Warm and cold gas in obscured quasars

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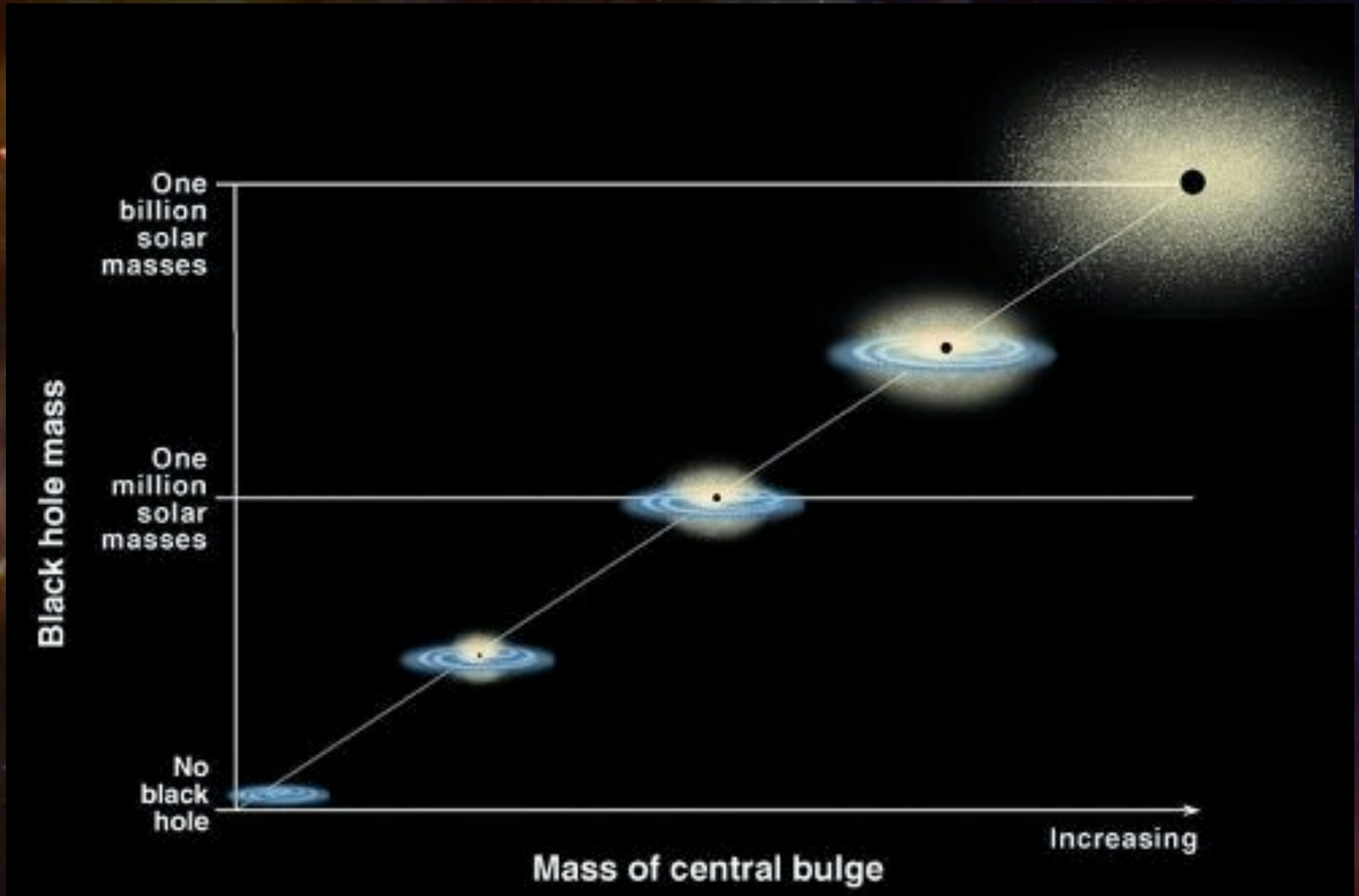
Motivation

A significant deployement of energy from the AGN onto the interstellar medium of the galaxy is assumed in cosmological simulations to:

- reproduce the M_{BH}-M_{bulge} relation and scatter (Richstone et al. 1998; Ferrarese & Merritt 2000; Tremaine et al. 2002)

