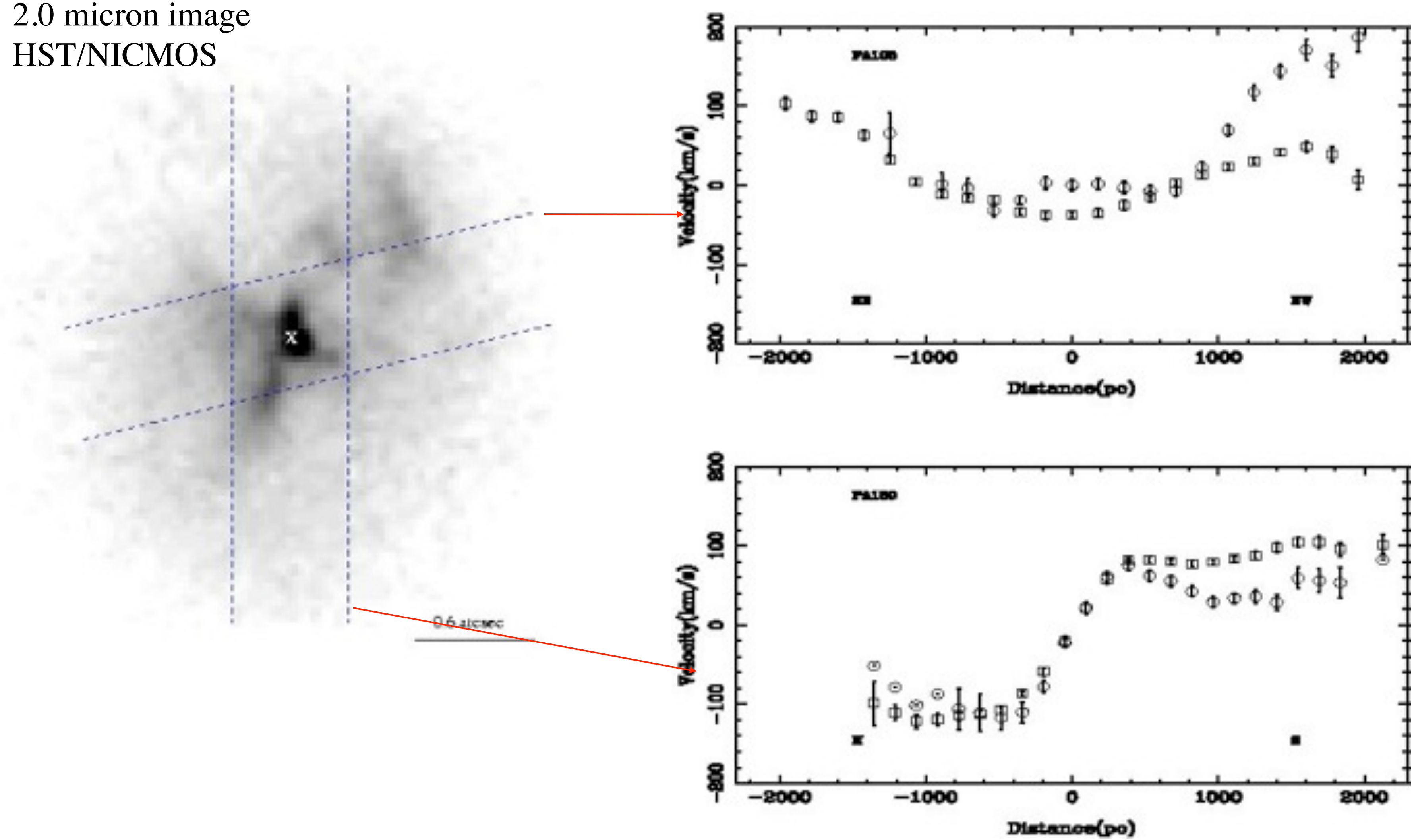


New estimates of the outflow velocities don't show such good agreement with the galaxy recession velocities...

Reeves et al. (2008)

