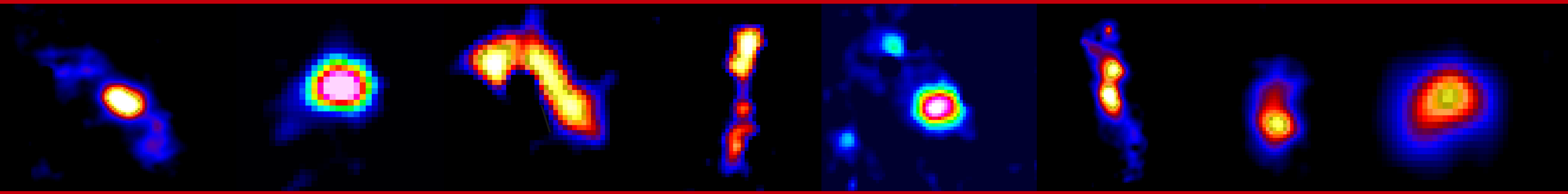
# Quantifying AGN feedback

## (Winds and more … )

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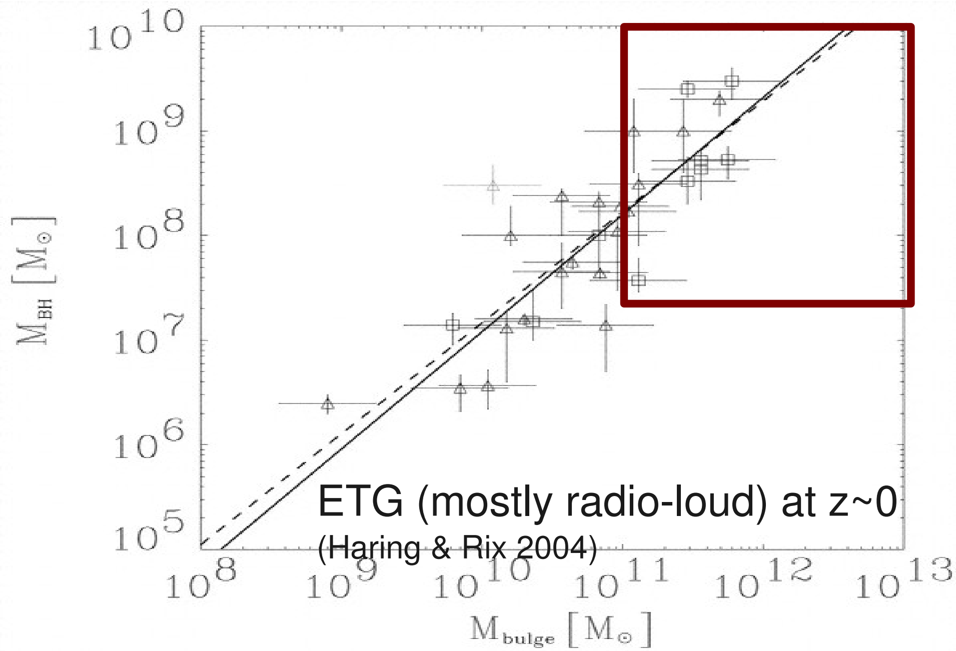
cnes

# *" Where does the energy go? "*

AGN energy output
≈
Binding energy of the host
Silk & Rees (1998)

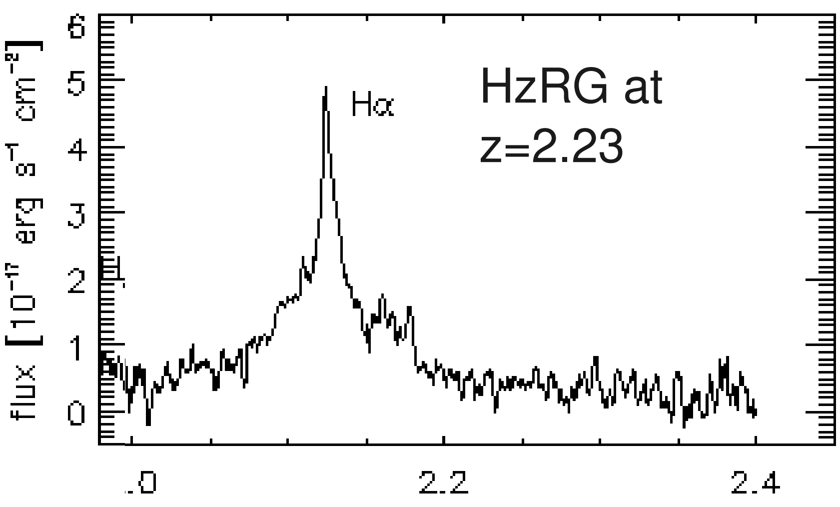
Coupling to the interstellar medium
How? How efficient?