Galaxies host black holes of mass proportional to their bulge mass, luminosity, velocity dispersion

Evidence that BHs regulated galaxies growth or viceversa



(Kormendy & Richstone 1995; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhard et al. 2000; Marconi & Hunt 2003; Häring & Rix 2004)

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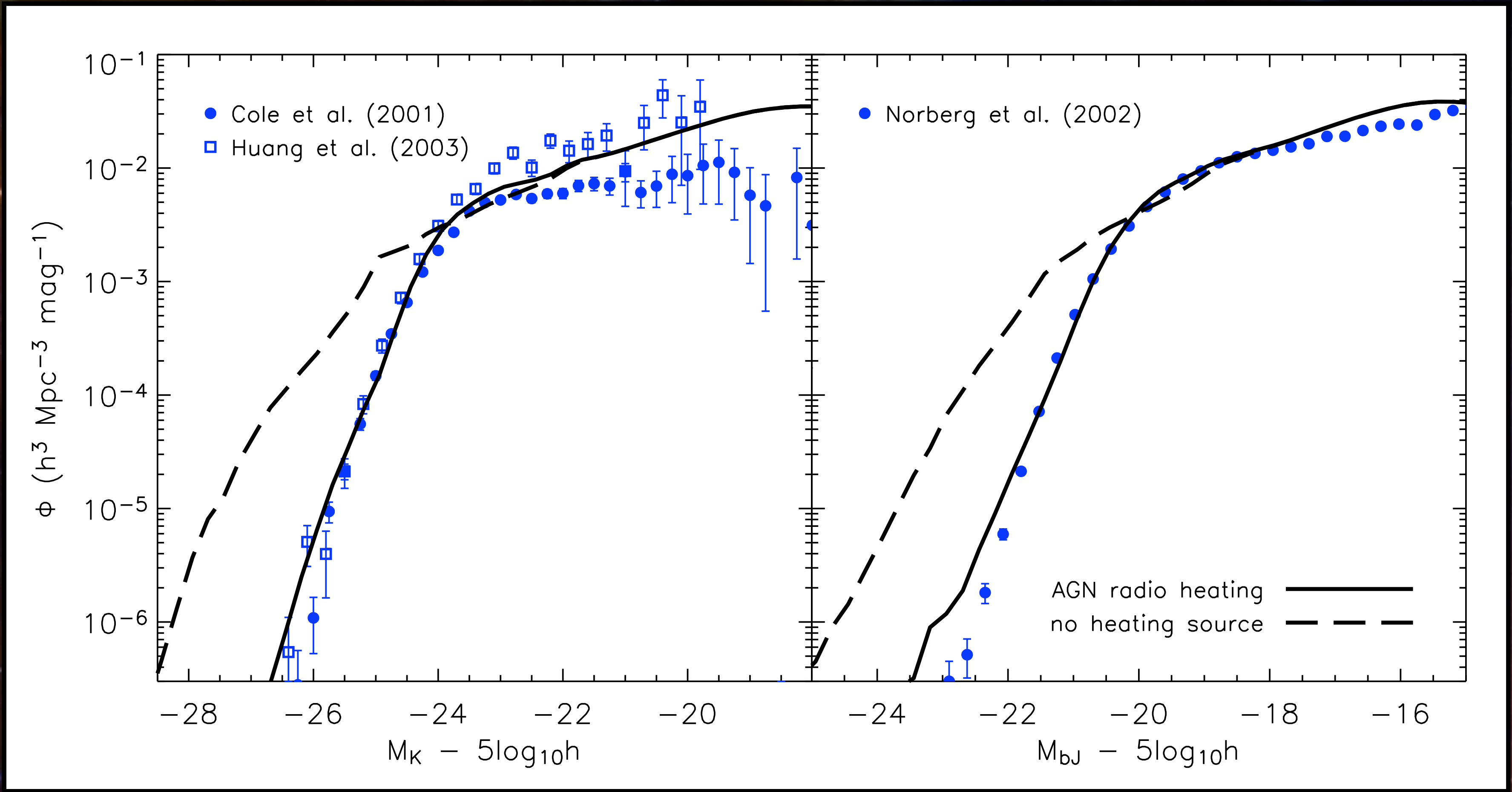
- reproduce the bright end of the galaxy luminosity and mass function (Bower et al. 2006, Croton et al. 2006)

With AGN heating
➩ good fit to the data.