The black hole in Cygnus A

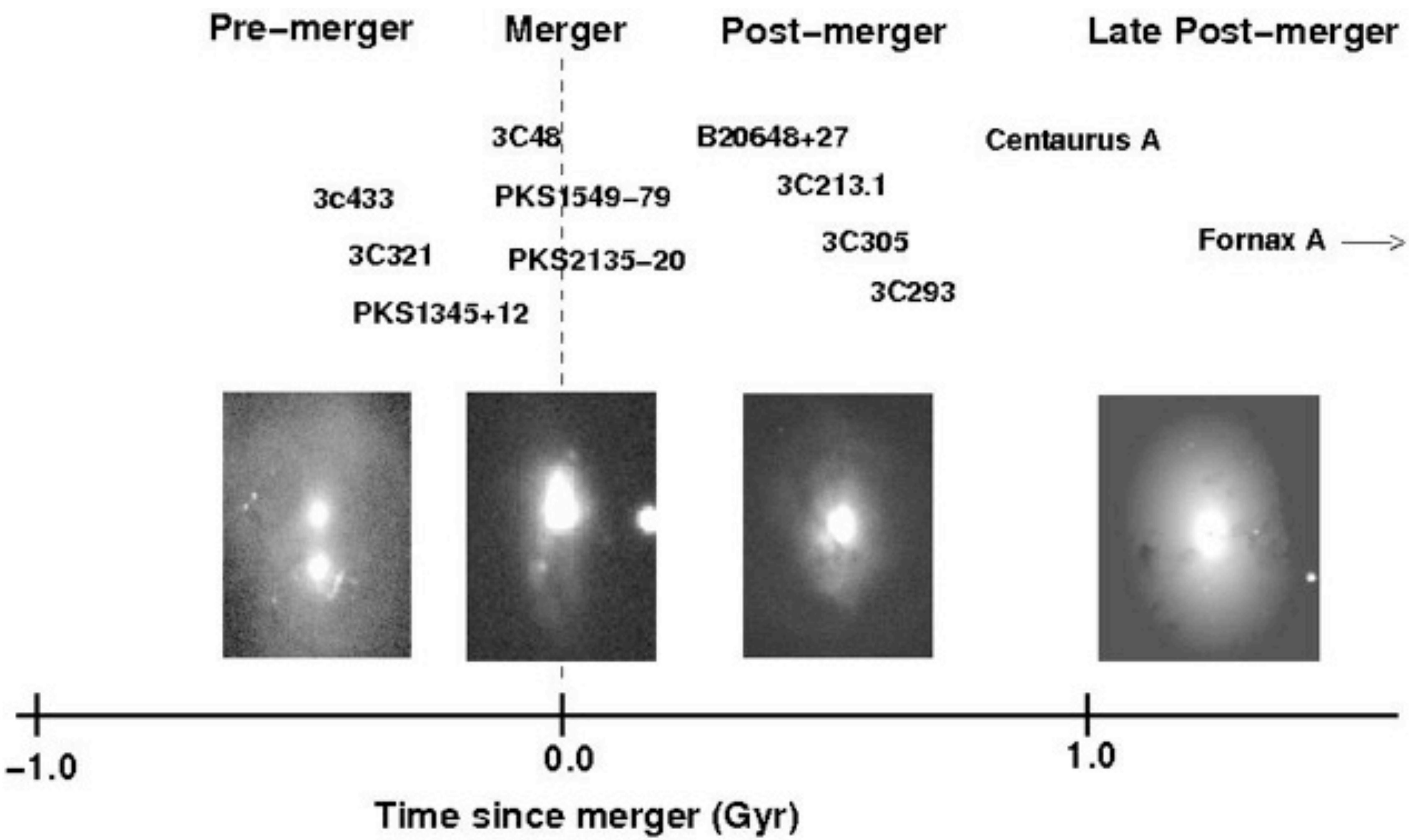
2.0 micron image
HST/NICMOS



$M_{bh} = (2.5 \pm 0.7) \times 10^{9}\ \mathrm{M_{sun}}$ $\qquad L_{bol}/L_{edd} < 0.06$

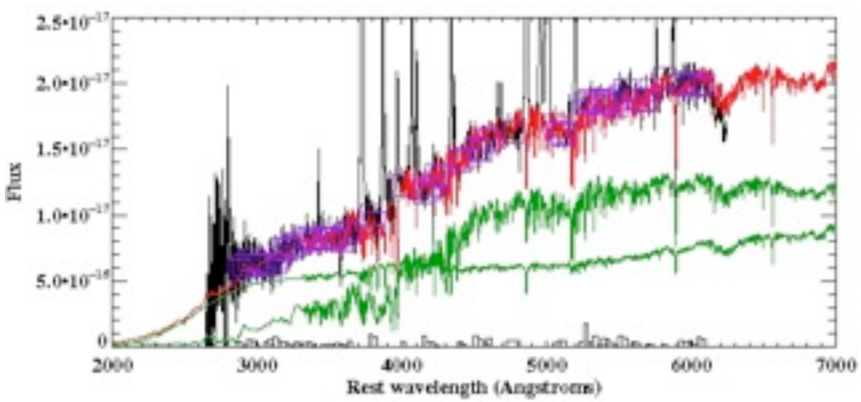
Tadhunter et al. (2003)

Merger sequence for starburst radio galaxies



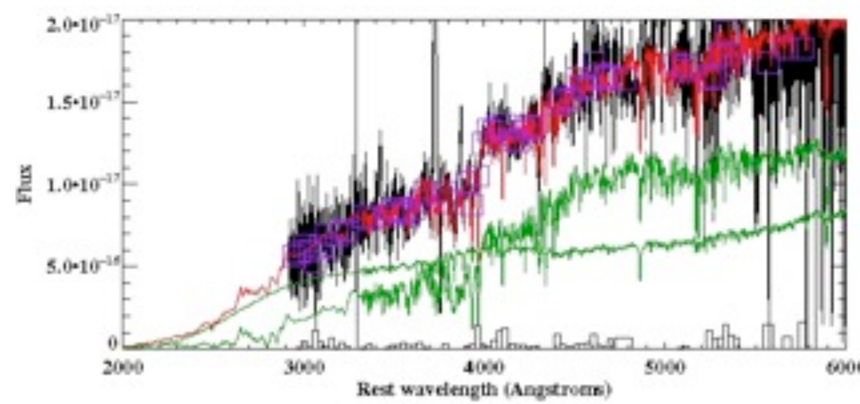
Objects with v.young starburst components

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

Starburst radio galaxies general properties

Overall, the results are consistent with the triggering of the activity in major, gas-rich galaxy mergers/interactions

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- 95% of starburst radio galaxies show signs of morphological disturbance (tidal tails, fans, shells, dust lanes, double nuclei etc.)

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- Young stellar populations (YSP) contribute a significant proportion of the total stellar masses (5-40%)
- The YSP are spatially extended -- they generally detected across the full extents of the host galaxies over which accurate measurements can be made (although brightest in the nuclei)

Overall, the results are consistent with the triggering of the activity in major, gas-rich galaxy mergers/interactions

Two main groups of starburst radio galaxies

- LIRG/ULIRG-like systems ($t_{ysp} < 0.1$Gyr)

  - Most have:

