Giant Outflows in z~2 Radio Galaxies

"Smoking Gun" Evidence for AGN feedback at the Quasar Peak

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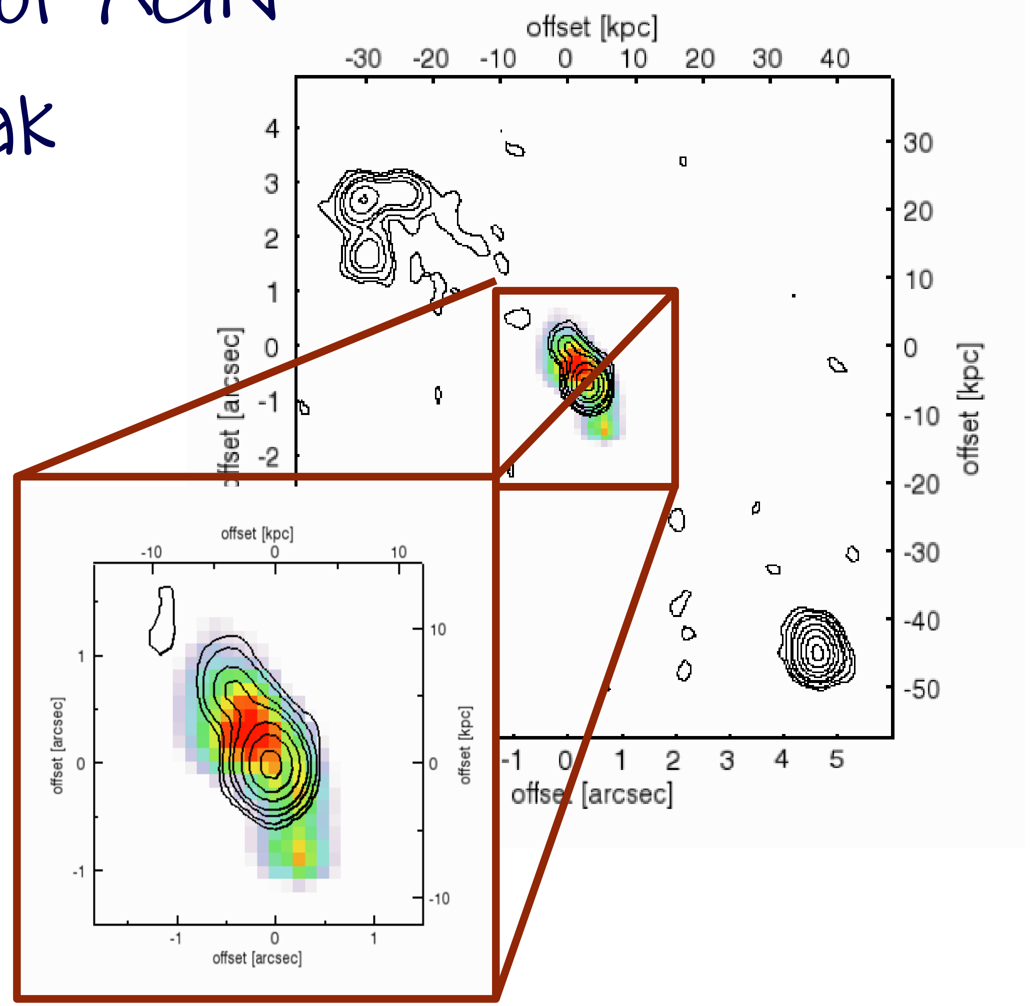
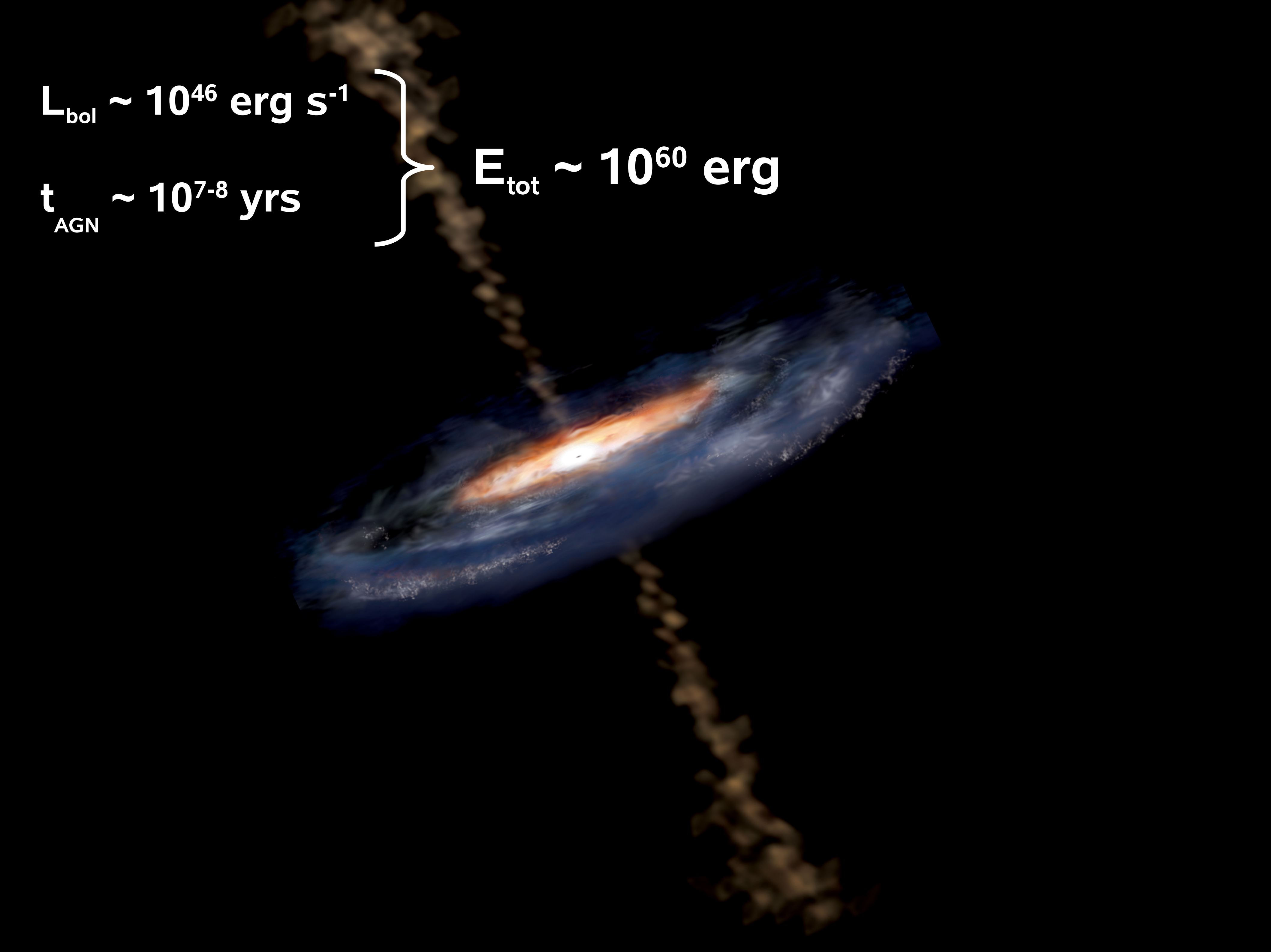
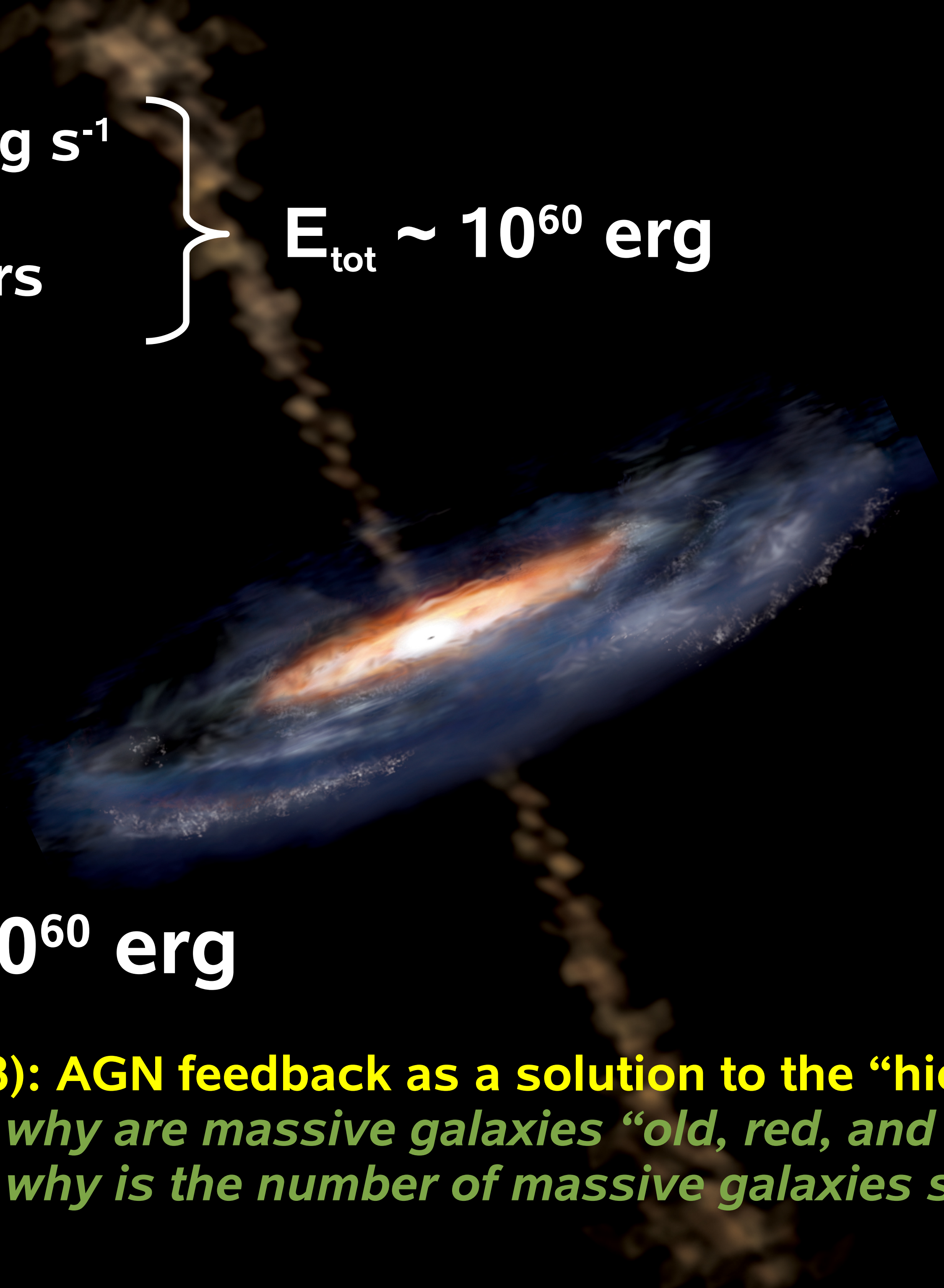


MARIE CURIE ACTIONS

European Commission
Research Directorate General
Human Resources and Mobility



$L_{bol} \sim 10^{46}$ erg s^{-1}
$t_{AGN} \sim 10^{7-8}$ yrs
$E_{tot} \sim 10^{60}$ erg



$L_{bol} \sim 10^{46}$ erg s^{-1}

$t_{AGN} \sim 10^{7-8}$ yrs

$E_{tot} \sim 10^{60}$ erg

$E_{bind} = 10^{60}$ erg

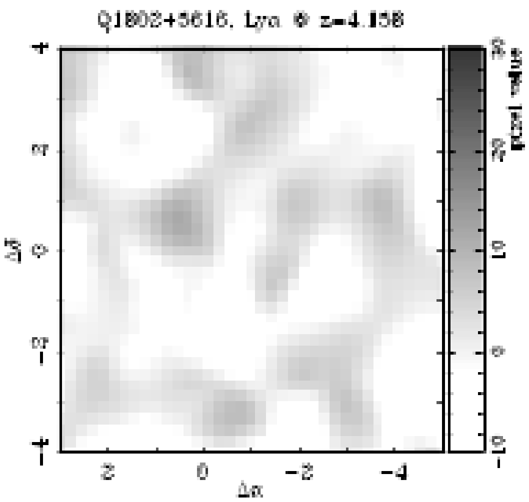
Silk & Rees (1998): AGN feedback as a solution to the "hierarchy problem"

why are massive galaxies "old, red, and dead" ?