Without AGN heating
➩ overprediction of luminous galaxies and failure to reproduce the bright end cut-offs in the luminosity functions.



(Croton et al. 2006)

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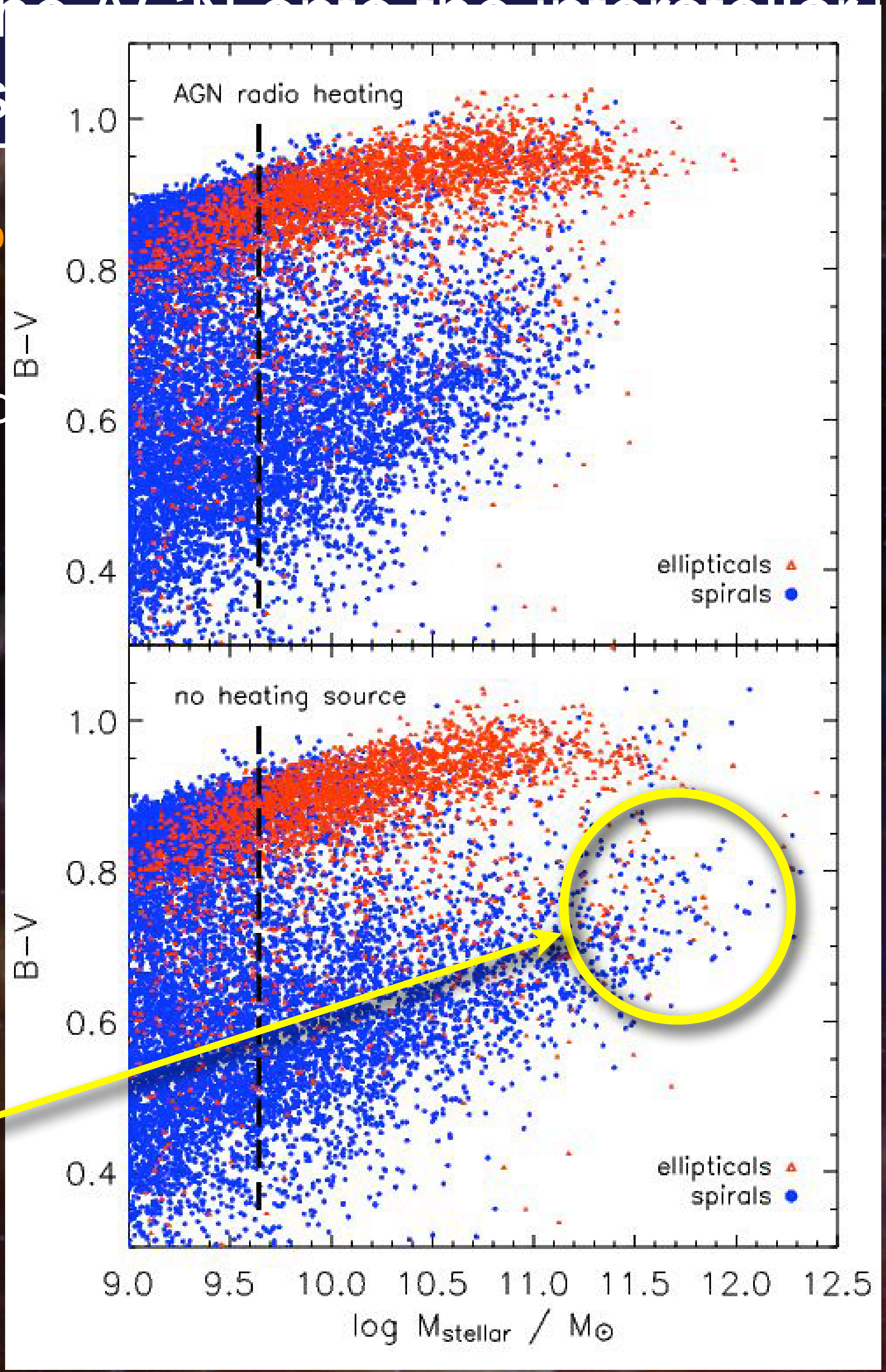
- reproduce the bright end of the galaxy luminosity and
  Croton et al. 2006)
- reproduce the galaxies color distribution
  (most massive galaxies are red and dead)