  $$L_{[OIII]} > 10^{35} W;\ \ L_{ir} > 10^{11} L_{sun}$$

  - Radio source triggered quasi-simultaneously with starburst

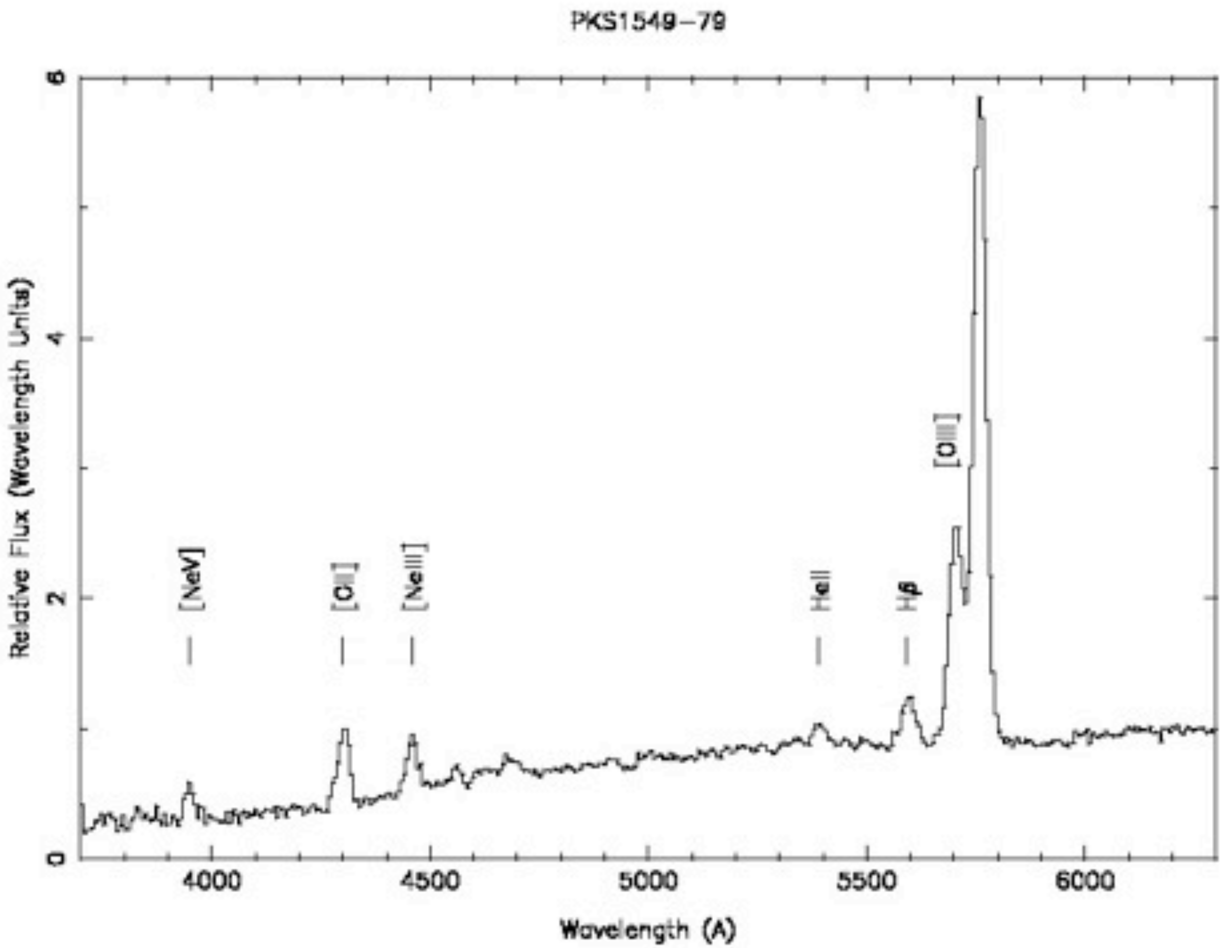
- Post-starburst systems ($t_{ysp} > 0.2$ Gyr)

  - Most have:

  $$L_{[OIII]} < 10^{35} W;\ \ L_{ir} \leq 10^{11} L_{sun}$$

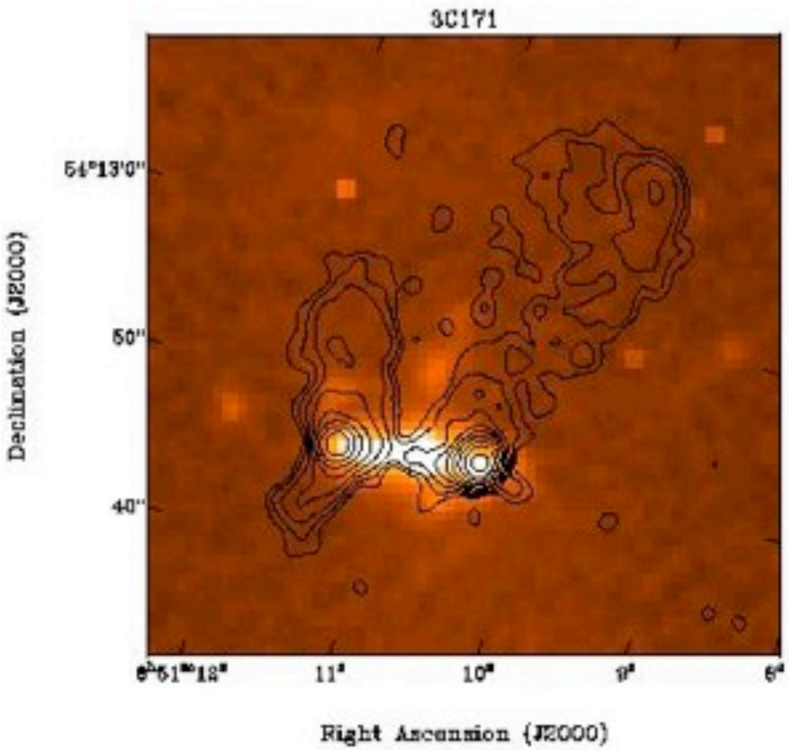
  - Radio source triggered (or retriggered) a significant period after the starburst episode

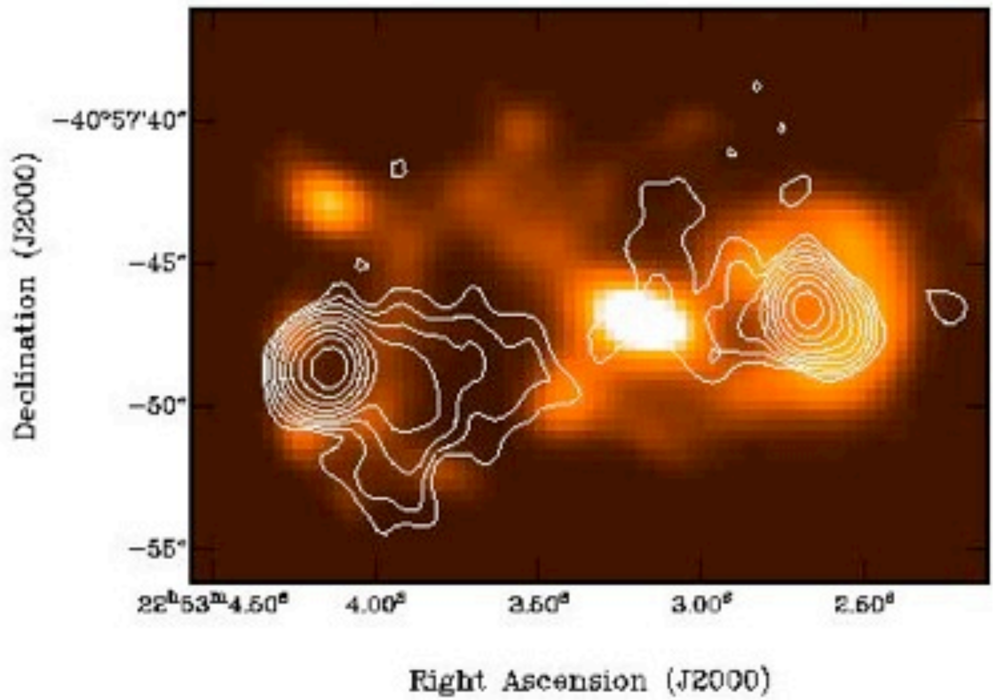
PKS1549-79: Optical Spectrum



Tadhunter et al. (2001)