# Why radio galaxies ?

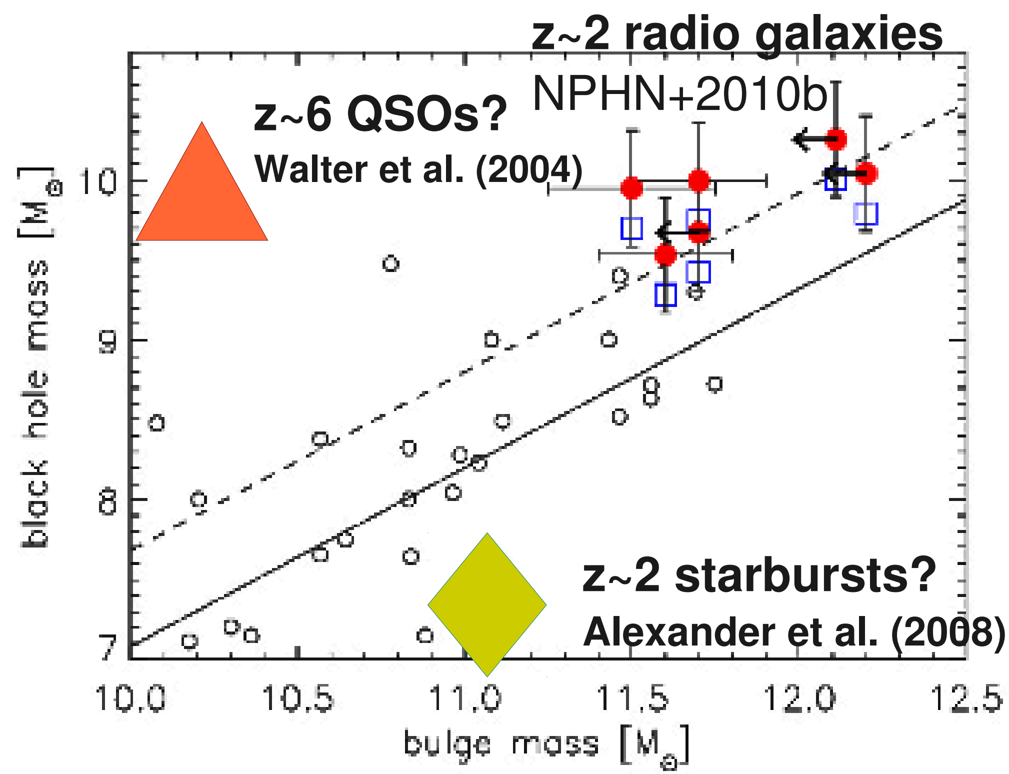



- most massive galaxies at all redshifts
- (e.g., De Breuck et al. 2001, Seymour et al. 2007)
- amongst the most powerful AGN
- Radio emission not uncommon at high mass
  e.g., 30% with $M_{stellar} > 10^{11}$ $M_s$
  (Best et al. 2005, SDSS analysis)

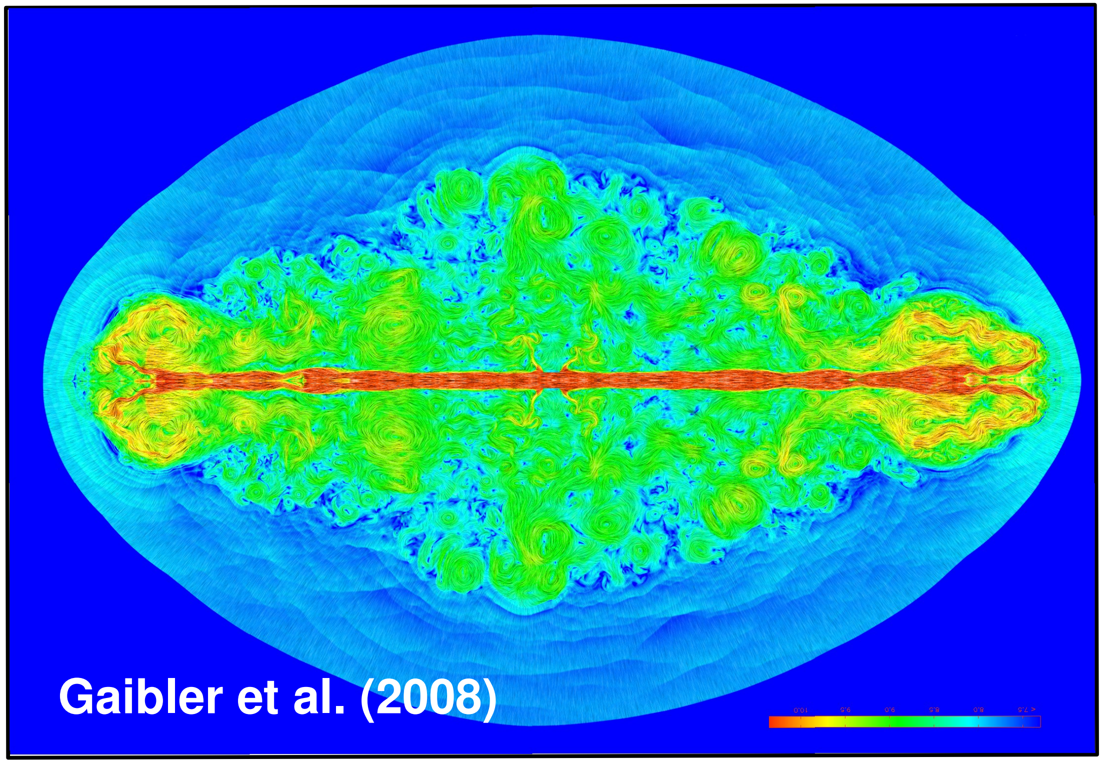
7 z>2 RGs with nuclear broad-line regions