Red sequence
(Passive galaxies)

Blue sequence
(Star forming galaxies)

Without AGN heating ➯ most massive
galaxies are blue rather than red



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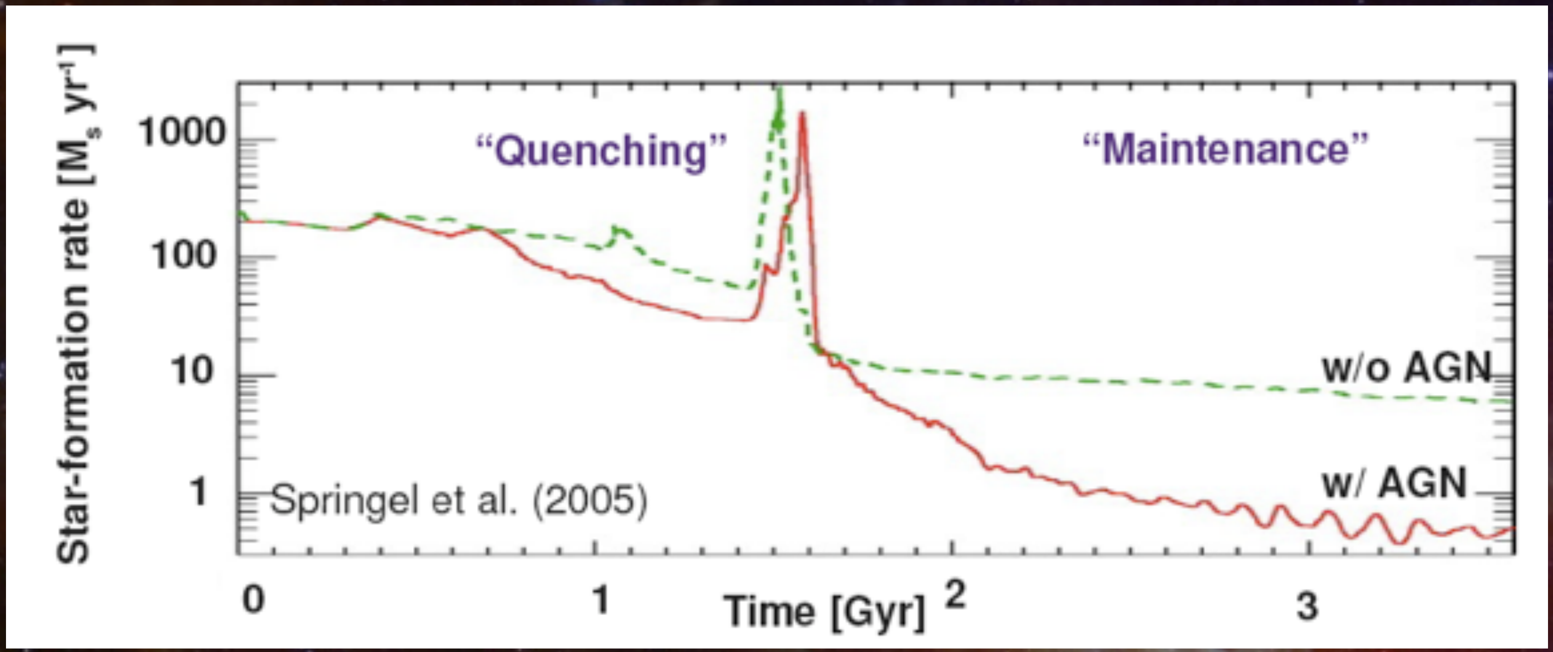
- reproduce the bright end of the galaxy luminosity and mass function (Bower et al. 2006, Croton et al. 2006)
- reproduce the galaxies color distribution (most massive galaxies are red and dead)
- keep massive galaxies old, red and dead

Secular processes replenish the gaseous reservoirs (gas infall & return from evolved stars)

Heating prevents the gas from forming new young stars



How can we heat the ISM?