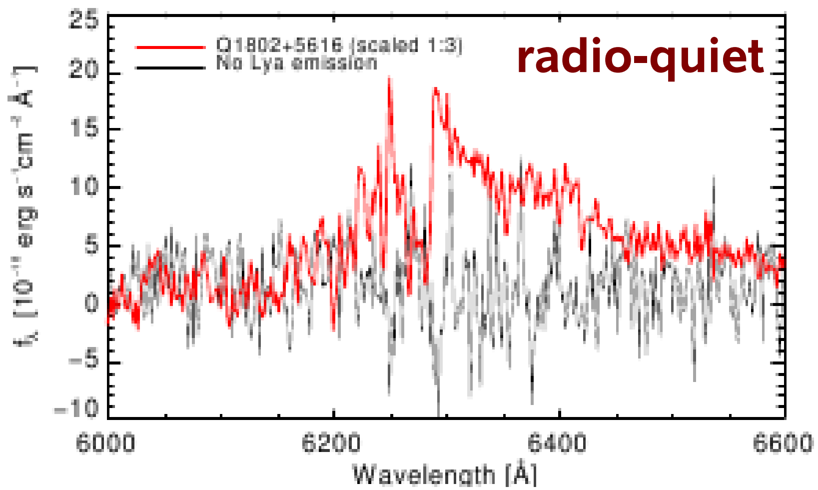
why is the number of massive galaxies so small ?

Kpc-scaled winds in powerful AGN?

PMAS, Calar Alto



Christensen et al. (2006)

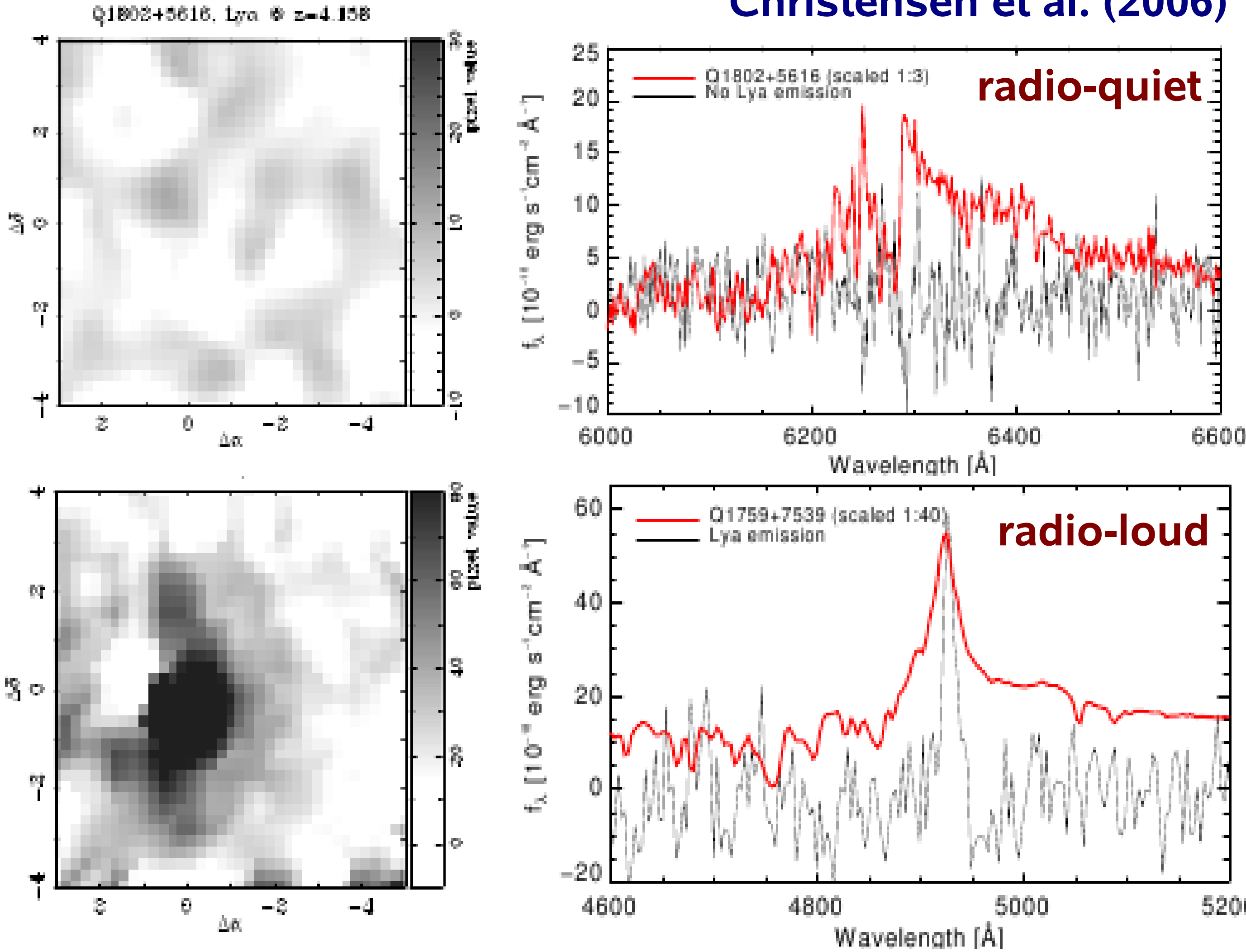


90 % of powerful AGN do not show extended gas ...

Kpc-scaled winds in powerful AGN?

PMAS, Calar Alto

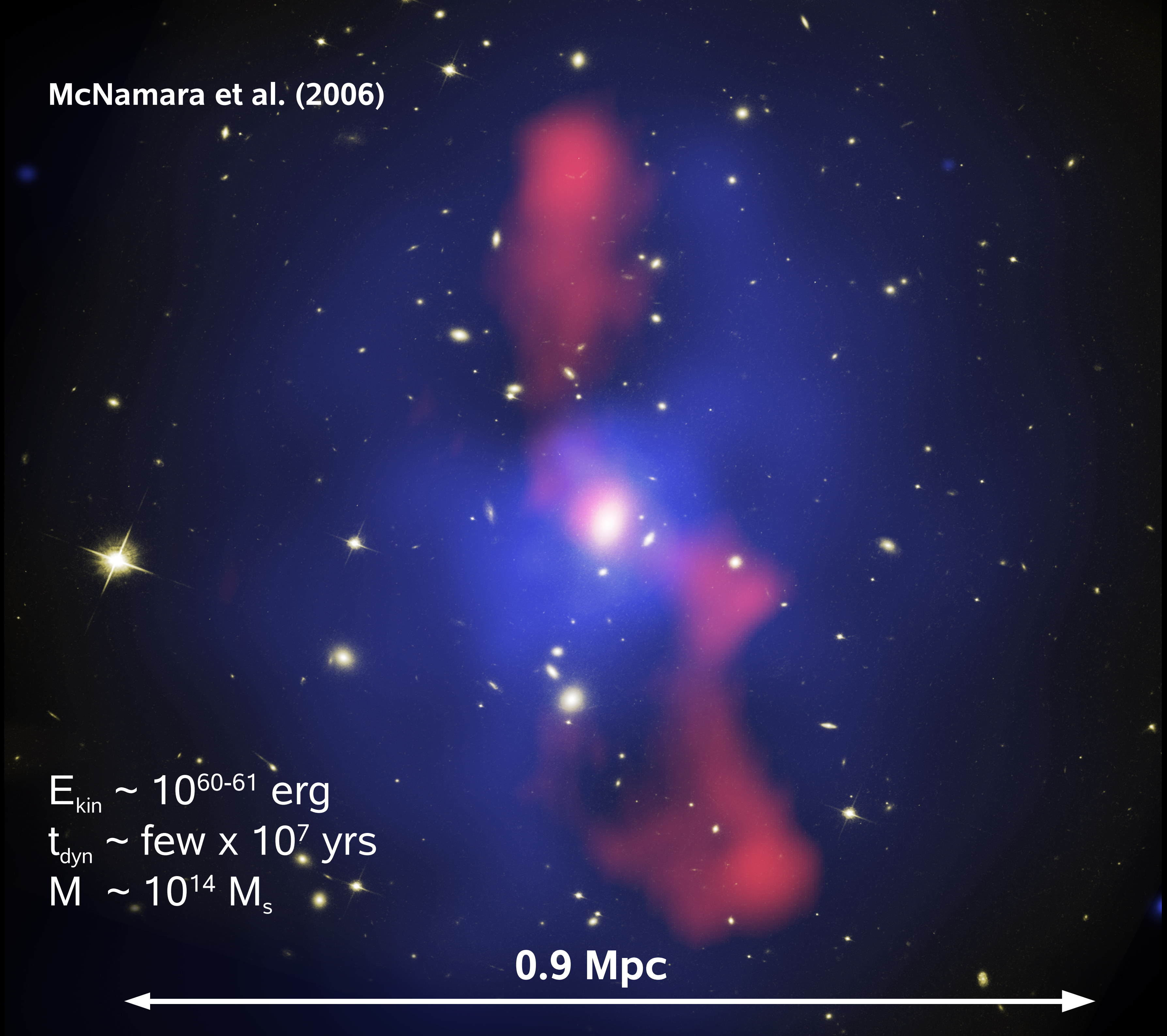
Christensen et al. (2006)



see also Heckman et al. (1989,1991)

90 % of powerful AGN do not show extended gas ...

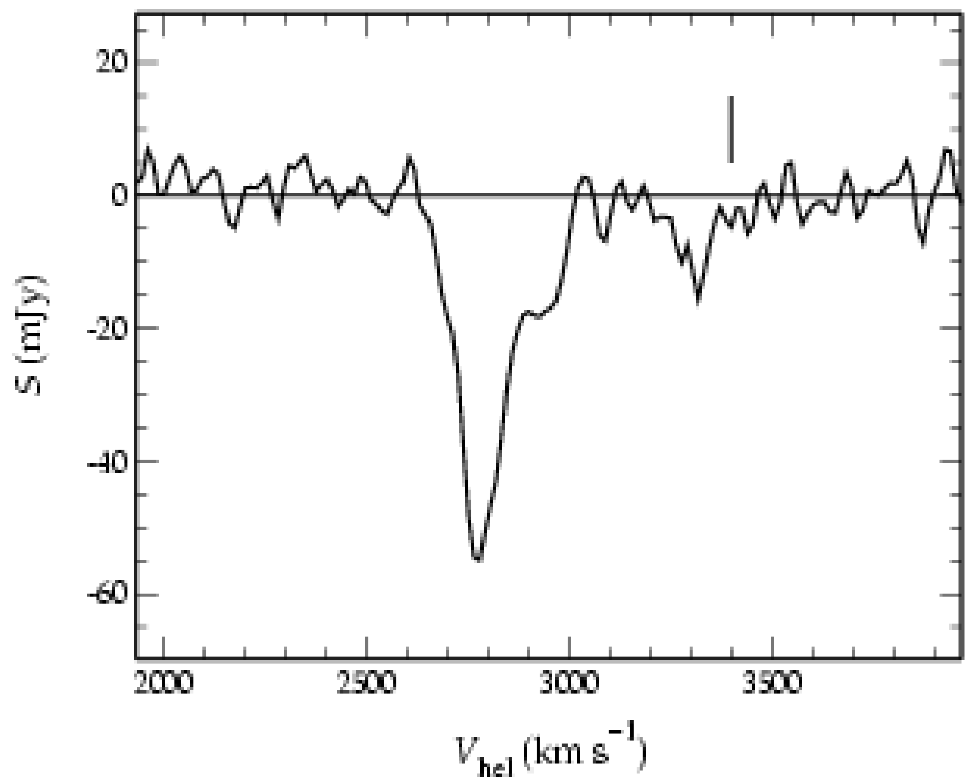
... those that do (10%) are radio-loud


McNamara et al. (2006)
$E_{kin} \sim 10^{60-61}$ erg
$t_{dyn} \sim$ few x 10^{7} yrs
$M \sim 10^{14}\ M_s$
0.9 Mpc