Radio–Optical Morphological Associations





3C171 (z=0.238)
Halpha/6cm

PKS2250–41(z=0.310)
[OIII]/6cm

Galaxy merger simulations

di Matteo et al. (2005)

Galaxy merger simulations

di Matteo et al. (2005)

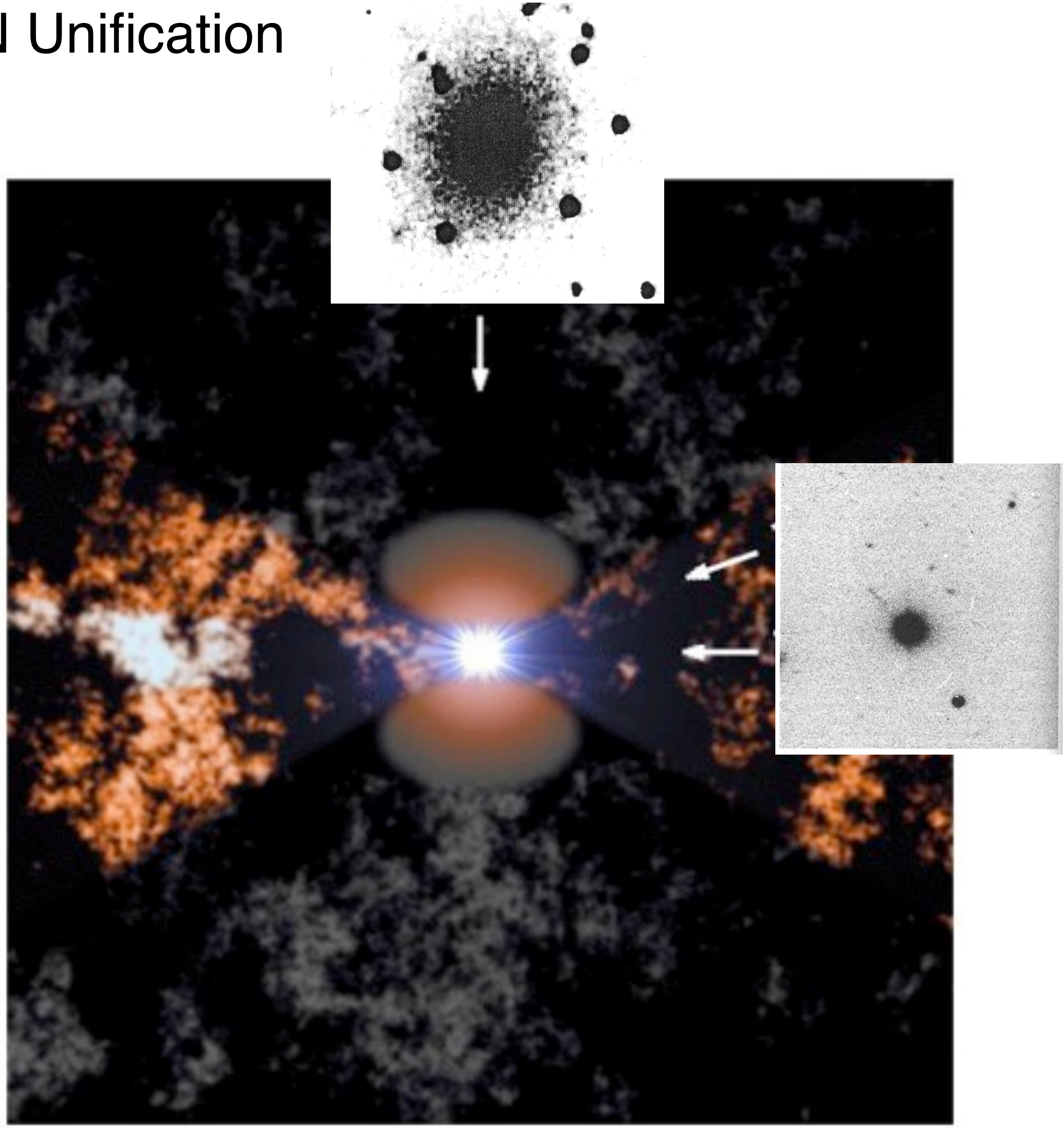
Models require:
L_{kin}~0.05-0.1L_{ed}

Galaxy merger simulations

di Matteo et al. (2005)