Nesvadba et al. (2010b)



# “ It can't be the radio because ...”




*... most of the energy escapes along the jet axis*

**“Cocoon model”**

Begelman & Cioffi (1989)

“a waste energy basket of hot plasma inflated by the jet which accelerates the ambient gas”
Scheuer, 1974

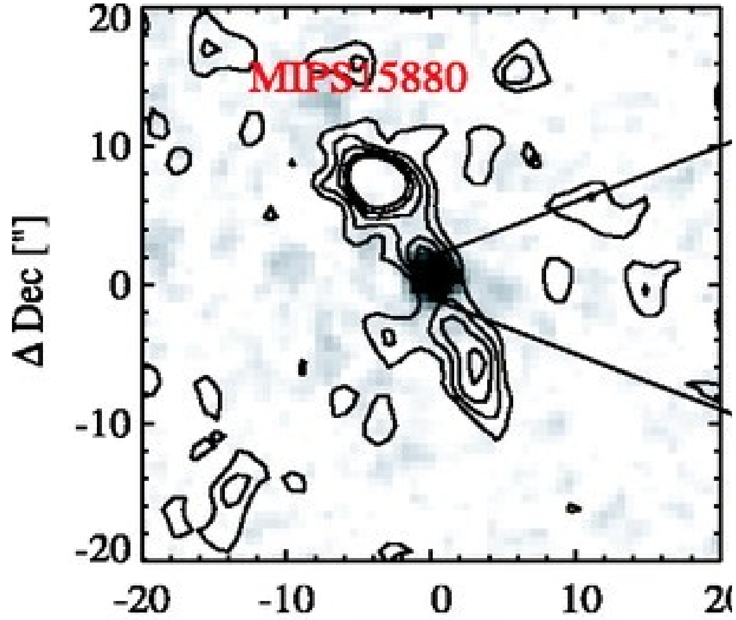
**In agreement with hydro models of radio jets**
(e.g. Sutherland & Bicknell 2007, Krause 2007)

**strongest interactions w/ young radio sources**
(e.g., Holt et al. 2008, Best et al. 1999, ...)

**Very long dissipation times in the ISM: $10^{7\text{-}8}$ yrs**
(NPHN+2010, see later)

**Powerful sources deposit relatively less energy in the gas than low-power sources**

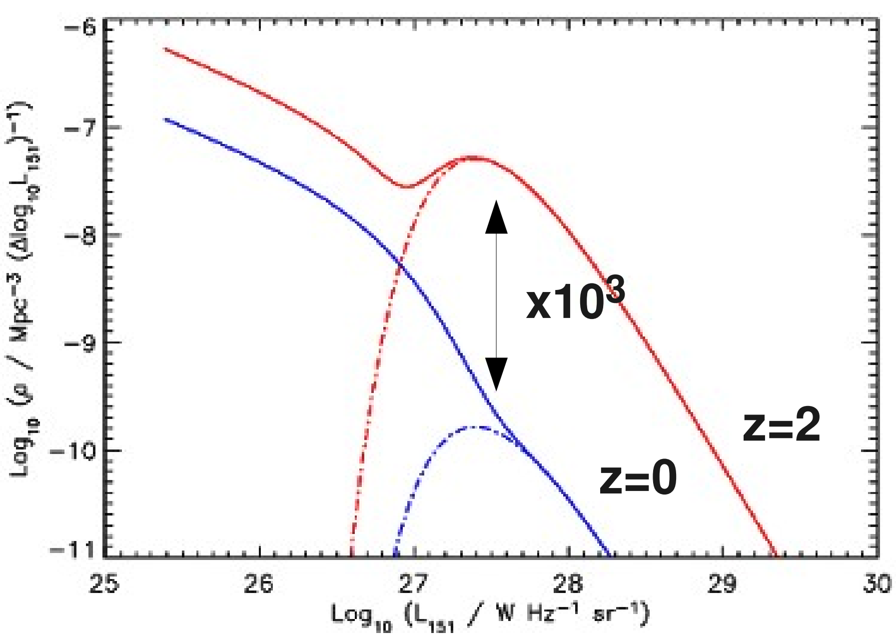
# “ It can't be the radio because ...”