Impact on early-type galaxies at low z

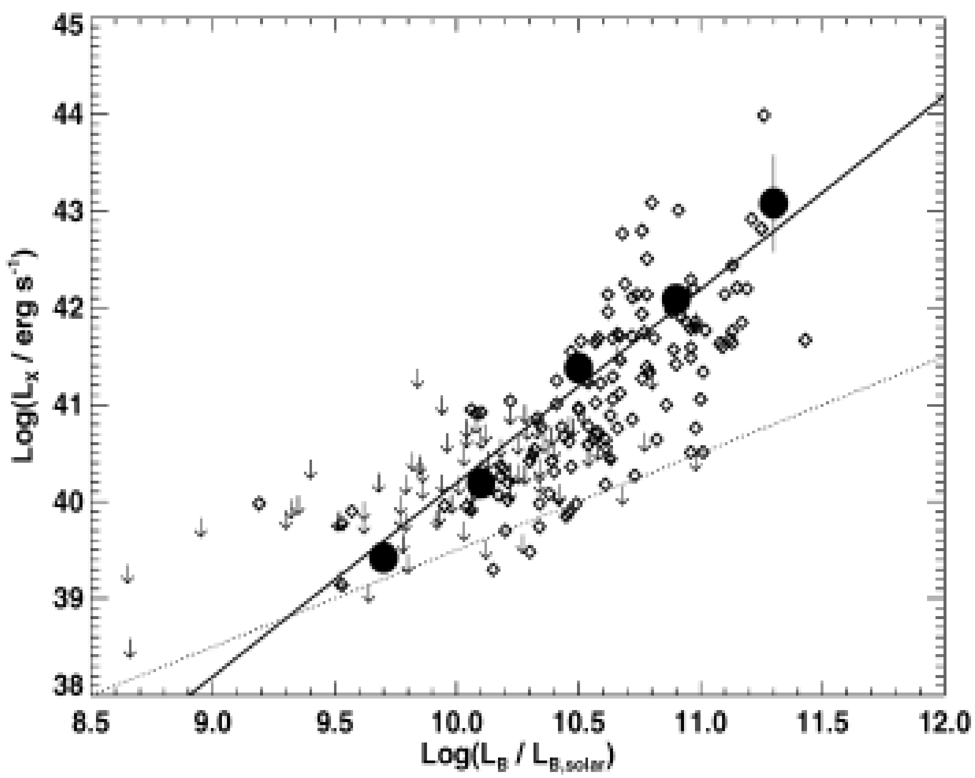
Morganti et al. (2005)

jet-driven outflows of neutral gas
nearby powerful radio galaxies



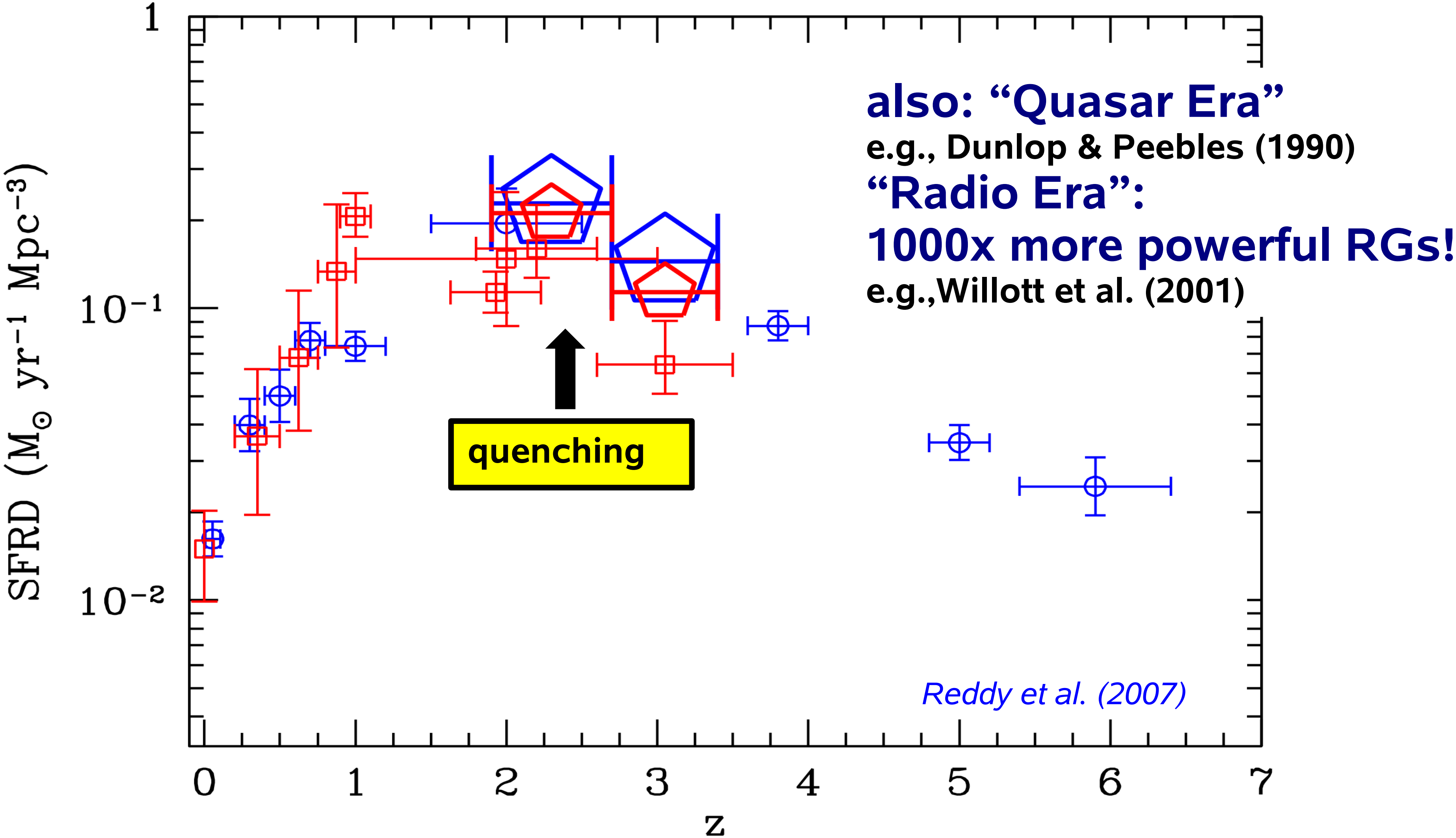
Best et al. (2006)

heating (radio source) ≈ cooling
SDSS study of nearby early-type galaxies



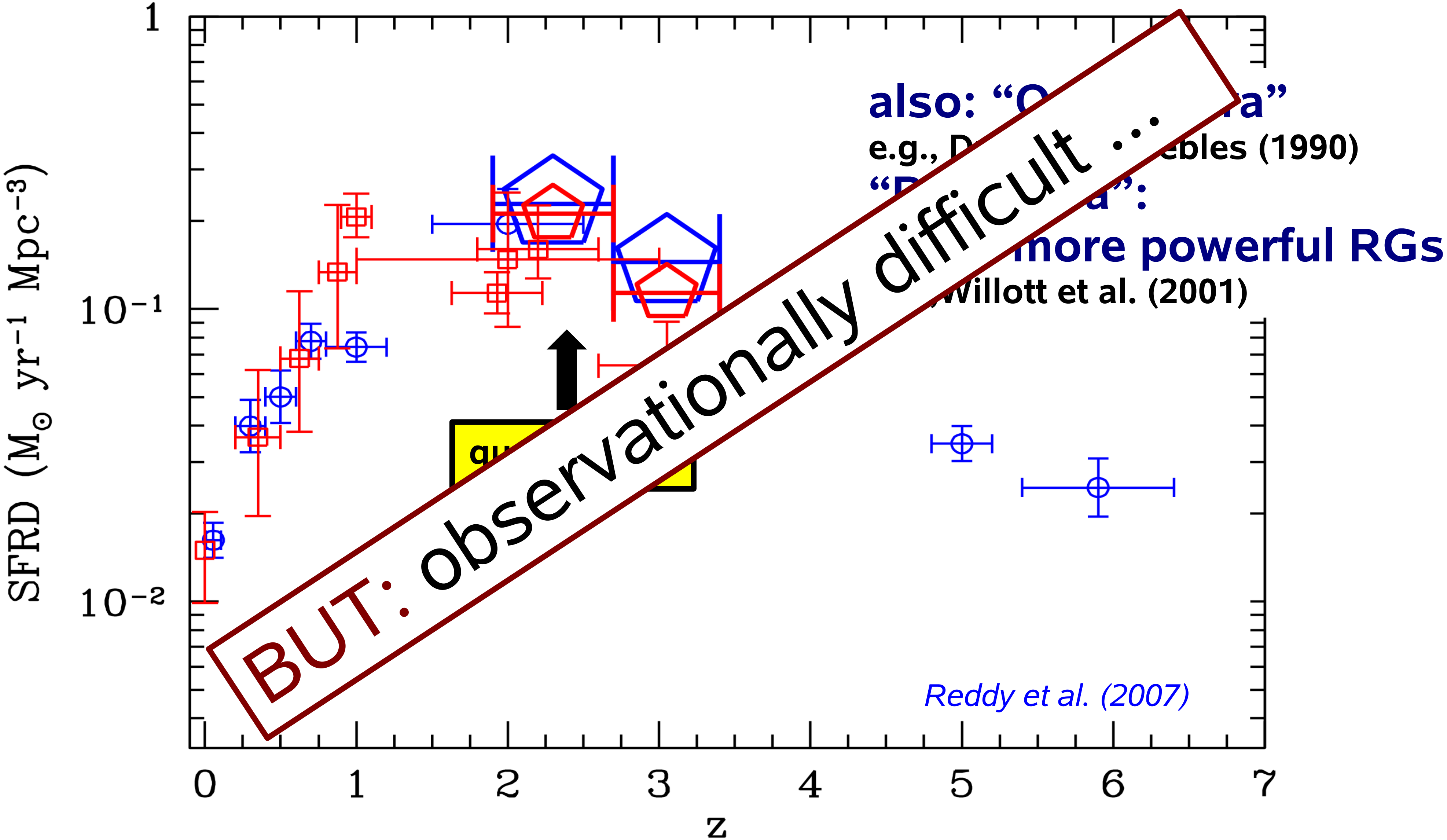
AGN outflows at high z ?

The star formation era



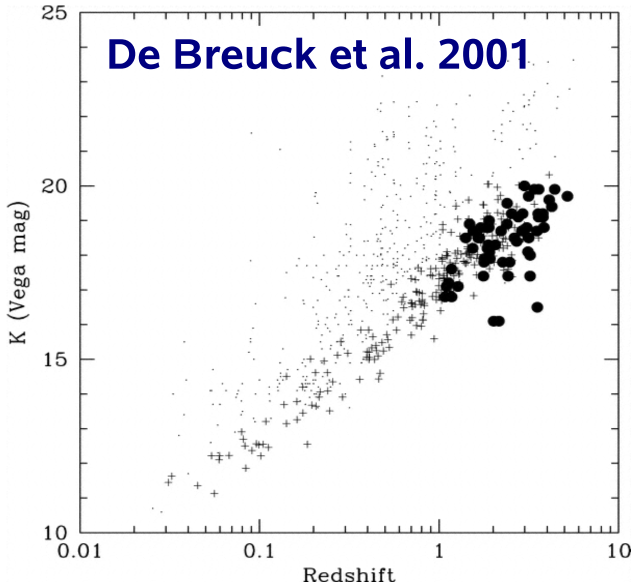
AGN outflows at high z ?