Models require:
$L_{kin} \sim 0.05\text{-}0.1 L_{ed}$

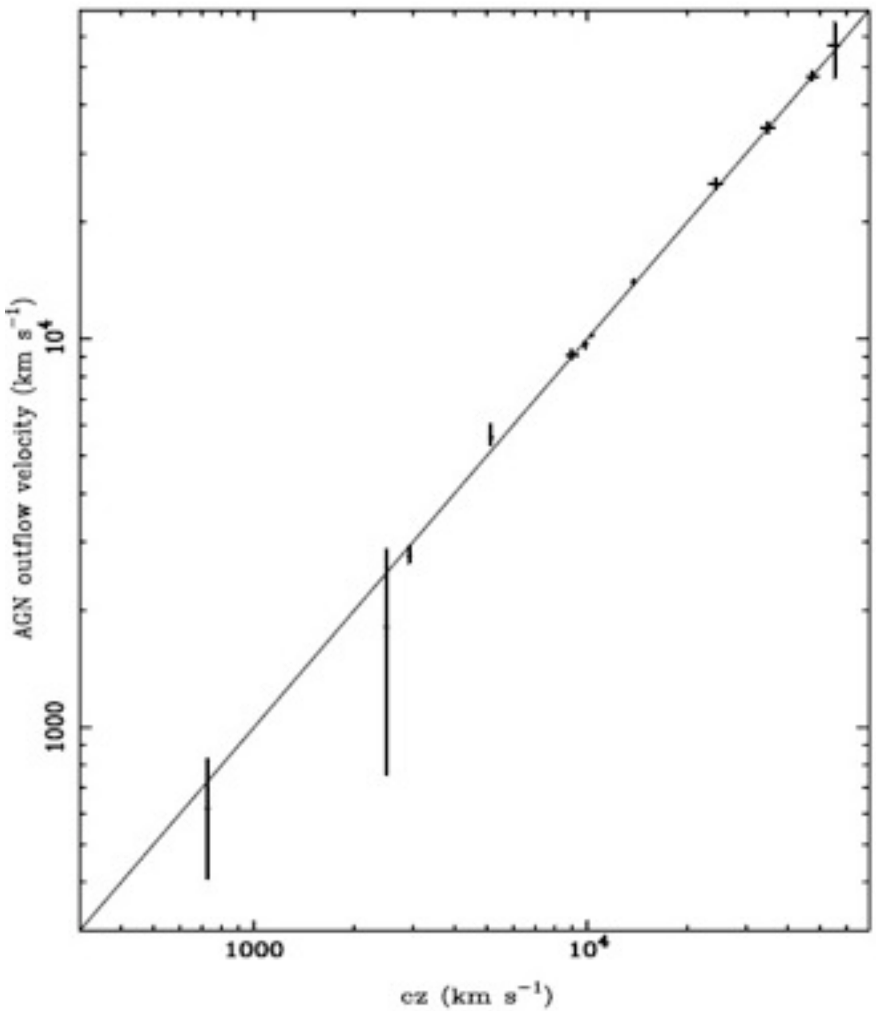
AGN Unification



Barthel (1989)

Intrinsic or local (Galactic) X-ray absorption?

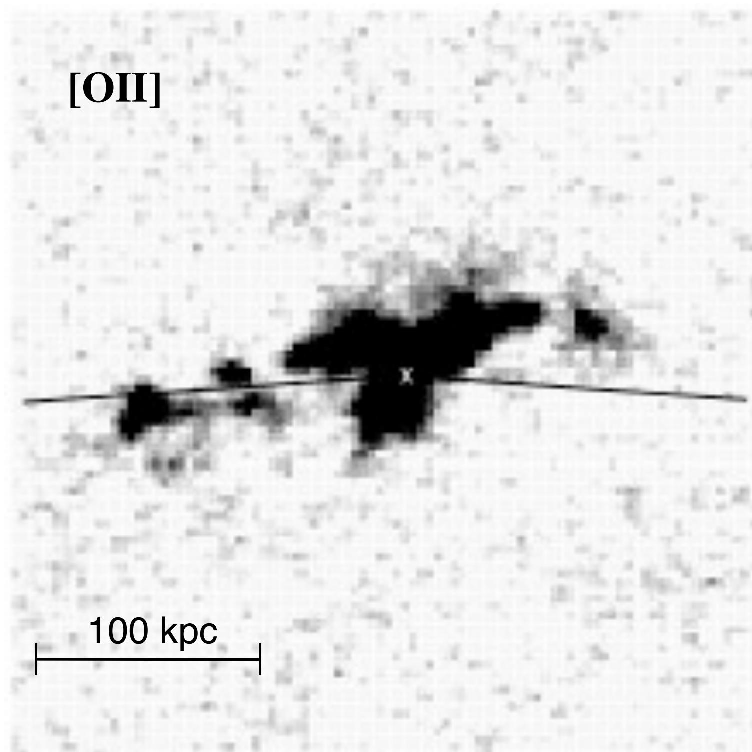
Inferred outflow velocity -->



McKernan et al. (2004)

cz -->

Outflows in 3C265 (z=0.82)



Solorzano Innarea et al. (2002)
Taurus Tunable Filter on WHT

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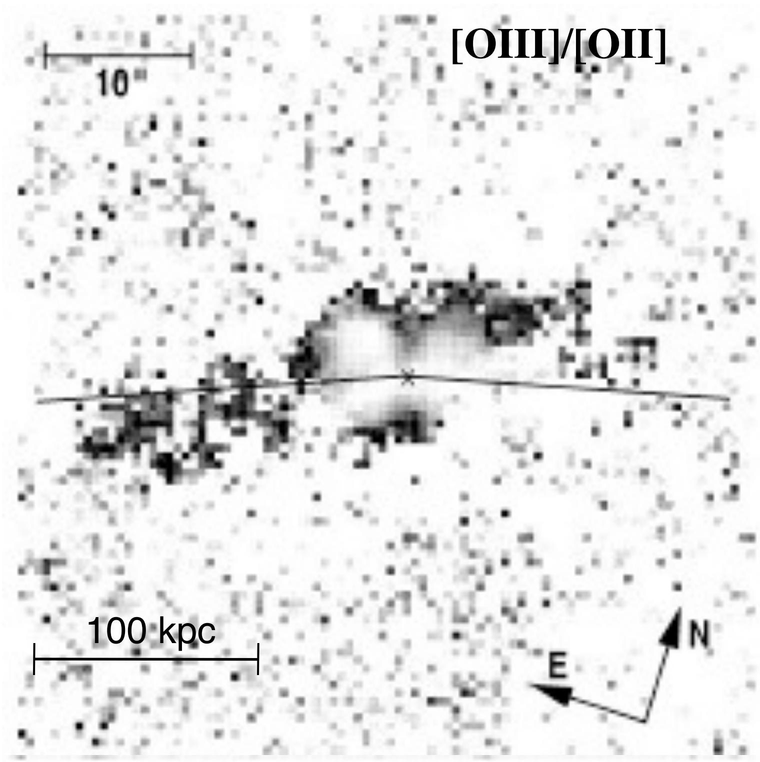