Need a mechanism that :

- affects the gas on galactic scales (kpc)
- carries enough energy to heat/eject the gas
- is quite common in galaxies

Radio jets
(radio loud AGN)

(Croton et al. 2006)

Supernovae
(star forming regions)

(Cen 2011)

Radiation driven winds
(radiatively efficient AGN)

(Silk & Rees 1998; Fabian 1999)

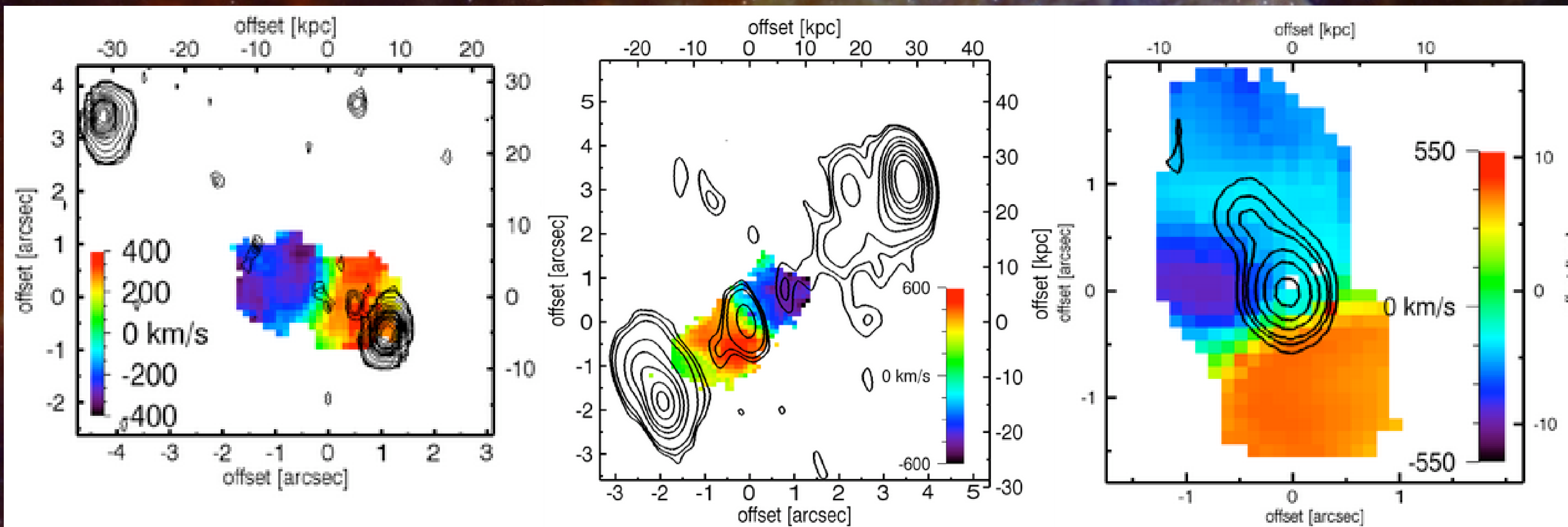

ANY OBSERVATIONAL EVIDENCE ?

AGN-driven outflowing gas

- X-ray warm absorbers (NGC 4151; Kraemer et al. 2005) SMALL SCALES !!
- UV absorption lines (e.g. Crenshaw et al. 1999) SMALL SCALES or LITTLE MASS !!
- broad (1000 km/s) HCO^+ coincident with jet (4C 31.04; Garcia-Burillo et al. 2007) Radio !!
- broad (1400 km/s) blueshifted absorption in HI (3C 293; Morganti et al. 2003) Radio !!
- broad blueshifted outflows of warm gas (high-z RG; Nesvadba et al. 2006, 2008) Radio !!
- galactic scale NLR disturbed by the AGN (Greene et al. 2011) But no winds...
- extended blueshifted broad [OIII] line (SMM J1237+6203; Alexander et al. 2010) Maybe ...
- high velocity warm and cold gas outflows (e.g. Mrk 231; Fischer et al. 2010; Feruglio et al. 2010) Great, but...