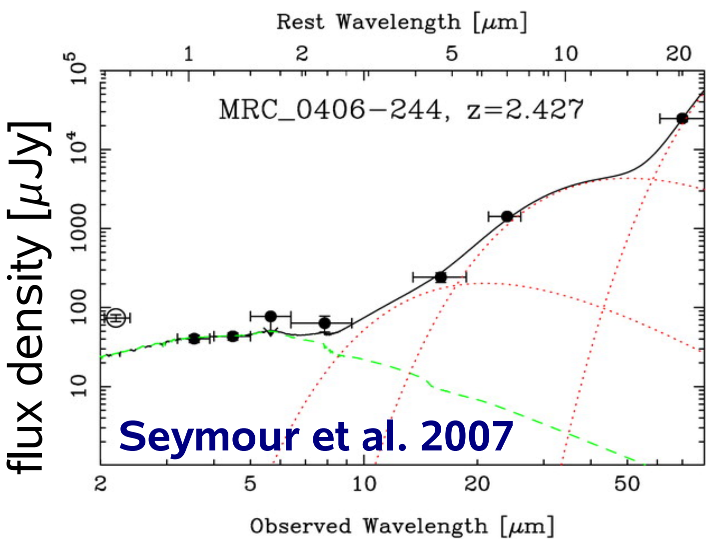
The star formation era

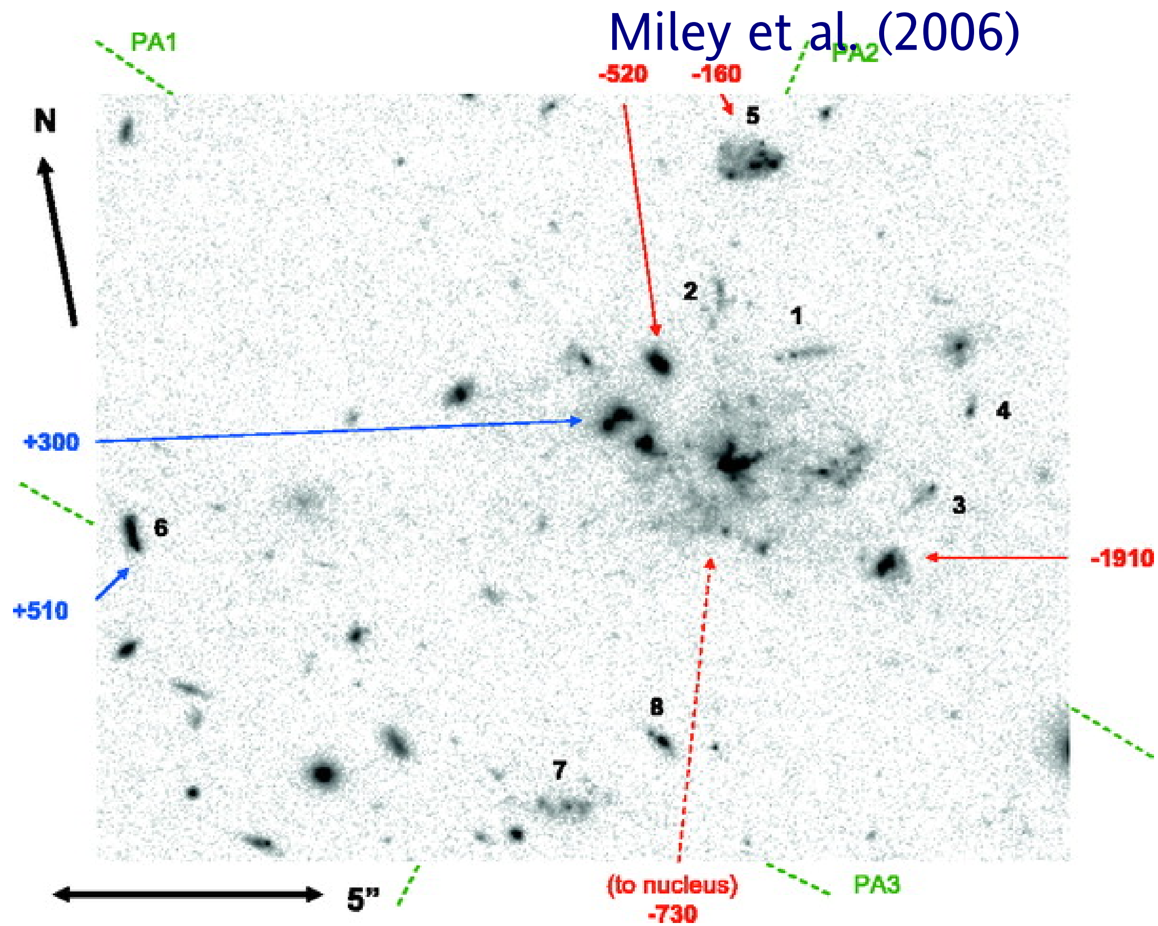


High-redshift radio galaxies

Tracing the upper end of the galaxy mass function at z>2





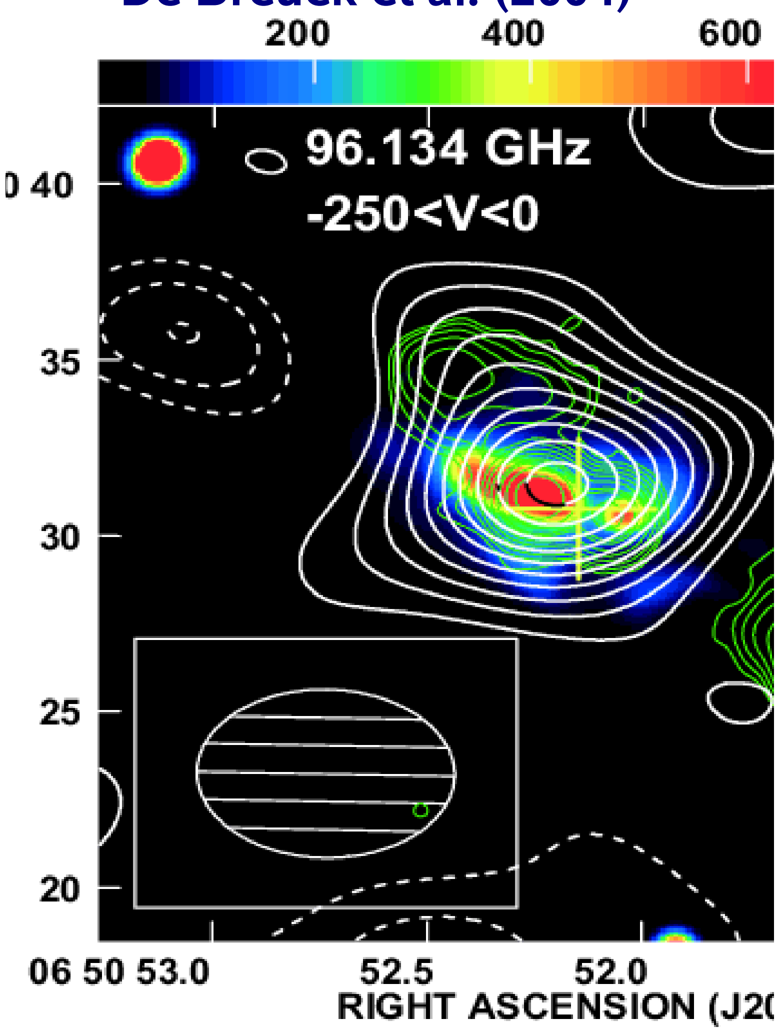


High-z RGs ≠ low-z RGs !

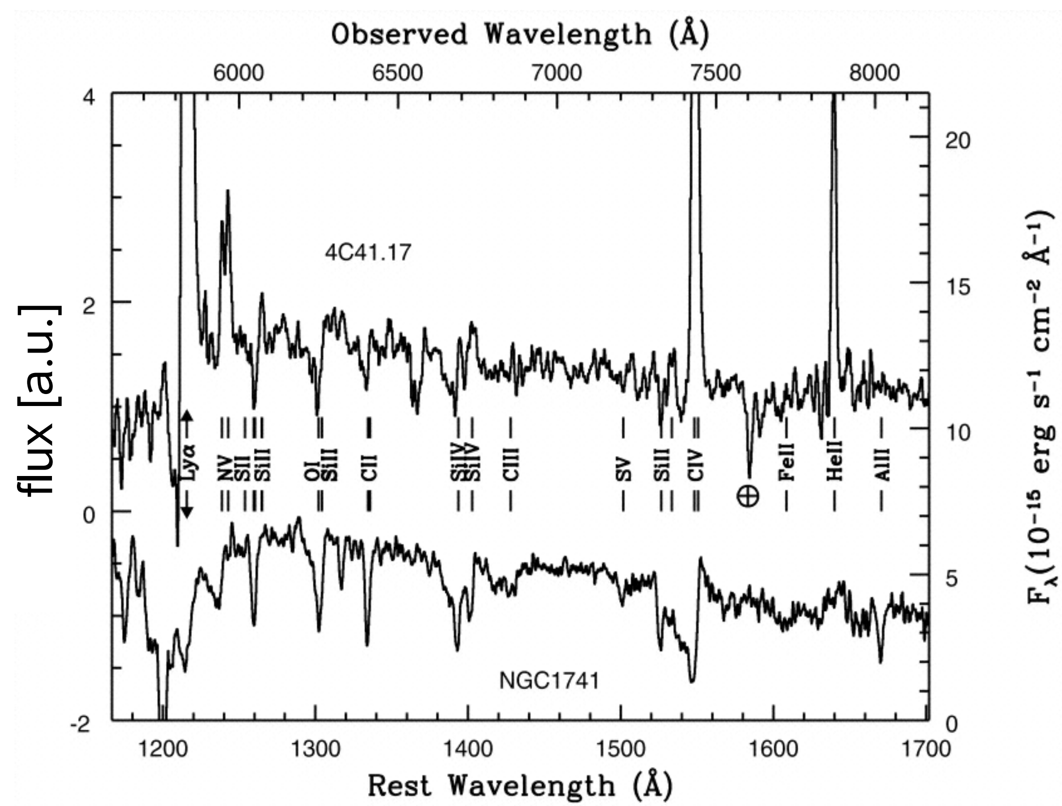
Very gas rich (f_{gas} ~ several x 10%), actively star-forming, SFR> 1000 M_{sun} yr^{-1}

e.g., Archibald et al. (2001)
Reuland et al. (2004)

De Breuck et al. (2004)

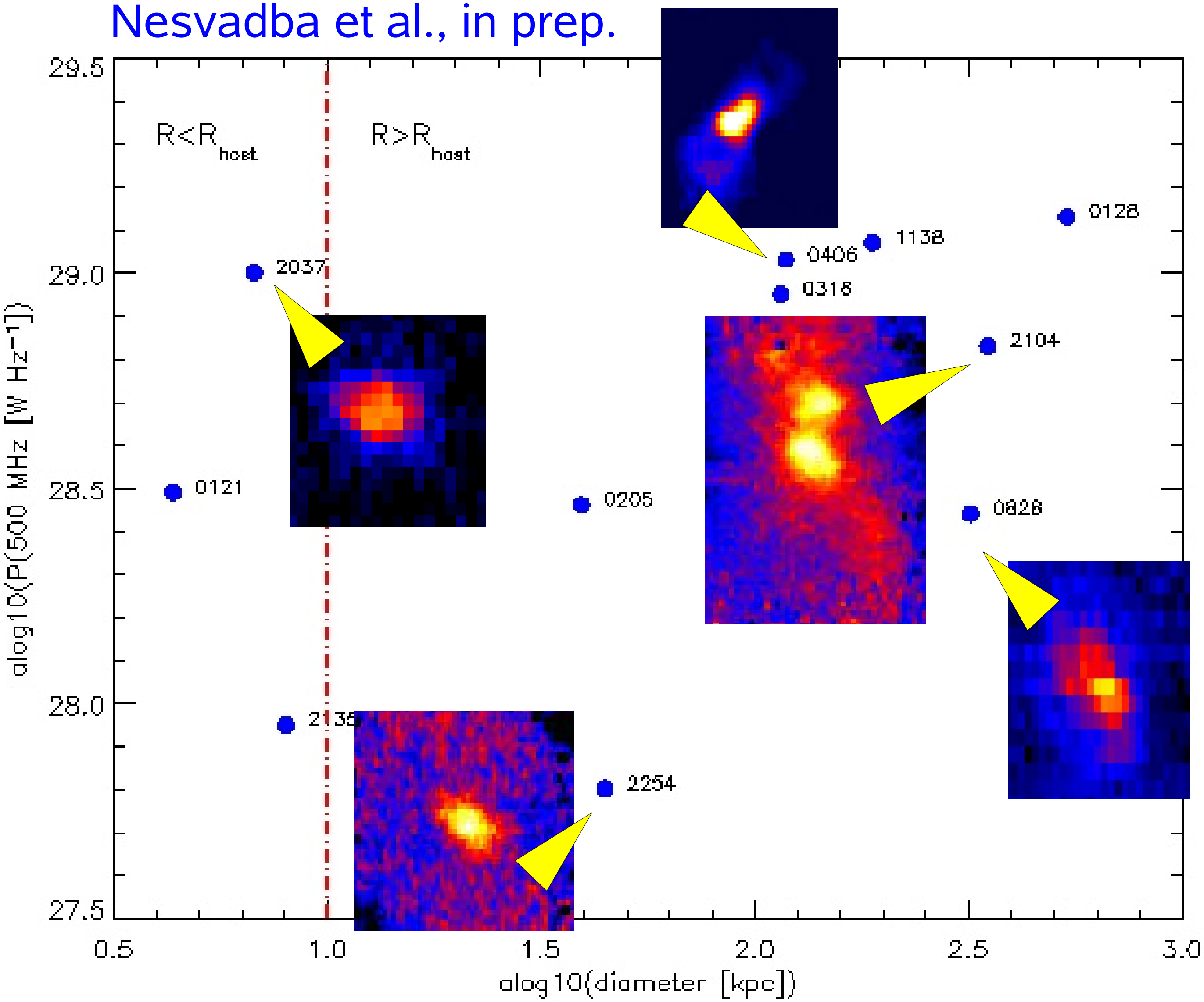


Dey et al. (1997)



A systematic study of z~2 radio galaxies

Nesvadba et al., in prep.