*... radio galaxies are so rare!*

~ **25-30 %** of 24$\mu$m-selected ULIRGs at z=2 have radio sources w/ ~ $10^{25}$ W $Hz^{-1}$ at 1.4 GHz
Sajina et al. (2007)

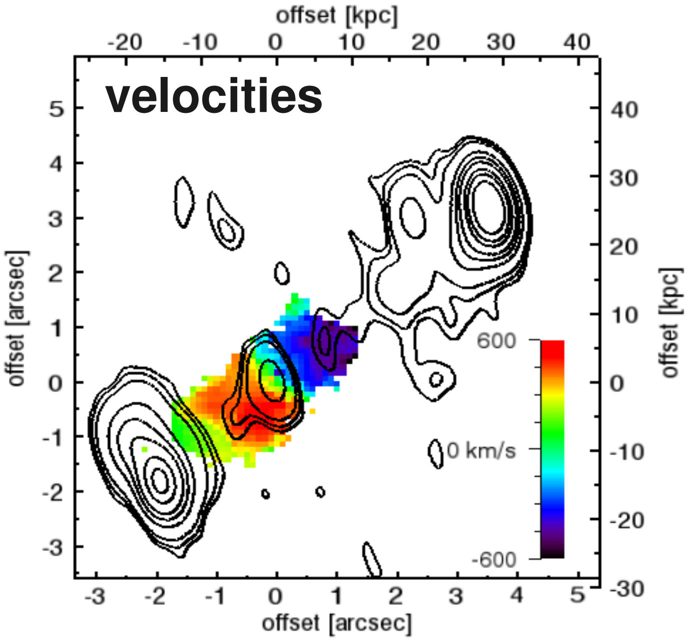
*similar to submm-selected quasars, few times > FIR-radio correlation*

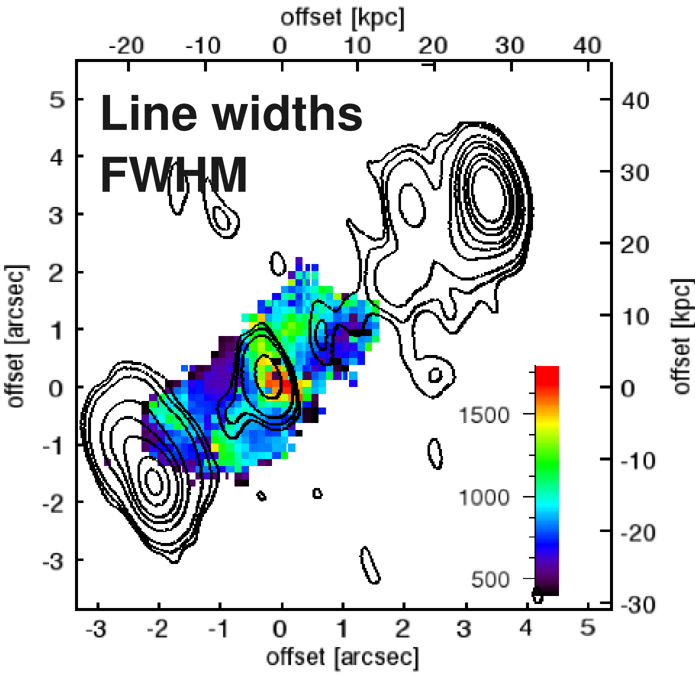



**factor $10^3$ increase** in powerful radio galaxies from z=1 to z=2-3
Willott et al. (2001)

# Energetics and other constraints

NPHN+ 2006, 07, 08




## Characteristic: blue / redshifted bubbles

- velocity offset 1000 km $s^{-1}$ (>> rotation)
- Line widths ~ 1000 km $s^{-1}$

## Gas extends along jet axis to R >> $R_{stars}$

- only extended gas where extended radio sources
- velocity along the jet axis

## $M_{gas,ion}$ ~ $10^{10}$ $M_s$ ~ $M_{gas, mol}$

- H$\alpha$ flux, extinction, electron densities measured
- starburst galaxies: $M_{mol}$ / $M_{ion}$ ~ $10^{2-3}$

## $E_{kin,gas}$ ~ $10^{59-60}$ erg

- ~ binding energy of a massive host galaxy
- 0.1 - 0.2 % of the rest-mass energy equivalent of the SMBH
- 1-10% of the jet power

## $T_{outflow}$ few x $10^7$ yrs ~ AGN lifetime

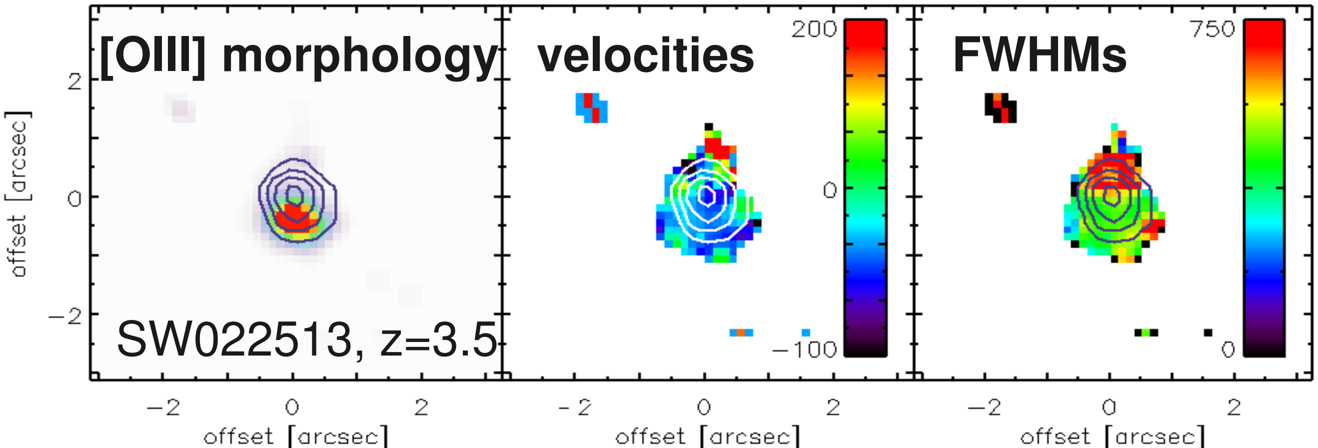
- characteristic time of a starburst ~ $10^8$ yrs