Outflows of warm gas in high-z Radio Galaxies

[OIII] relative velocity maps (Outflow) & Radio contours (Jet)



MRC 0316-257 (z=3.1) MRC 0406-244 (z=2.4) TXS 0828+193 (z=2.6)

Powerful radio jets entrain warm gas and carry material out of the host

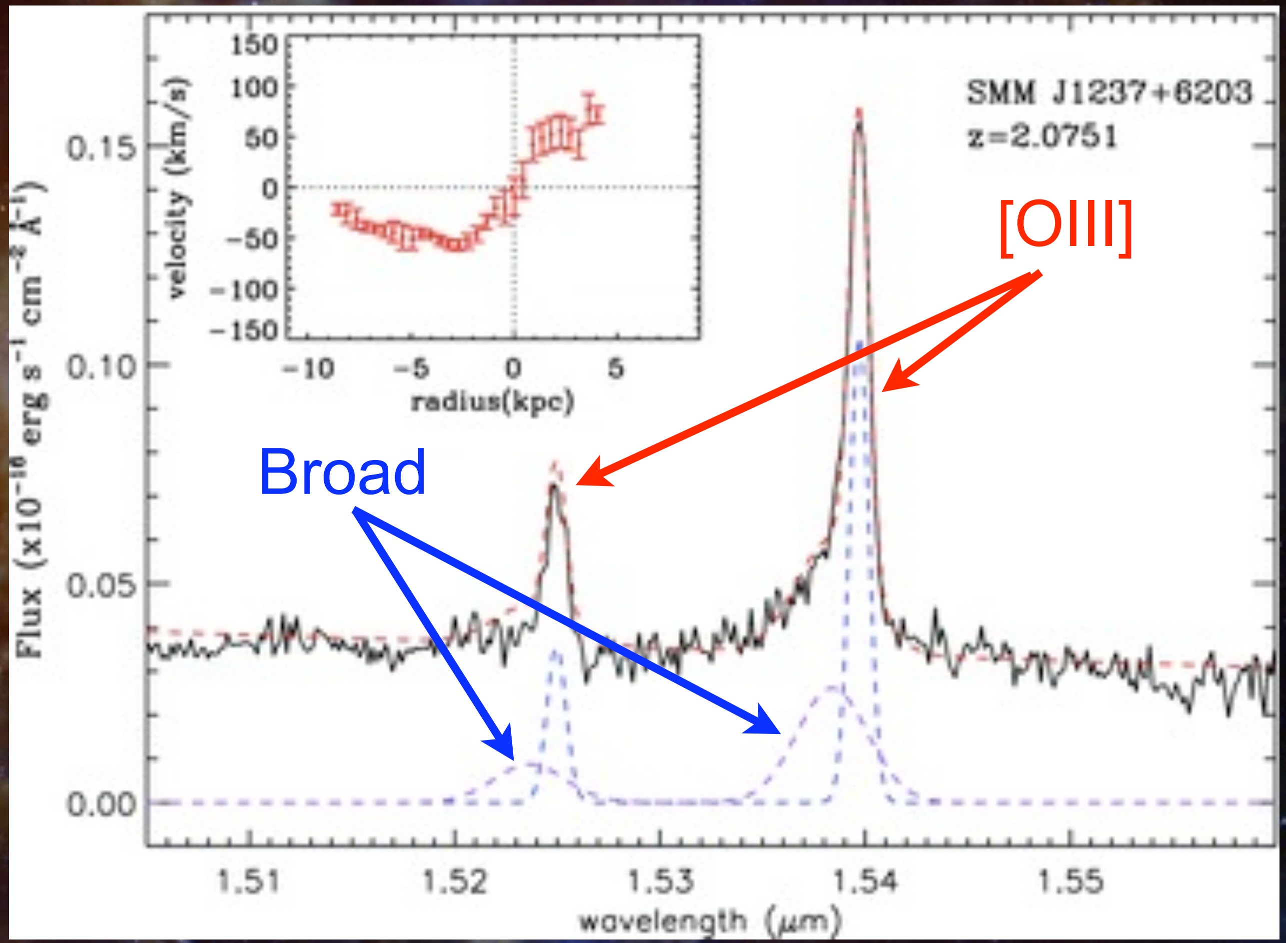
Gas kinematics from [OIII] (IFU observations)

(Nesvadba et al. 2008)