> 10^{46} erg s^{-1}

~ factor 100 in size

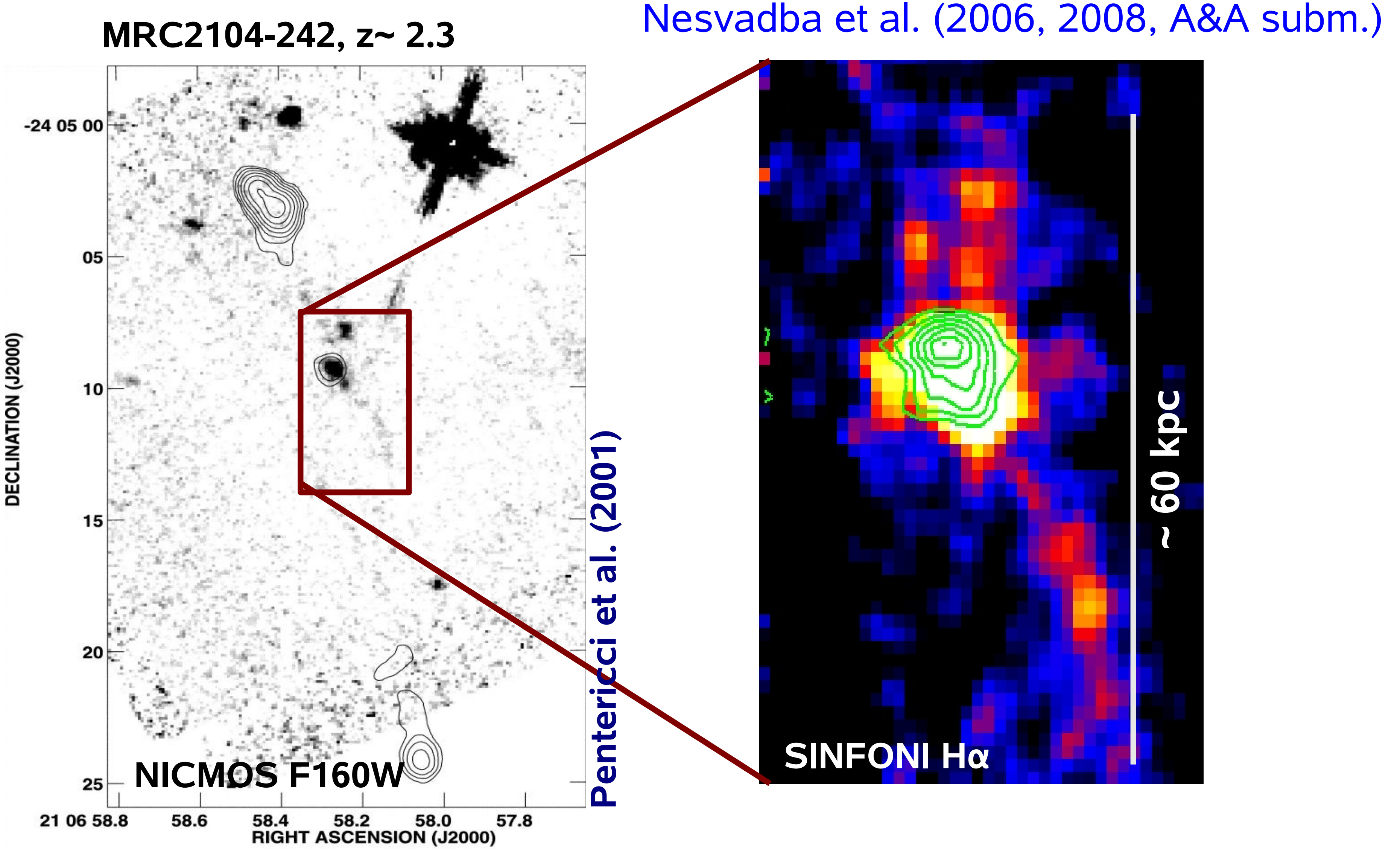
~ factor 100 in power

8 (D_{radio} ~ 30-100 kpc)
3 (D_{radio} < 10 kpc)

+12 more ....
(7 already taken)

Morphologies of high-z radio galaxies

Stellar continuum: compact; ionized gas: often extended

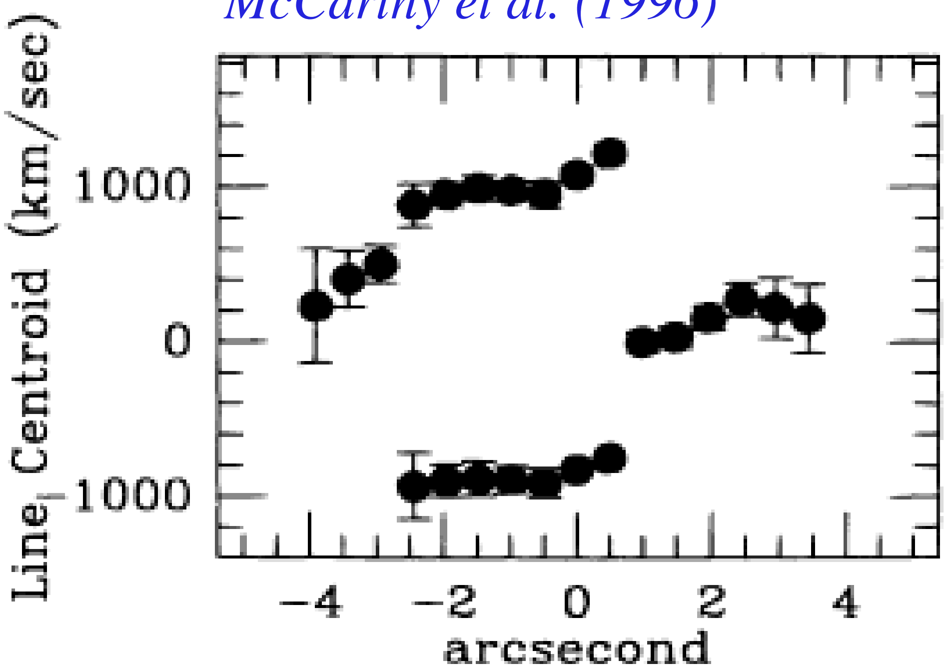


Gas kinematics

[OIII]5007 velocities / widths

MRC0406-244, z=2.42

McCarthy et al. (1996)



also: Tadhunter et al. (1991), Villar-Martin et al. (1999), Baum et al. (2000)

Gas kinematics

[OIII]5007 velocities / widths

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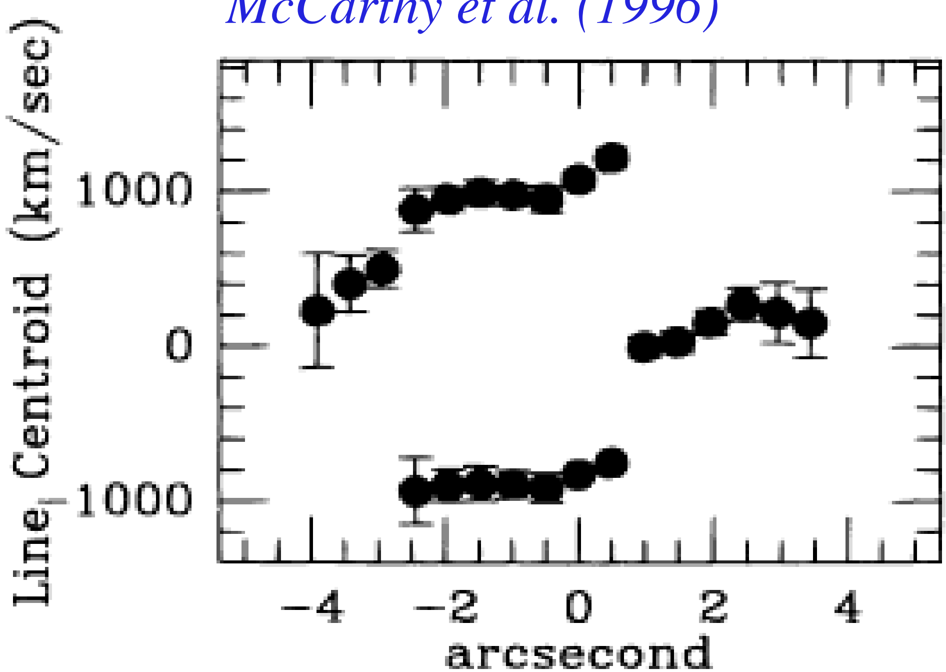
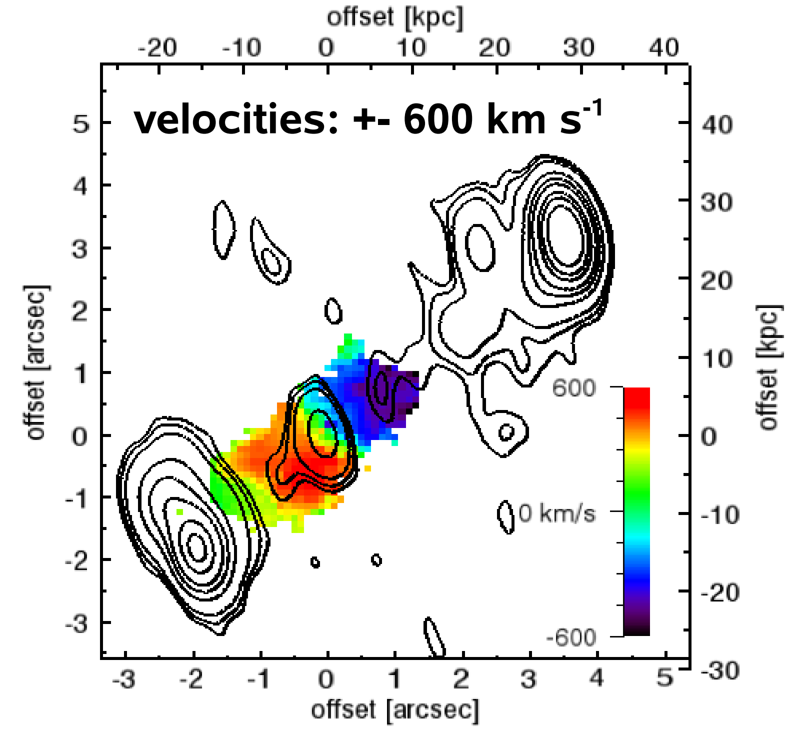
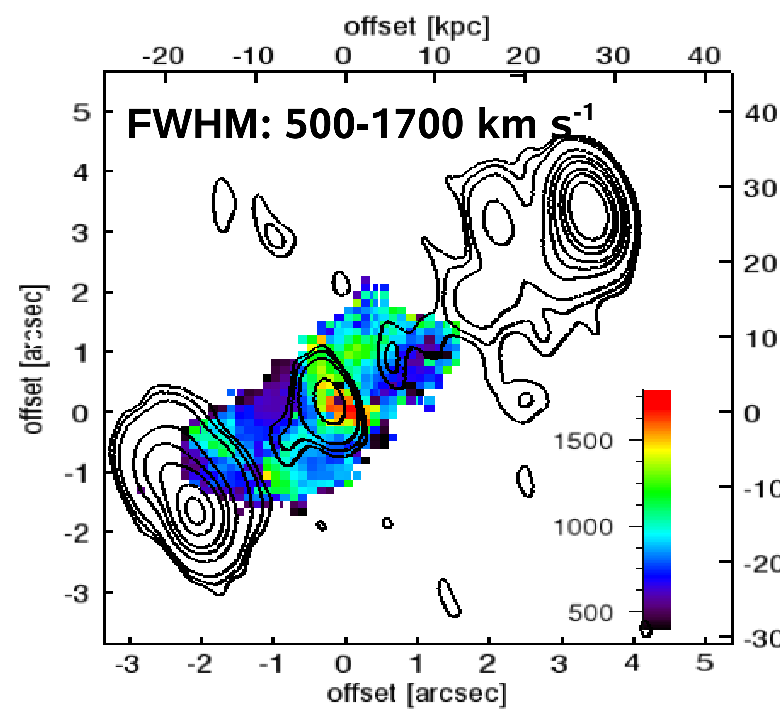