**Expected characteristics of AGN-driven winds quenching intense starbursts in massive high-z galaxies**

# ... and quasars w/o (strong) radio source ... ???

Heckman et al. (1991):

Only optically selected quasars with radio sources have extended Ly$\alpha$ halos w/ disturbed kinematics , quasars w/o radio have more quiescent, fainter halos

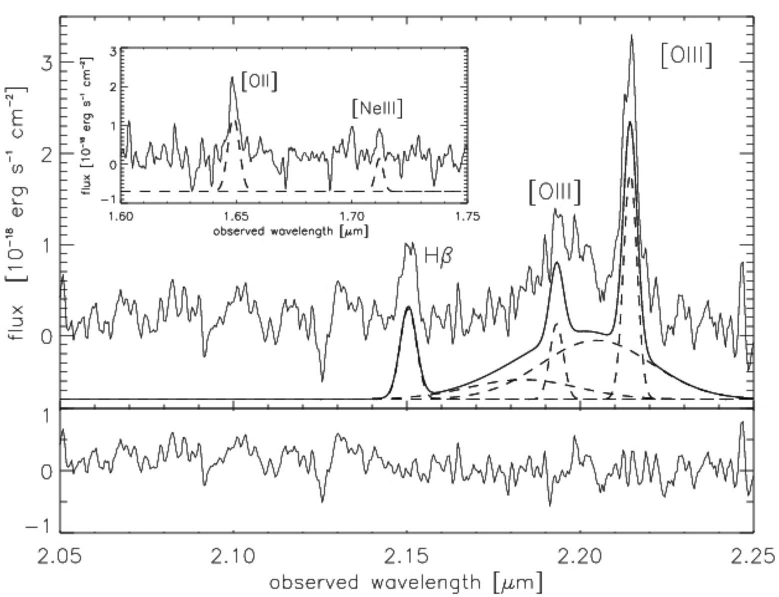



NPHN+ (2010c), see also Alexander et al. (2010)

### ... but how about obscured quasars?

- **in dusty starbursts**
- **nascent quasars?**

(e.g., Sanders et al. 1988, Hopkins et al. 2006, ...)




Blueshifted [OIII]4959,5007 w/ FWHM =5000 km s$^{-1}$ but compact (r < 2-3 kpc)

H$\beta$, CO up to -350 km s$^{-1}$ and FWHM ~ 1000 km s$^{-1}$

**Weak radio source**
**(but still, few x $10^{25}$ W Hz$^{-1}$ @ 1.4 GHz ...)**
**Radiation pressure: too low velocities**

## Scaled-up versions of NLS1s?

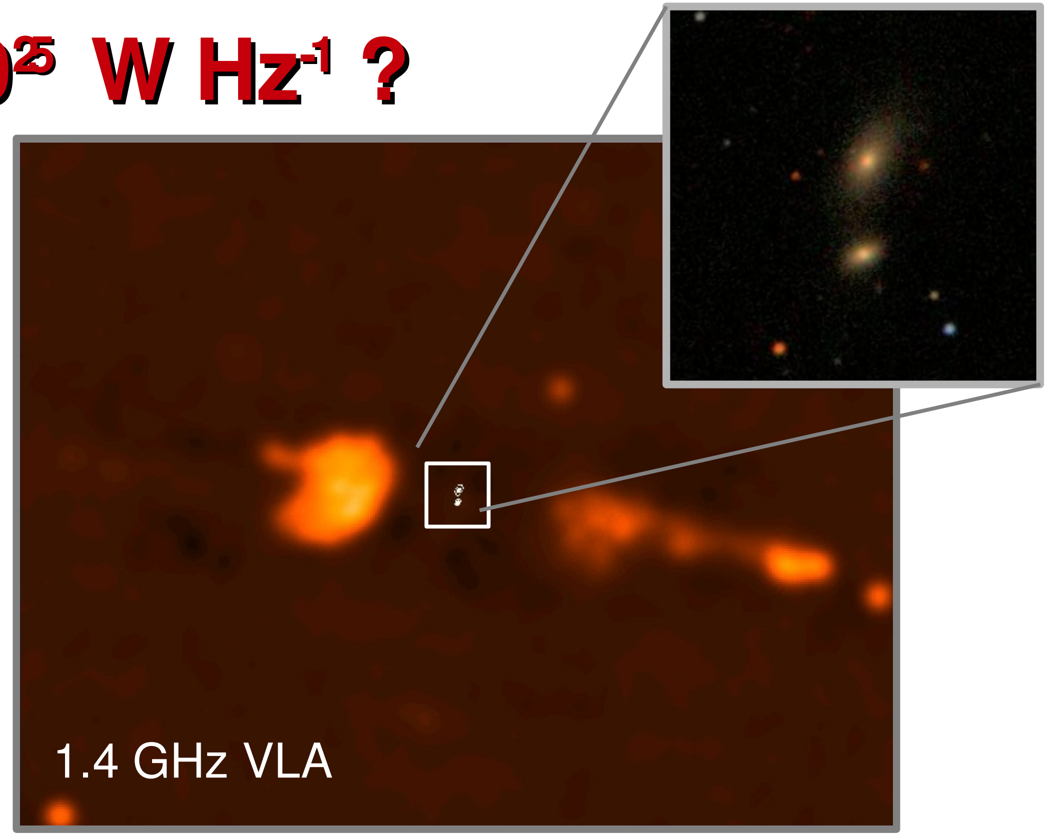
e.g., Komossa et al. (2008)