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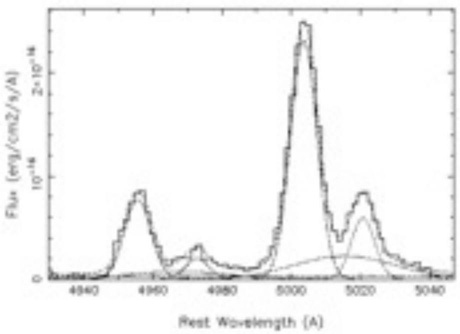
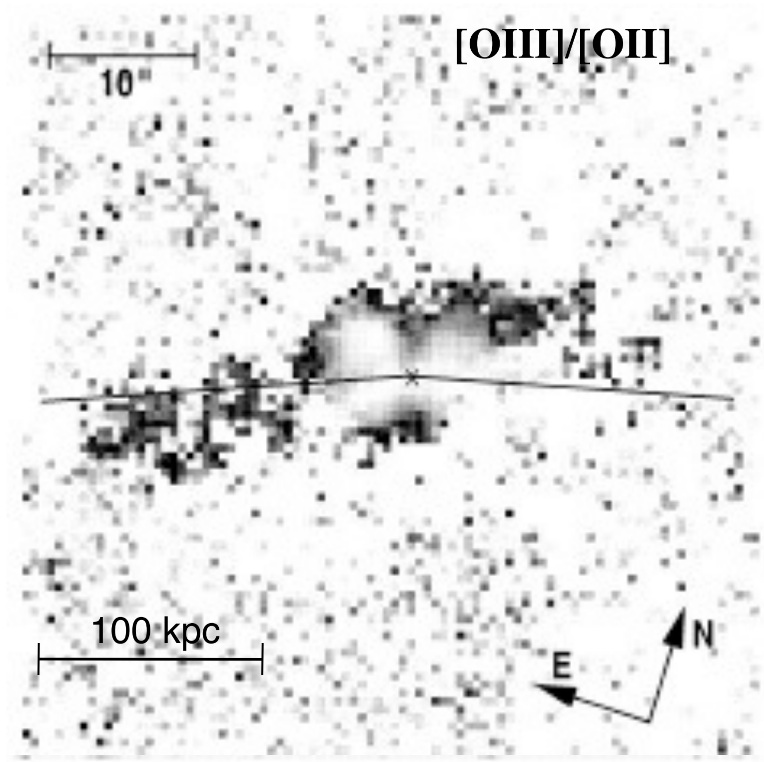
High velocity cloud



Tadhunter (1991)



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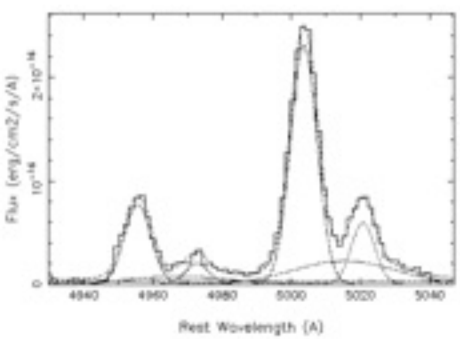

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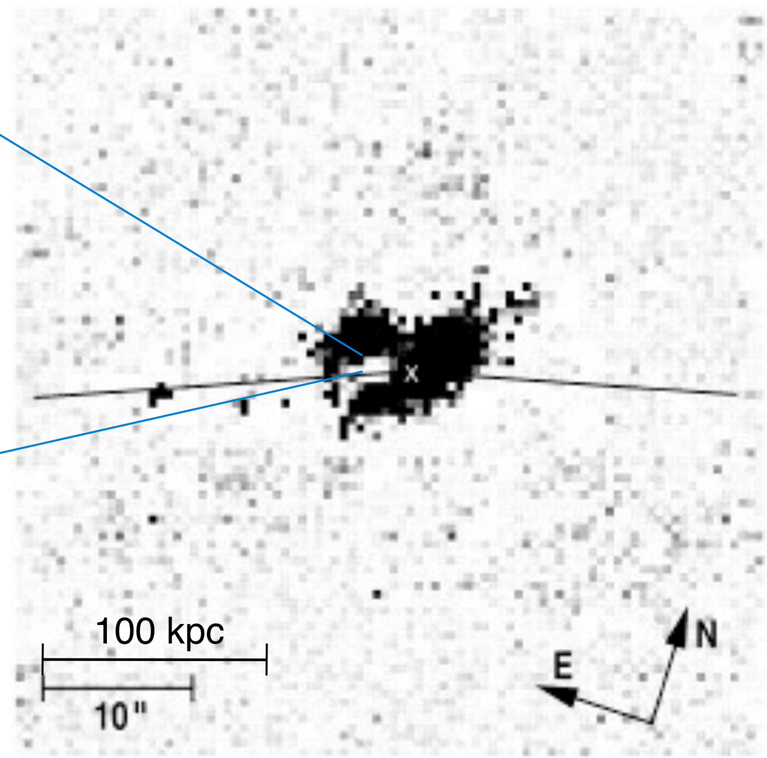