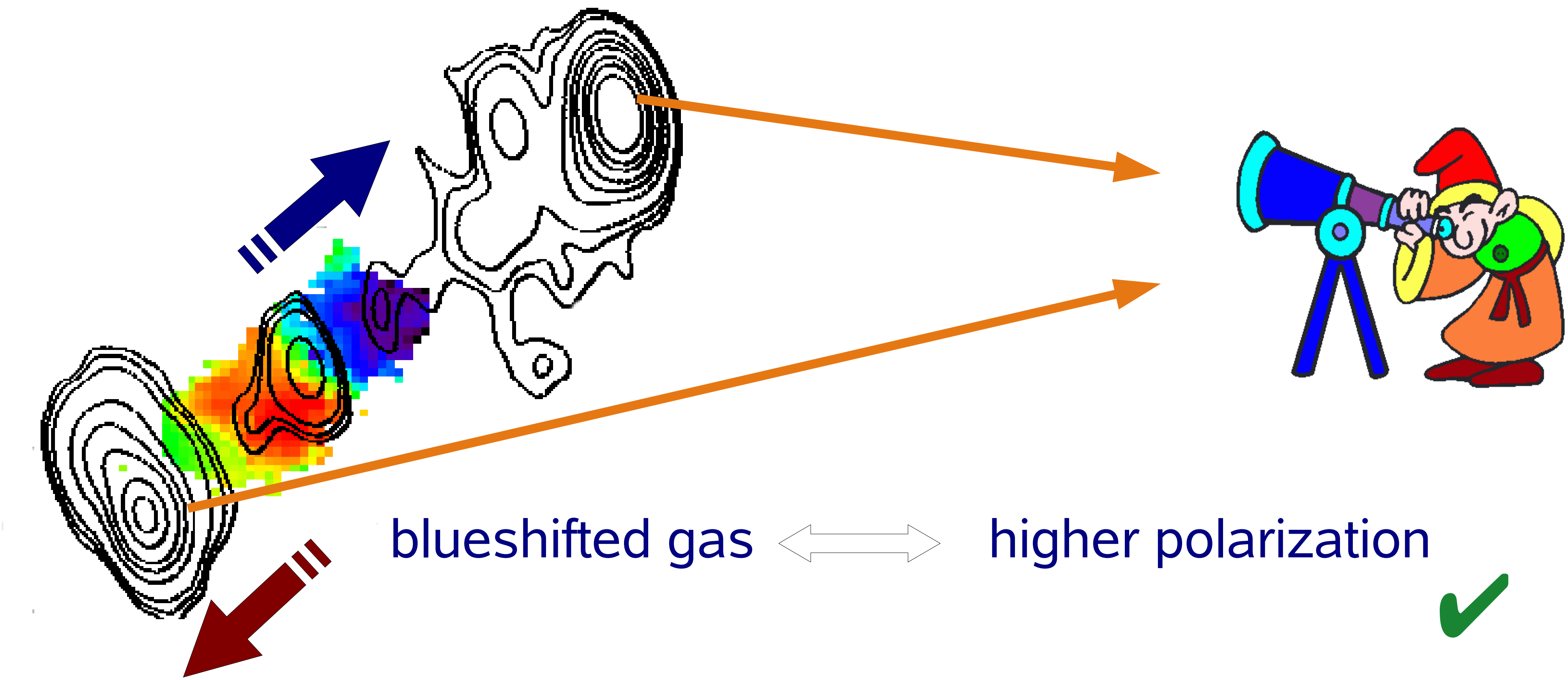
Nesvadba et al. (2008, A&A submitted)

Jet Orientation: Evidence for Outflows

Nesvadba et al. (2008), A&A submitted

passage through magnetized plasma ⟺ depolarization

"Laing-Garrington effect" Laing (1988), Garrington et al. (1988)

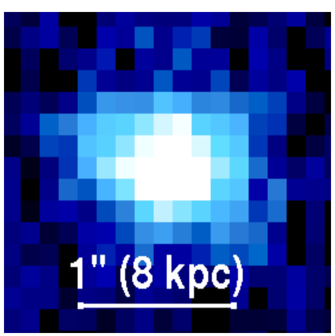


blueshifted gas ⟺ higher polarization ✔

Jet and ionized gas: Coordinated growth

predicted radio morphologies
(Sutherland & Bicknell, 2007)

observed emission line morphologies (Hα + [NII])



D_{radio} < 0.4” (2 kpc)

Jet and ionized gas: Coordinated growth

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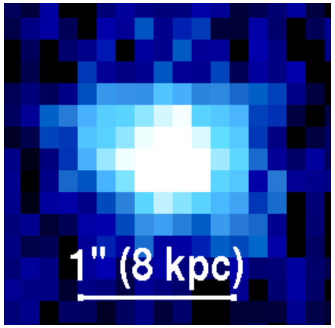

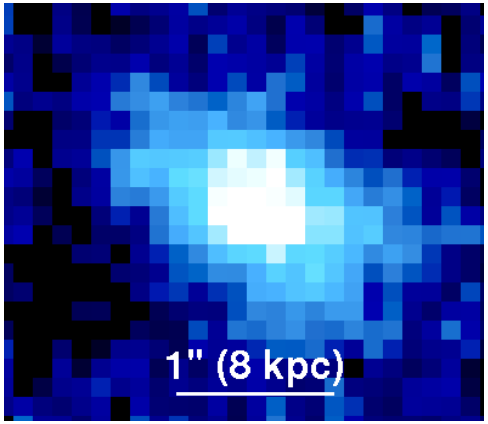

D_{radio} < 0.4" (2 kpc) **D_{radio} = 2.4" (20 kpc)**

Jet and ionized gas: Coordinated growth

predicted radio morphologies
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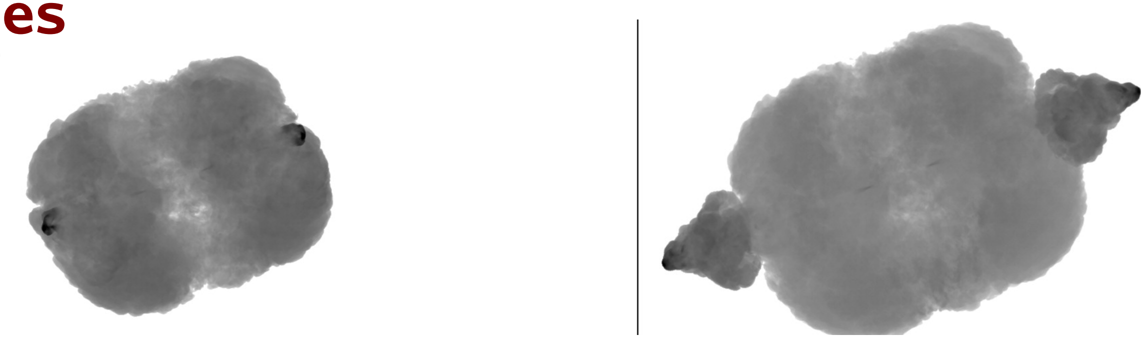
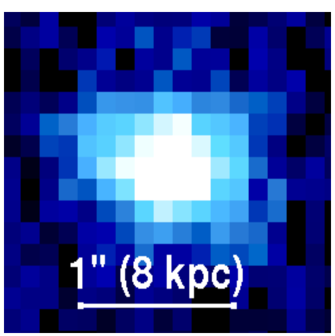
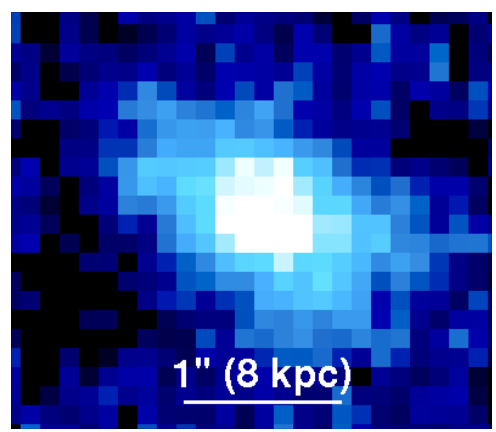
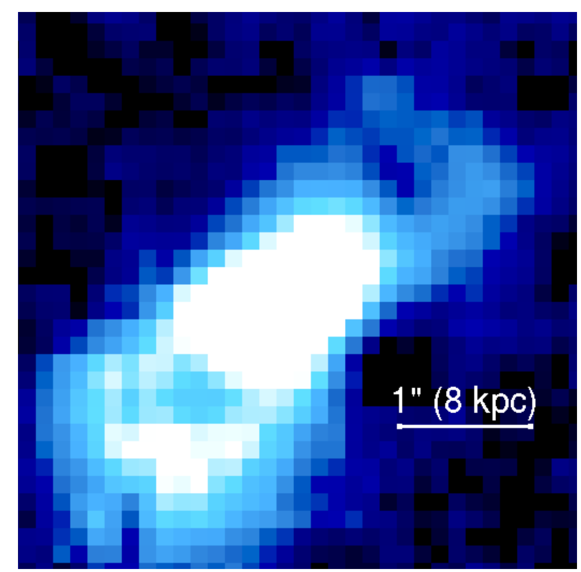


observed emission line morphologies (Hα + [NII])







D_{radio} < 0.4” (2 kpc) **D_{radio} = 2.4” (20 kpc)** **D_{radio} = 7.6” (60 kpc)**

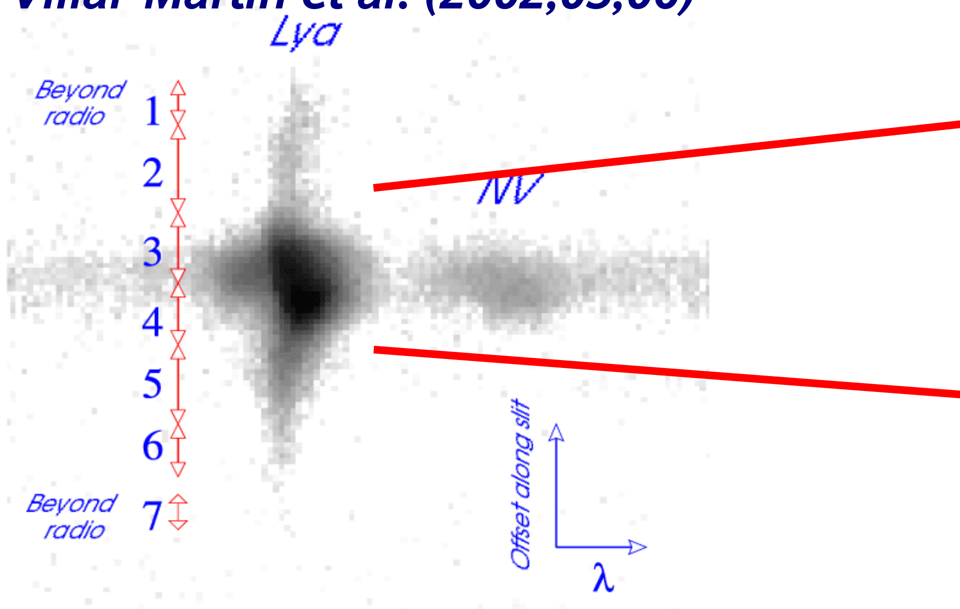
Evidence for jet-driven outflows

Correspondence between the radio and line emission

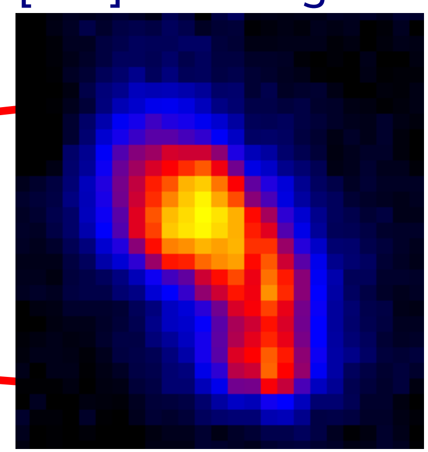
(1) Geometry:

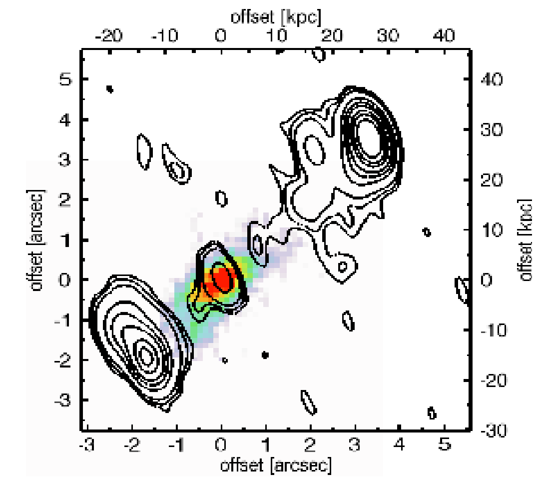
alignment with jet axis / size of emission line region

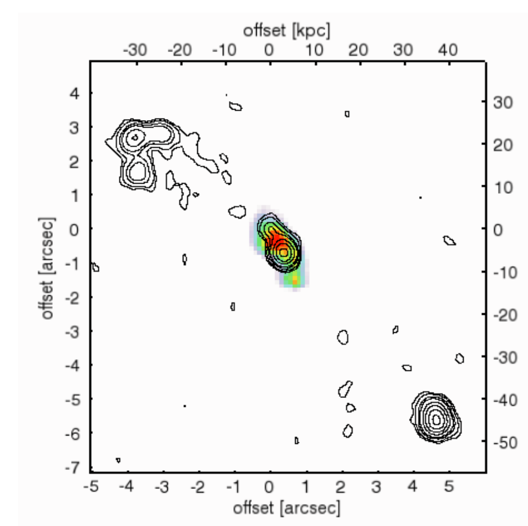
Villar-Martin et al. (2002,03,06)