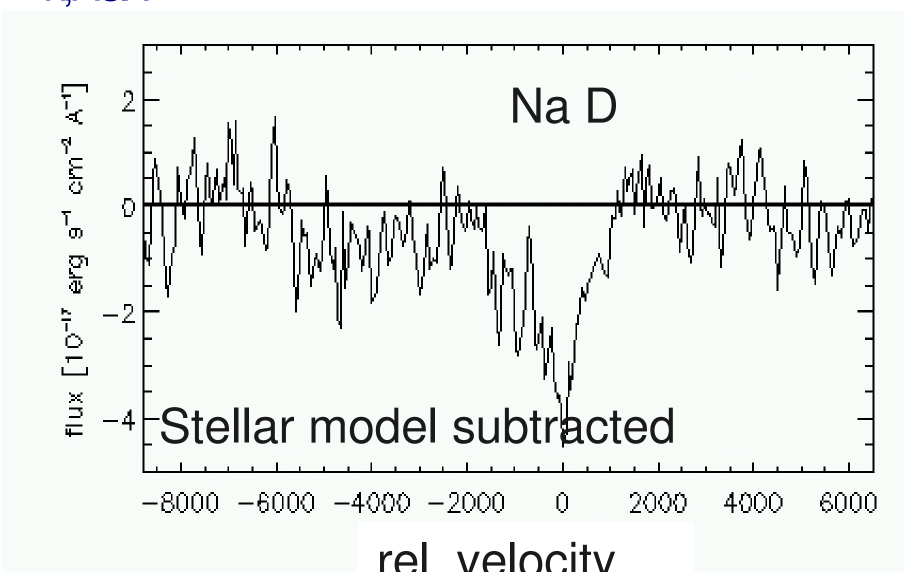
# What can you do with $10^{25}$ W Hz$^{-1}$ ?

NPHN+, 2010, A&A in press,
astro-ph/1003.3449

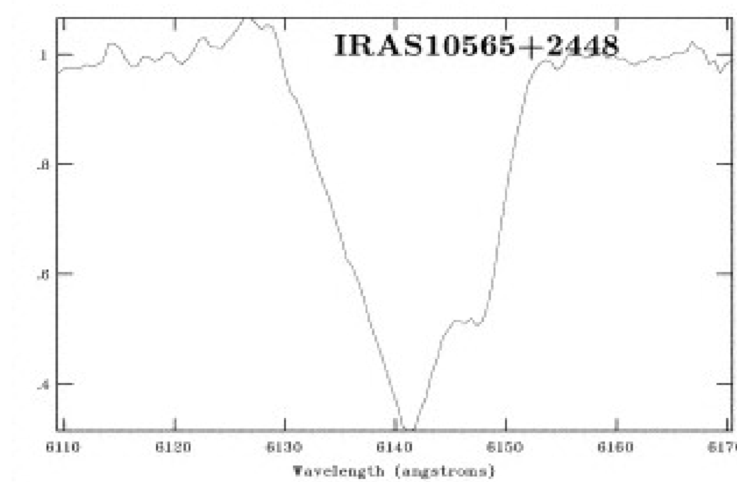
- $10^{11}$ $M_s$ elliptical galaxy
- ≥97% stellar pop. older than 10 Gyr
- undergoing a dry merger
- old radio source (6-20 x $10^7$ yrs)

- 3 x$10^{25}$ W Hz$^{-1}$ at 1.4 GHz
- SFR < 0.07 $M_s$ yr$^{-1}$ (Spitzer phot.)
- $L_{x,AGN}$ < $10^{40.6}$ erg s$^{-1}$