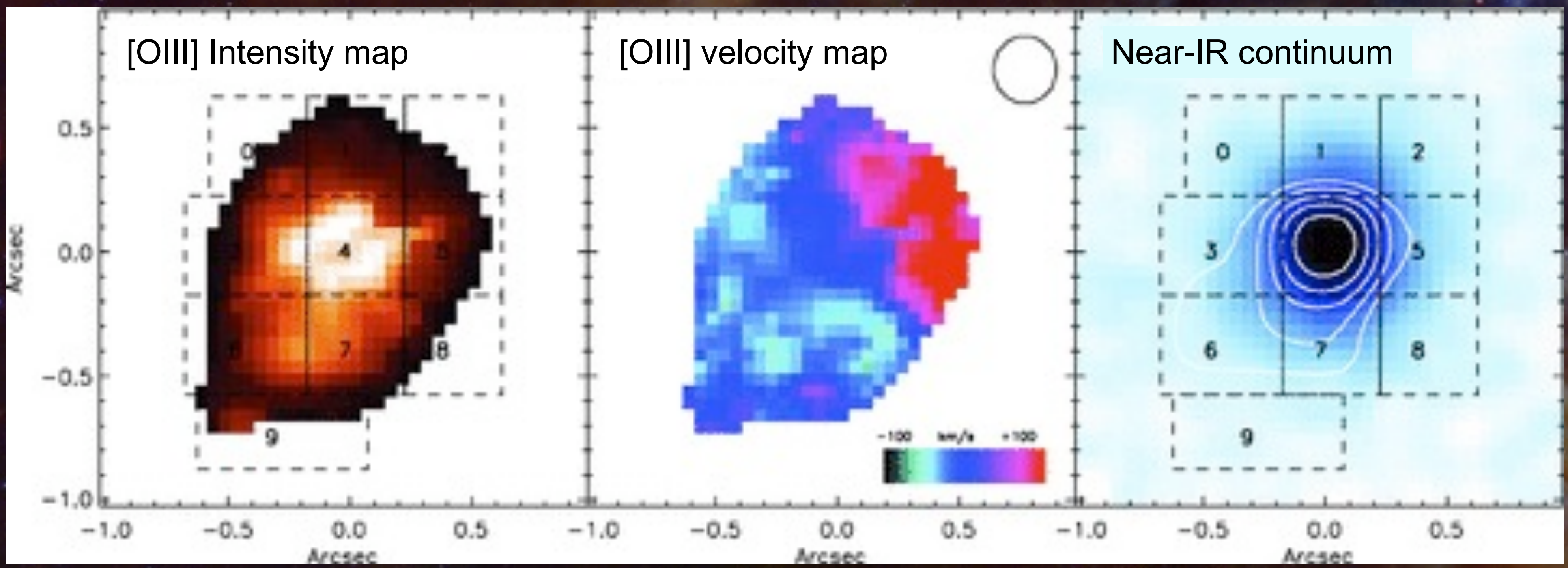
Turbulent high velocity extended warm gas in a z~2 SMG

Sub-millimetre galaxy SMM J1237+6203

Blueshifted broad
(FWHM=823 km/s)
[OIII] component



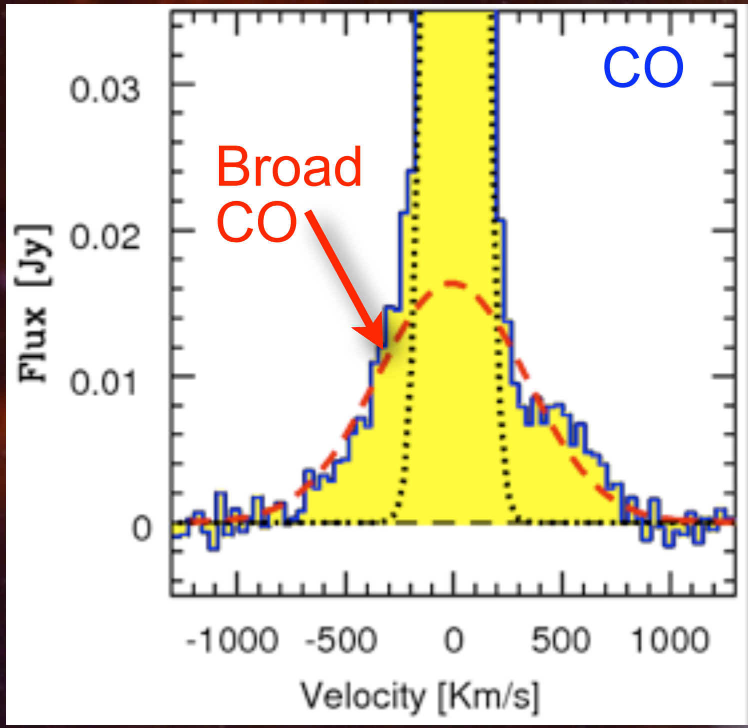
Turbulent, high velocity gas
extended over kpc scales (8kpc)