[OIII] line image







Nesvadba et al. (2008)

Evidence for jet-driven outflows

Nesvadba et al. (2007) A&A 475,145
Nesvadba et al. (2008)

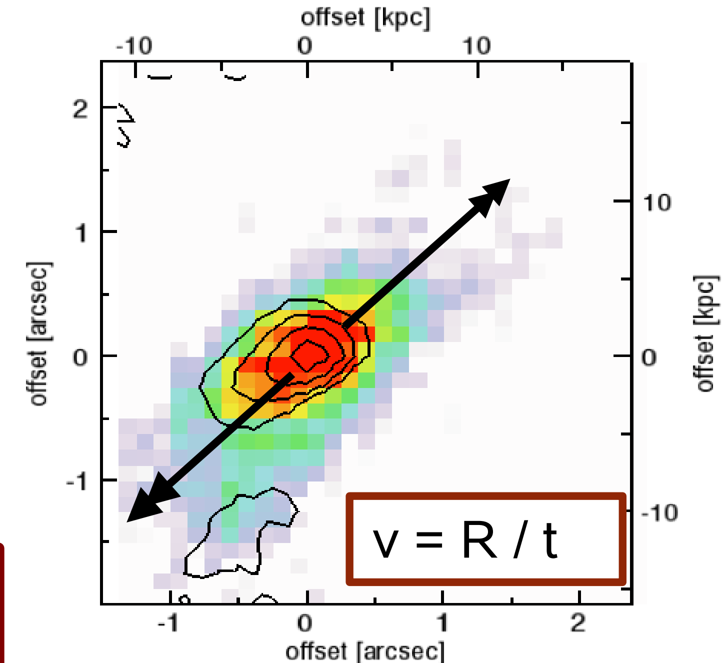
Correspondence between the kinematics and the jet properties

AGN lifetimes ~ $10^{7\text{-}8}$ yrs
Martini 2004

(2) Time scales:

jets / outflows with similar t_{dyn}

$$t_{dyn} = \text{few x } 10^7 \text{ yrs}$$



"coupling efficiency"
η ~ 0.1

(3) Energies:

jets can provide 10^{46} erg s^{-1},

$$E_{tot,jet} \approx 10^{60\text{-}61} \text{ erg}$$

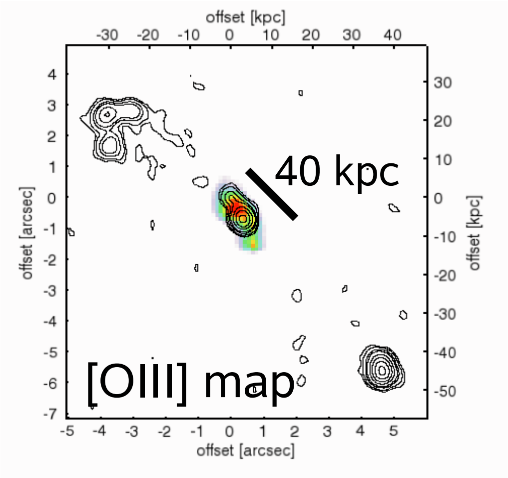
(e.g., Bicknell et al. 1997, Wan et al. 2000, Birzan et al. 2004)

e.g., for swept-up bubbles:
(Dyson & Williams, 1980)

$$v_{shell} = 235\, [dE/dt]_{44}^{\,1/5}\, n_0^{\,1/5}\, t_7^{\,-2/5} \text{ km s}^{-1}$$

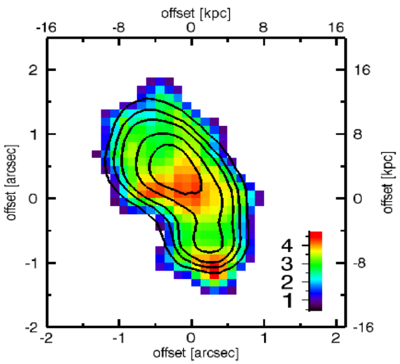
$$E_{tot} \approx 10^{59\text{-}60} \text{ erg in } 10^7 \text{ yrs}$$

Impact on the ISM: Ionized and …

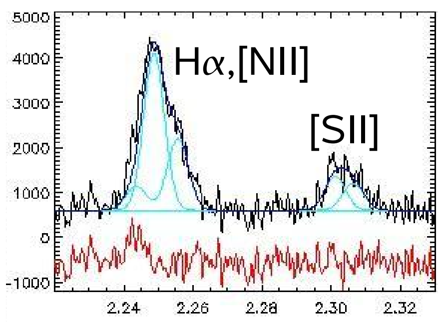


Ionized gas mass:

$M_{HII} = L_{H\alpha}\, m_p \,/\, (h\nu_{H\alpha}\, \alpha_{eff}^{H\alpha}\, n_e)$



Hα/Hβ map
extinction



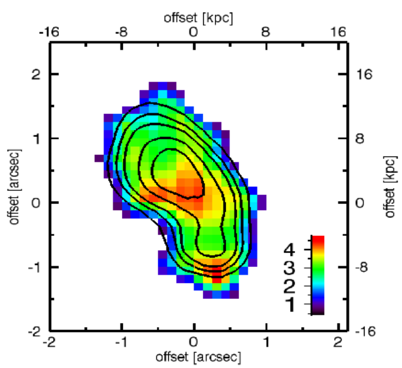
[SII] doublet
density

$M(H_{ion}) \sim$ few x 10^{10} M_s

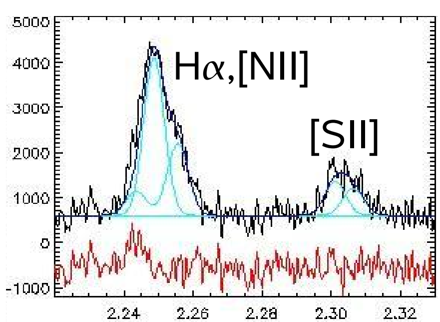
Impact on the ISM:
Ionized and molecular gas

Ionized gas mass:

$$M_{HII} = L_{H\alpha}\ m_p\ /\ (h\nu_{H\alpha}\ \alpha_{eff}^{H\alpha}\ n_e)$$



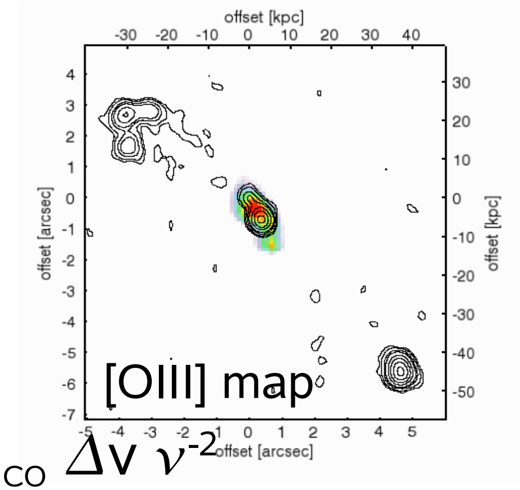
$H\alpha/H\beta$ map
extinction

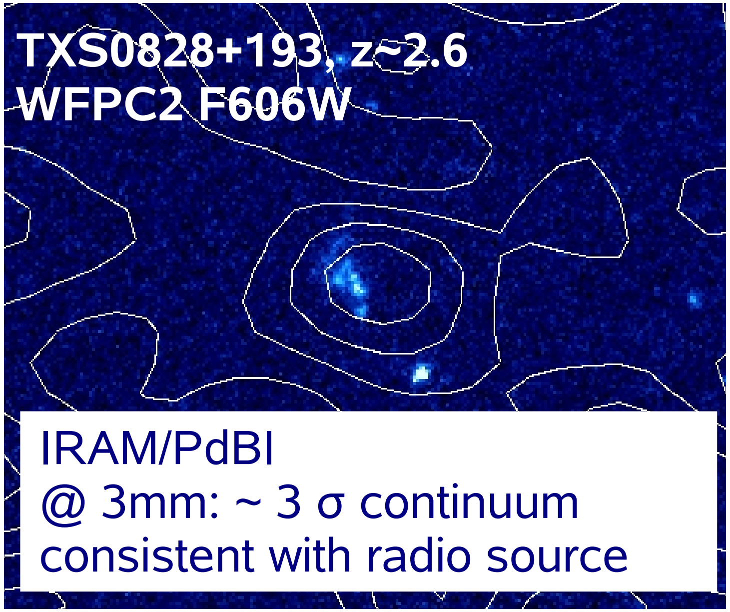


[SII] doublet
density

Molecular gas mass:

$$M_{H2} = X_{CO}\ \ \text{x}\ 2.5\text{x}10^6\ S_{CO}\ \Delta v\ \nu^{-2}$$





???

2000 km s^{-1} bandwidth, ~ 2 x $\Delta v_{outflow}$

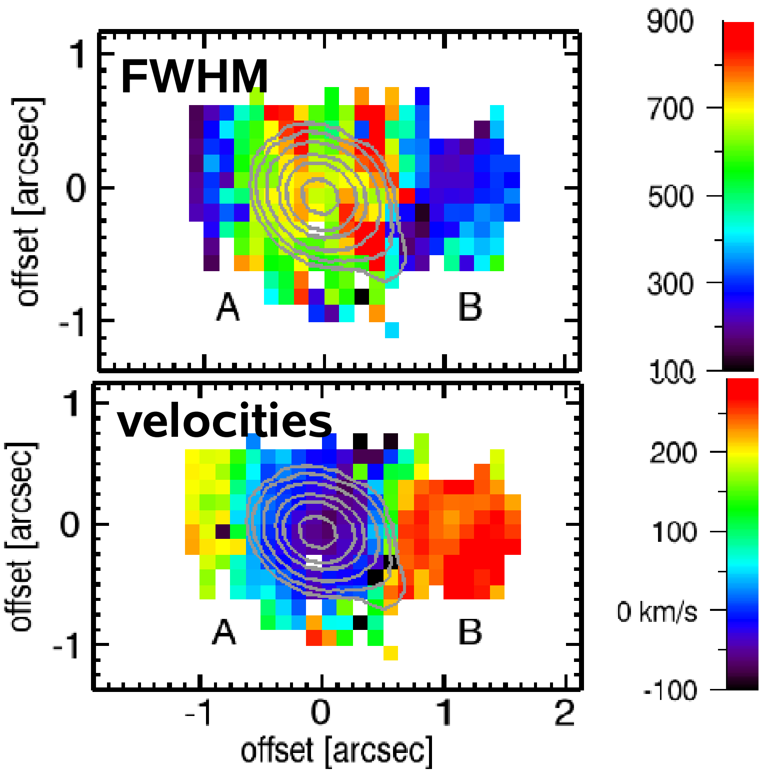
$M(H_{ion})$ ~ few x 10^{10} M_s

CO(3-2): $M_{H2} \leq 10^{10}\ M_s$

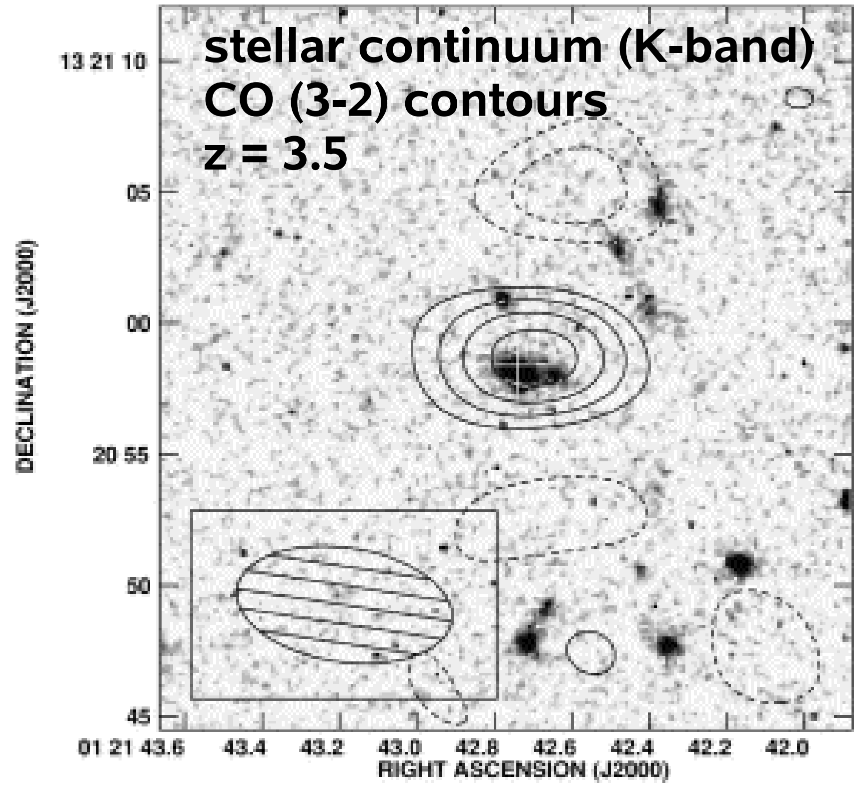
Nicole Nesvadba – AGN-driven Winds in HzRGs