Heckman et al. (2000)




**Morganti et al. (2005): Neutral winds common in powerful radio galaxies**

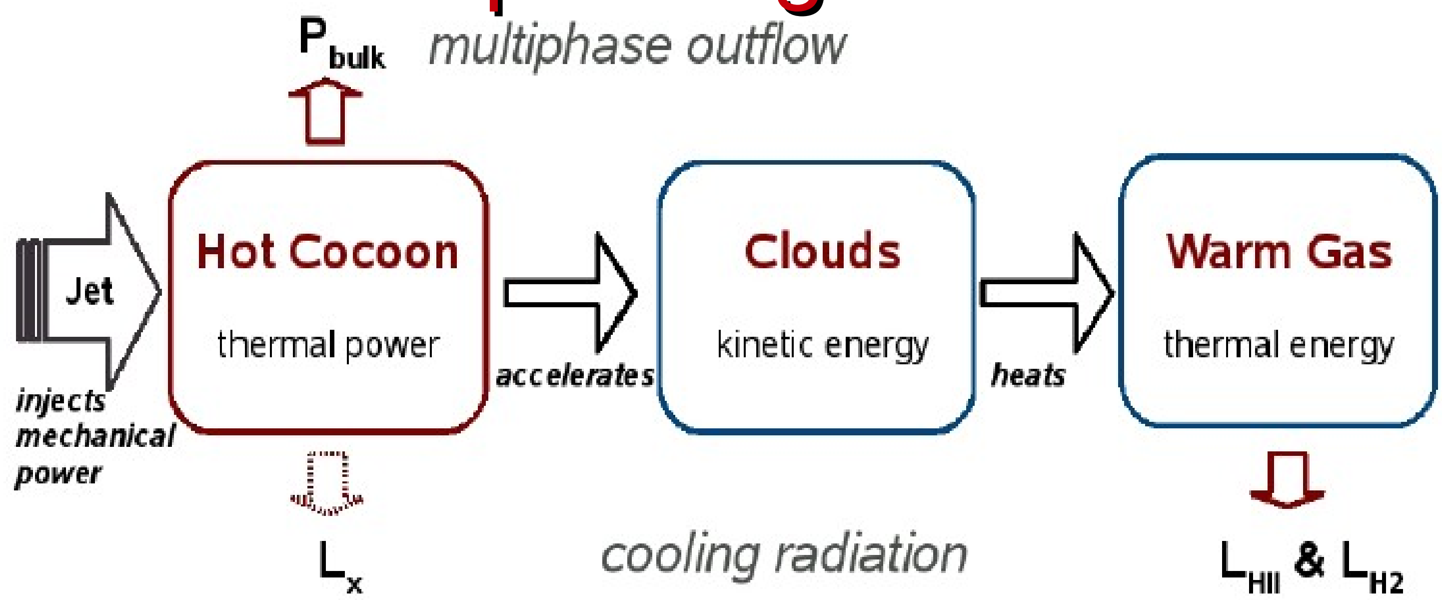
# AGN feedback and multiphase gas: a case study

Nesvadba et al. (2010a)

**Energy injection rate**

$L_{radio} \sim 10^{42}$ erg $s^{-1}$

$L_{mech} \sim 10^{44\text{-}45}$ erg $s^{-1}$




thermal Bremsstrahlung & line cooling

???

Missing the piston!

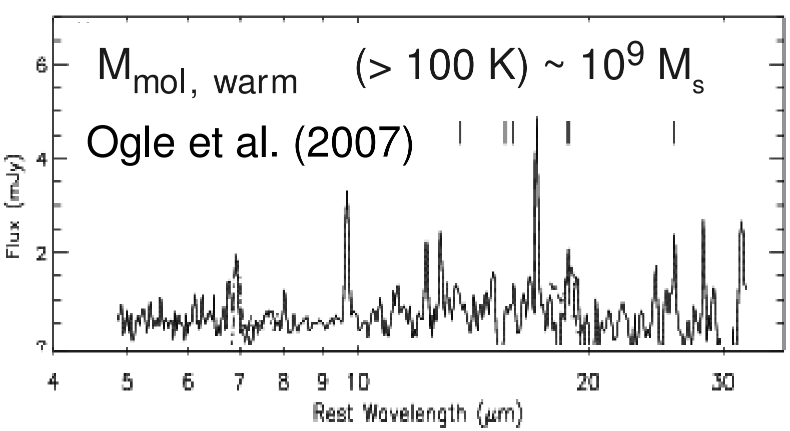
**Kinematics of emission and abs line gas**

$E_{kinetic} = \Sigma_{phases} M \sigma^2$

$E_{kinetic} \sim 10^{42\text{-}43}$ erg $s^{-1}$

**Line Cooling from Spitzer and optical spectroscopy**

$L_{lines} \sim 10^{42}$ erg $s^{-1}$




- $M_{outflow} \sim 30\text{-}40\ M_\odot\ yr^{-1}$
- $\tau_{dissipation} \sim 10^{7\text{-}8}$ yrs or $\geq t_{AGN} \sim t_{duty\text{-}cycle}$
- $E_{cycle} \sim 1\text{-}10\%$ of $L_{mech}$