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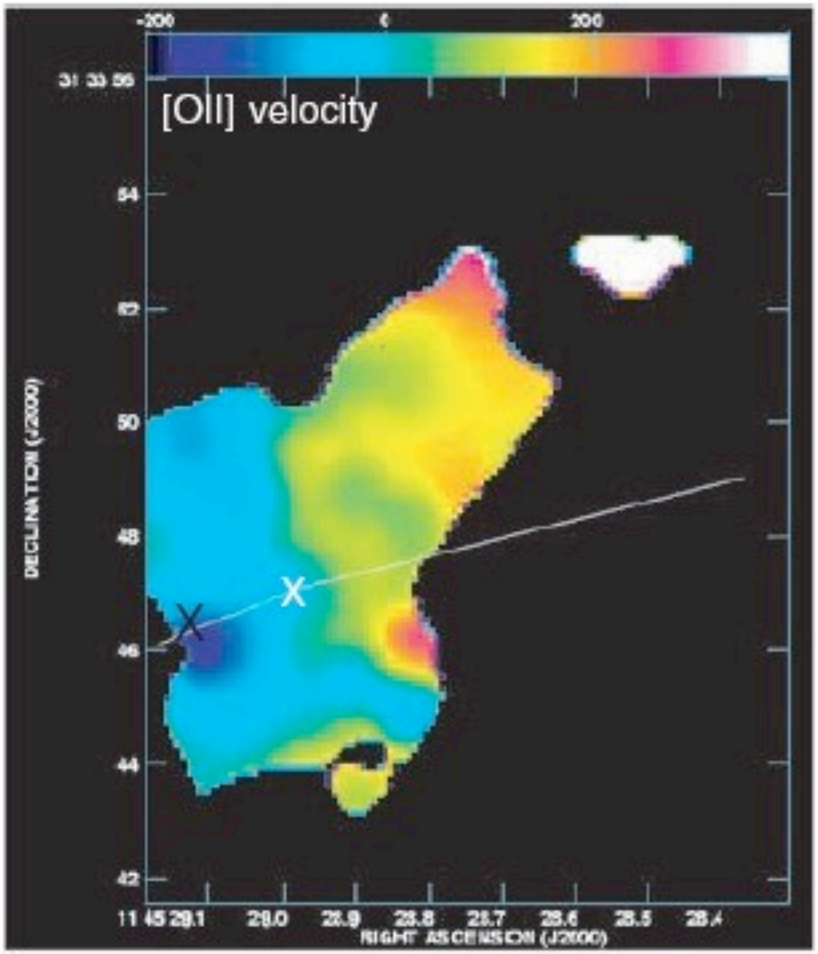
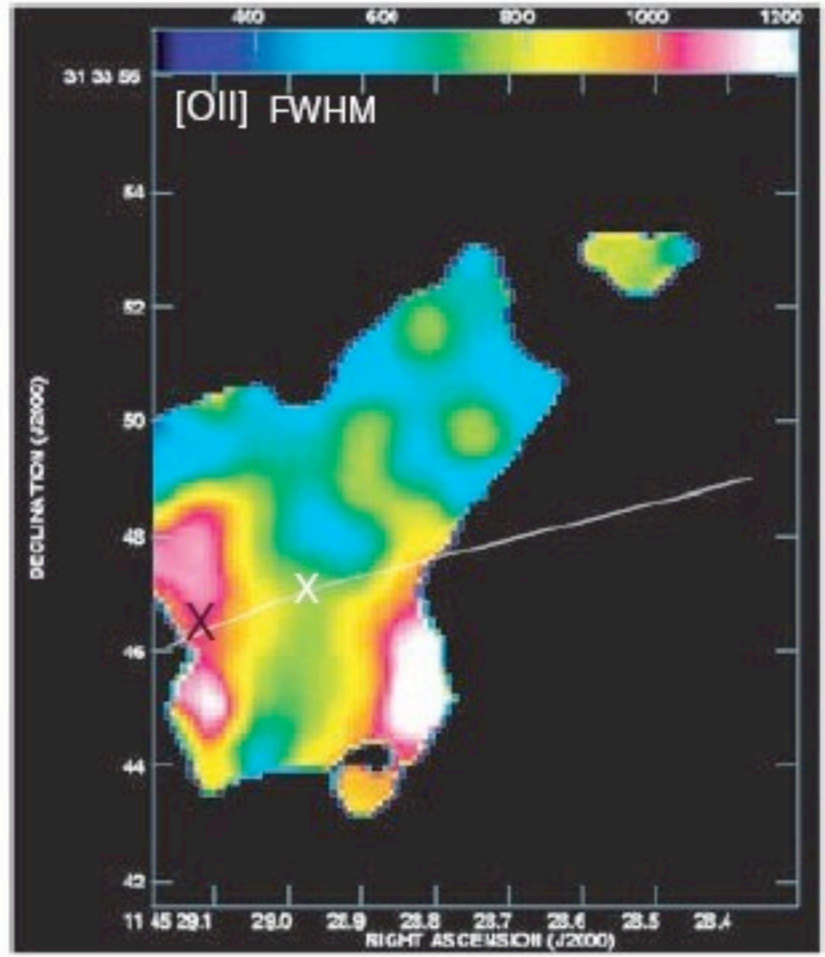
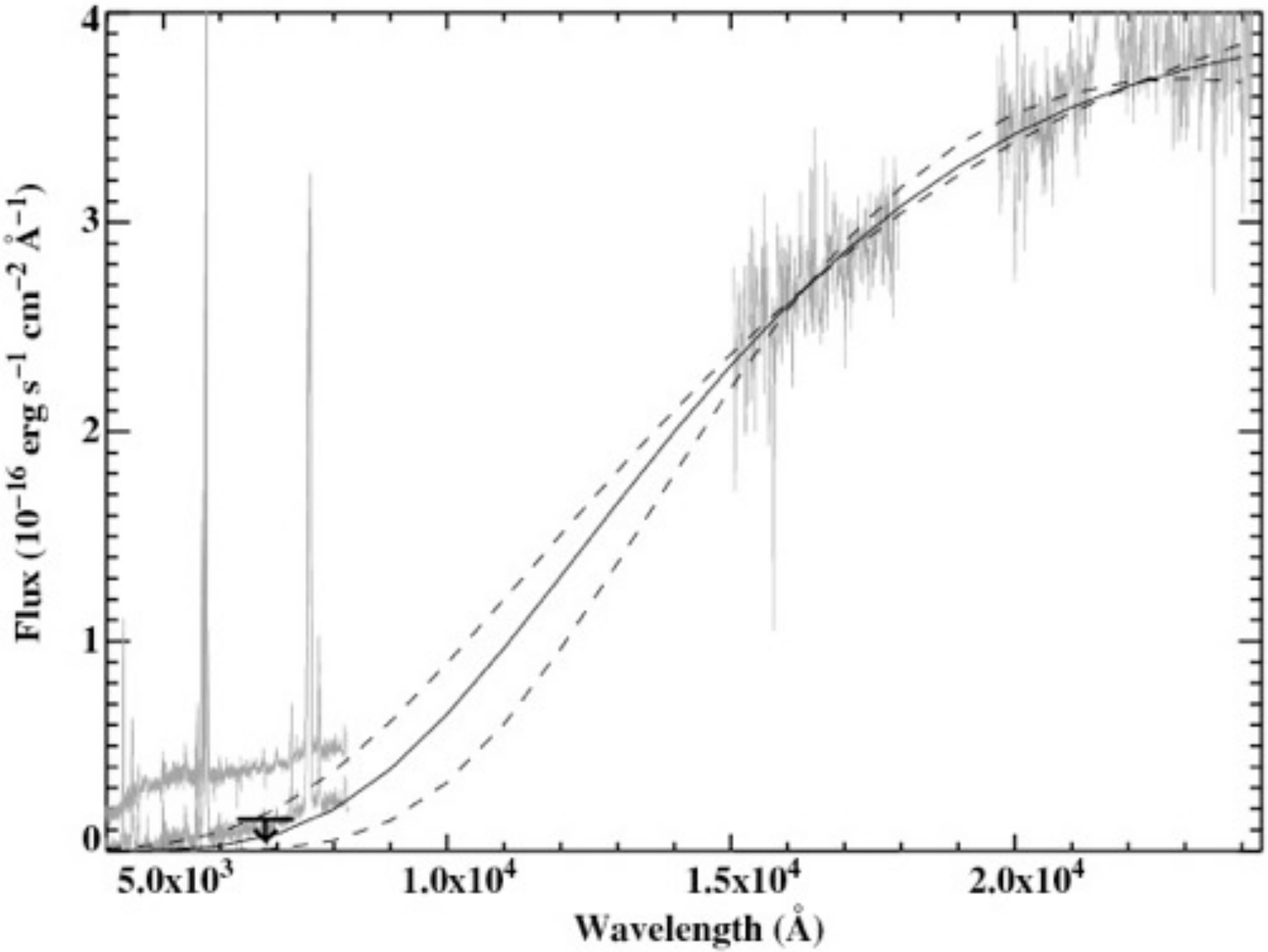
Integral field spectroscopy of 3C265