A compact source: TN J0121+1320

Nesvadba et al. (2007), A&A 475,145



De Breuck et al. (2003)



stellar continuum in A, B
$\Delta v \sim 300$ km s^{-1}, B: $\sigma \sim 70$ km s^{-1}

merging / interacting galaxies A, B
$M_{dyn}(A) \sim 2 \times 10^{11} M_s$

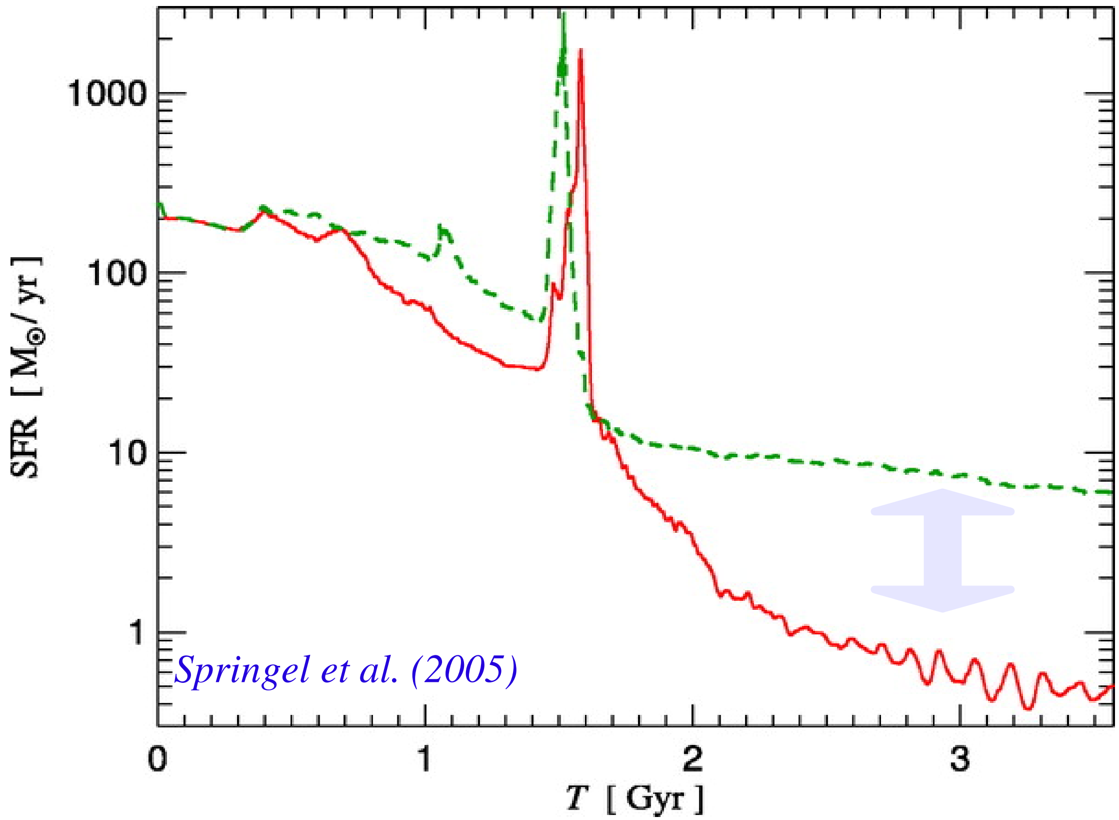
E_{jet}: ~9 $\times 10^{59}$ erg in 10^7 yrs
need 4 $\times 10^{59}$ erg to unbind M_{mol}

!! { $M_{mol} \sim 4 \times 10^{10} M_s$ ($f_{gas} \sim 20\%$)
M_{ion} few $\times 10^9 M_s$

Impact on the Host Galaxy

(A) stellar mass assembly

Nesvadba et al. (2006), ApJ 693,651
Nesvadba et al. (2008), A&A submitted



Requirements for gas removal:

$E \geq E_{bind}$ ~ $10^{59\text{-}60}$ erg

$v \geq v_{esc}$ ~ 700 km s^{-1}

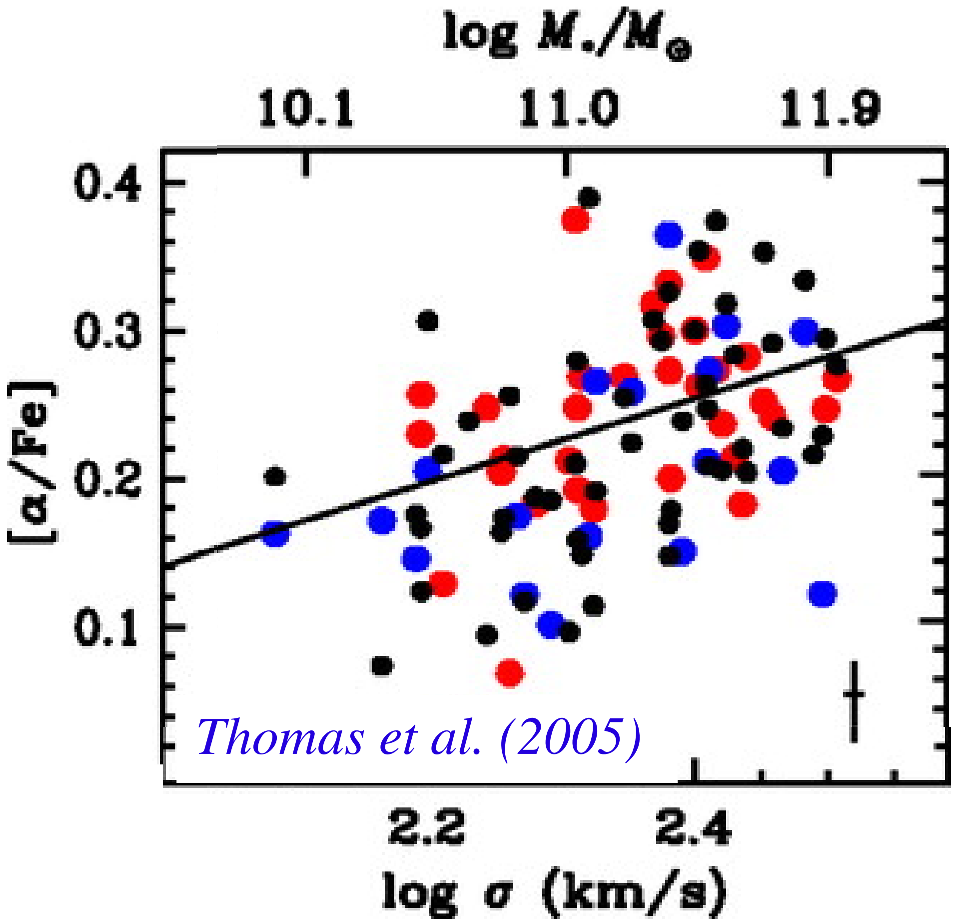
$M \sim M_{ISM}$ ≤ few x 10^{11} $M_\odot$

Outflows in HzRGs correspond to the dynamical requirements of AGN feedback as postulated by the evolutionary models

Impact on the host galaxy

(B) Chemical Evolution

Nesvadba et al. (2006), ApJ 693,651



Differential Enrichment as "Cosmic Clock", abundance ratios in stellar atmospheres

↓

different SNII / SNIa timescales

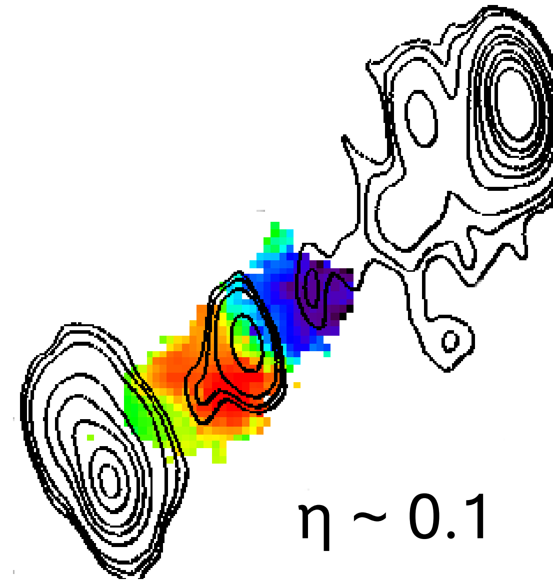
↓

[α / Fe] enhancement

$t_{SB} < 10^9$ yrs, $M(10^8$ yrs$) \sim 10^{10\text{-}11}\ M_\odot$

Efficiency of AGN feedback: A global view

efficiency ?



$\eta \sim 0.1$

local black hole mass density
Yu & Tremaine (2002)

rest mass energy equivalent

5×10^{59} erg Mpc^{-3}

+ radio luminosity function
Willott et al. 2001

global energy output of HzRGs

9×10^{56} erg Mpc^{-3}

models: 0.5%

$\eta_{BH} \sim 0.2$ %

Springel et al. (2005)
Di Matteo et al. (2005), Hopkins et al. (2006)
Scannapieco et al. (2004)

AGN-driven outflows do exist at z~2

... but it's the jet

Mass

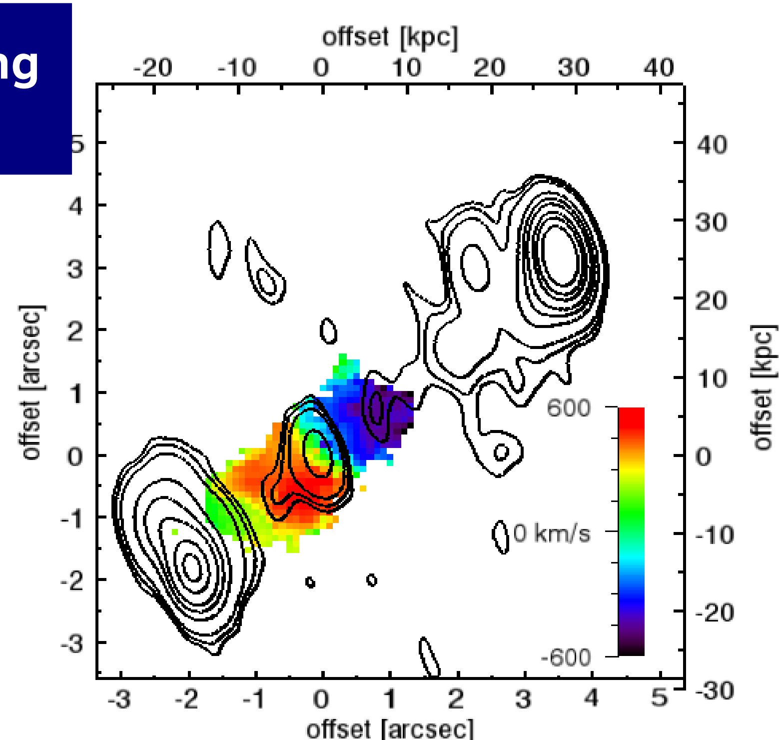
ionized		few x 10^{10} M_s
molecular,CO	$\leq$	few x 10^{10} M_s
M_{ion}	$\geq$	$M_{H2,cold}$

~ ISM of 10^{11} M_s galaxy at z~2

Sizes

ionized gas	~ 20-30 x 10 kpc
continuum	~ 5-8 kpc

elongated along jet axis



Kinematics

Δ v	~ 1000 km s^{-1}
FWHM	~ 1000 km s^{-1}
t_{dyn}	~ 10^7 yrs
E_{kin}	~ 10^{60} erg
η(jet/gas)	~ 10%

$v \sim v_{escape}$
$E_{turb} \sim E_{bulk}$
$t_{dyn} \sim t_{jet}$
$E_{kin} \sim E_{bind}$

... evolutionarily significant!

$\eta(M_{BH}/E_{kin}) \sim 0.2\%$

Nicole Nesvadba – AGN-driven Winds in HzRGs