~ ½ outflow & ½ dissipation

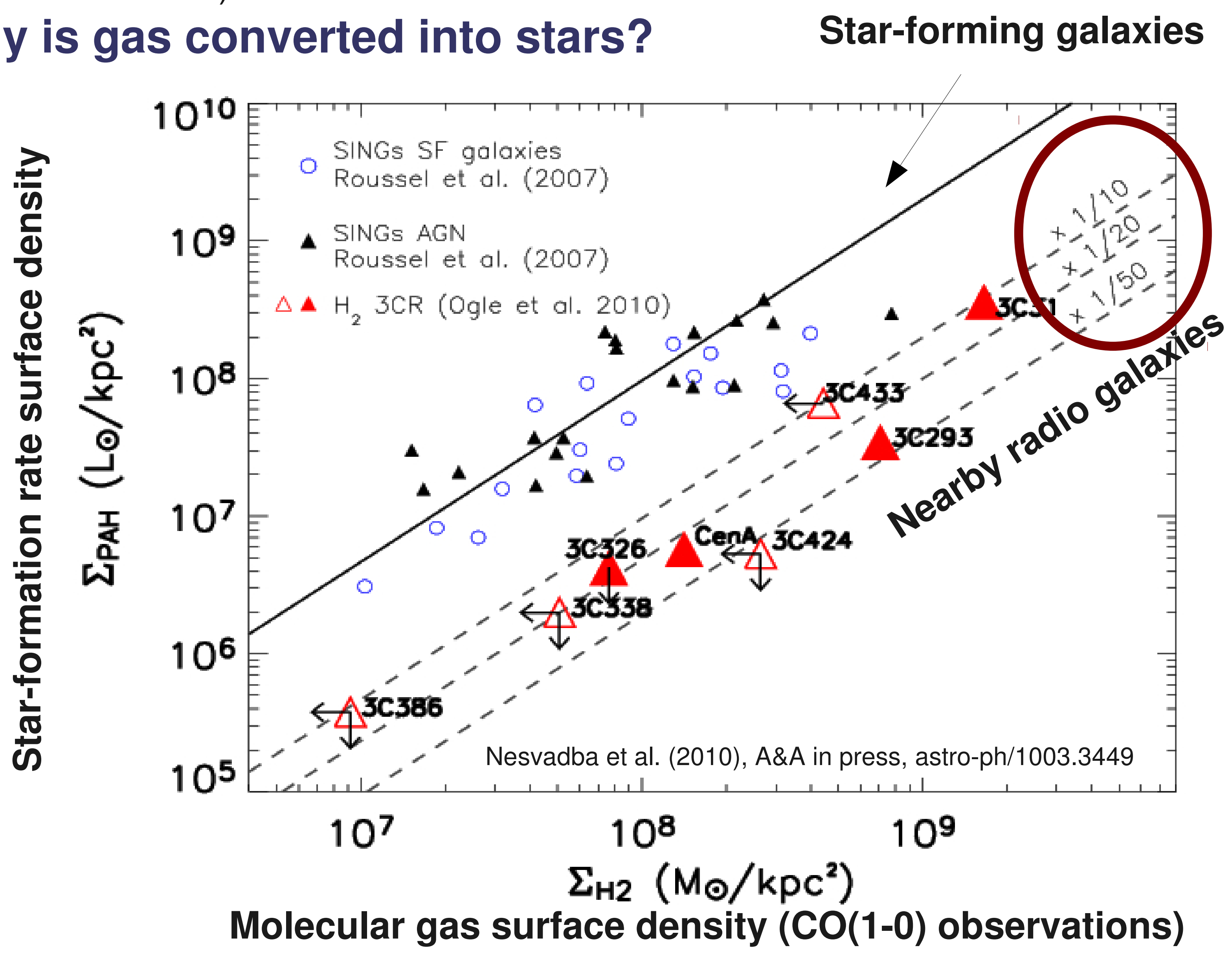
**1/3 of nearby radio galaxies *could* show similar phenomenology** (Ogle et al. 2010, ApJ subm.)

# Linking AGN and star formation

Schmidt-Kennicutt relationship

(Schmidt 1959, Kennicutt 1998)

**How efficiently is gas converted into stars?**



# Conclusions

**Winds are one signature of feedback, but not the only one**

**Outflows of ionized gas in z~2 radio galaxies**

- significant fractions of the ISM in outflows and warm gas
- spatially extended, R~50 kpc
- velocities near escape velocity, $E_{kin} \sim E_{binding}$
- outflows in quasars definitely at work in near-nuclear regions

**"Moderate-power" radio galaxies can do feedback (even in Seyferts!)**

- significant outflows ~ starbursts
- equal share of kinetic and turbulent energy
- can accelerate molecular gas, may suppress star formation
- characteristic mid-IR line emission of warm H2
  - 30 % of nearby RGs could be affected

**Can do "radio mode" w/ population constraints of Best et al. (2005,06)**