Solorzano Innarea et al. (2003)
WHT+Integral

Optical/near-IR continuum SED



VLT+
FORS2

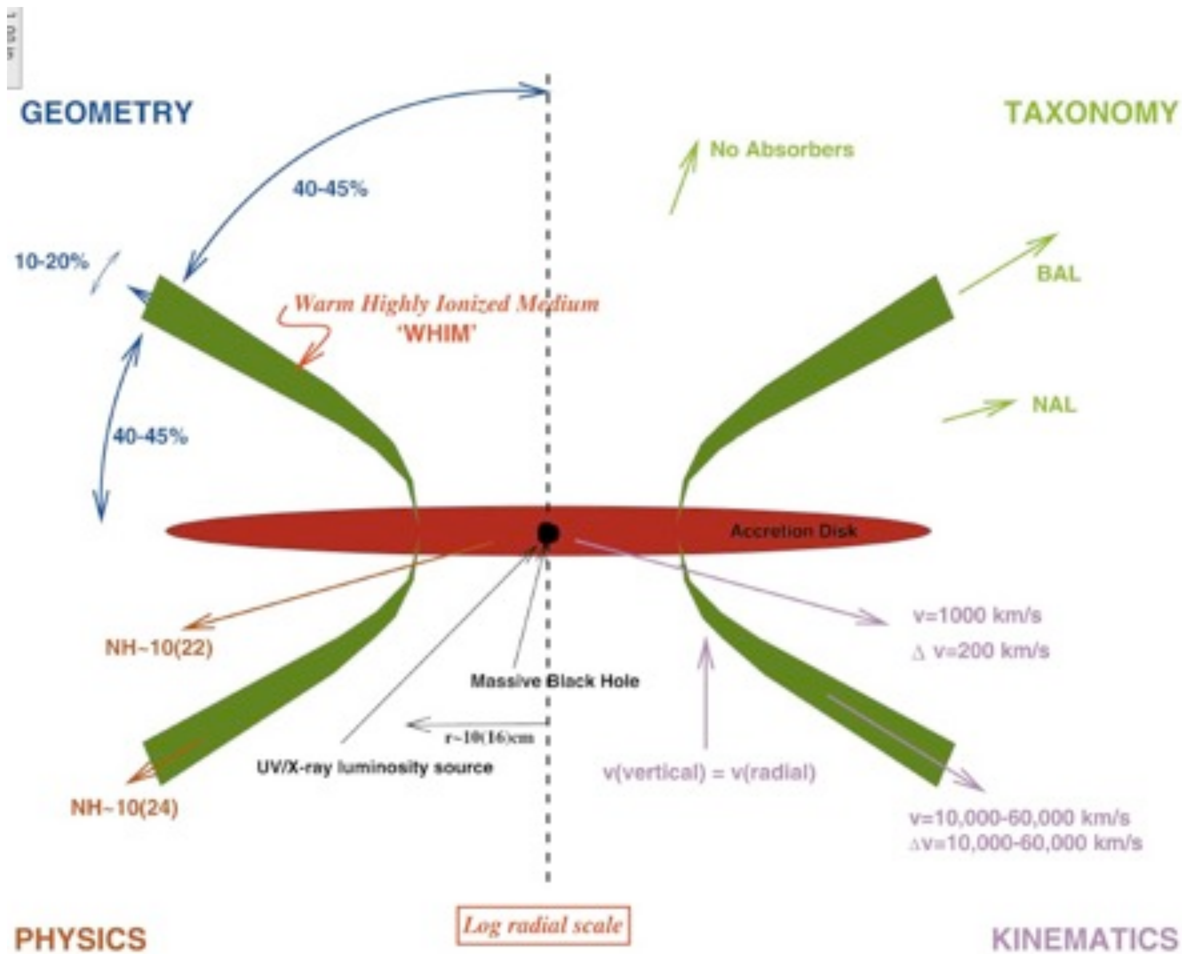
NTT+
SOFI

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

$6.4 < A_v < 13.2$

Holt et al. (2006)

Disk wind models of outflowing absorbers



Elvis (2000)

What next?

- Neutral outflows: sensitive searches for neutral outflows in complete samples of AGN using NaID line
- Highly ionized warm/hot outflows: continuing searches at X-ray wavelengths, perhaps also using optical/IR coronal lines
- Most promising targets: ULIRGs, NLSy1 -- objects with large Eddington ratio -- perhaps also the population of red quasars detected in near-IR surveys

Outflows in AGN and starbursts: comparison

- Neutral outflows in ULIRG/LIRGS:
- Jet-cloud interactions in radio galaxies:
- Warm outflows in radio galaxies (NLR):
- Neutral (HI) outflows in radio galaxies (NLR):
- High ionization X-ray absorber in PDS456:

Outflows in AGN and starbursts: comparison

- Neutral outflows in ULIRG/LIRGS: $9 < \dot{M} < 316\ M_{sun} yr^{-1}$

$$4 \times 10^{-5} < \dot{E}/L_{edd} < 1 \times 10^{-2} \quad 2 \times 10^{41} < \dot{E} < 6 \times 10^{43} erg\ s^{-1}$$

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$$1 < \dot{M} < 60\ M_{sun} yr^{-1}$$

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- High ionization X-ray absorber in PDS456: $\dot{M} \sim 10\ M_{sun} yr^{-1}$

  $\dot{E}/L_{edd} \sim 0.1$ $\quad \dot{E} \sim 10^{46} erg\ s^{-1}$

Black hole growth/feedback models: the quasar mode

- AGN and starbursts triggered in major galaxy mergers
- The black holes grow rapidly through merger-induced accretion; in some phases this accretion occurs at close to the Eddington rate
- The major black hole growth phase is obscured by the large concentration of dust/gas concentrated in the nucleus by the merger
- The AGN drive powerful outflows that remove the gas from the central regions and halt both star formation and further accretion
- The models require that ~5-10% of the accretion power of the AGN drives the winds

(e.g. di Matteo et al. 2005, Hopkins et al. 2005)