(Alexander et al. 2010)

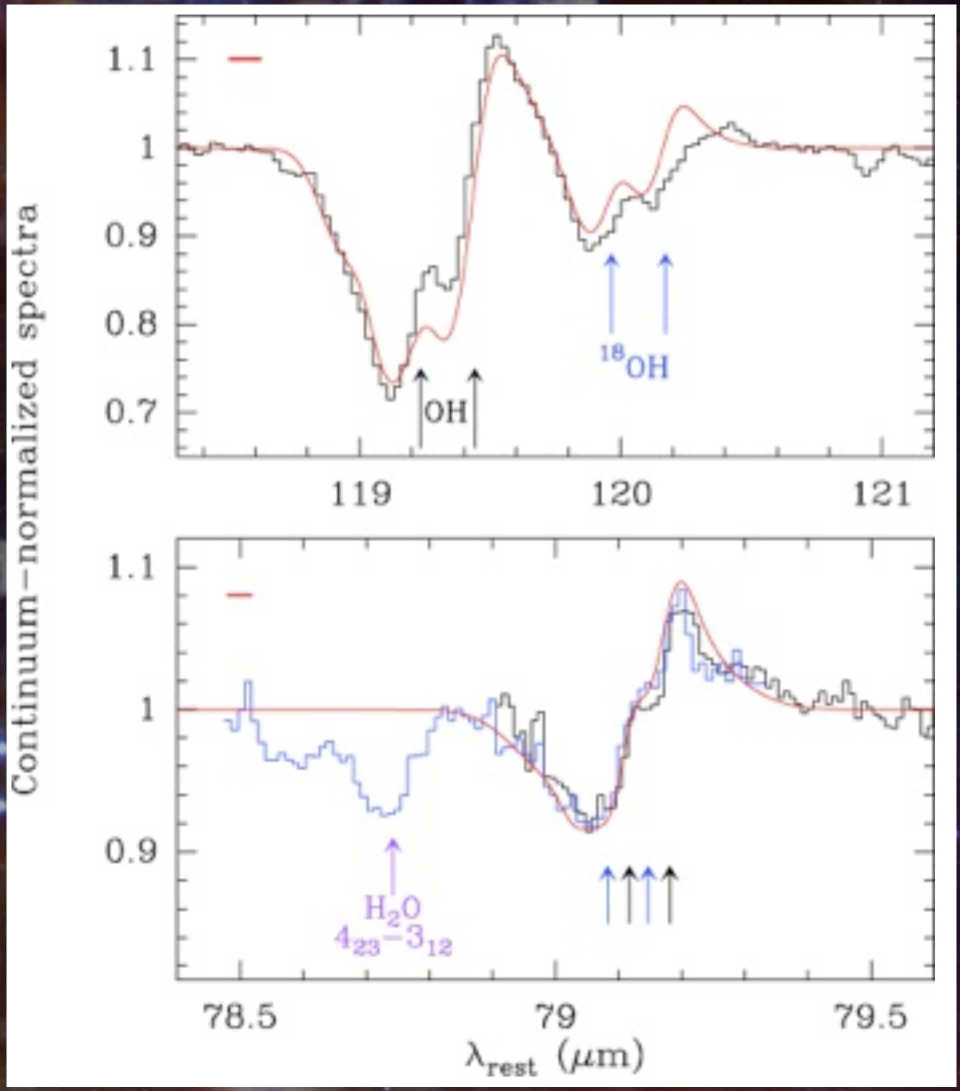
Outflowing molecular gas in Mrk 231

- Broad (~750 km/s) CO wings (Feruglio et al. 2010)
- OH and H_2O absorption lines, outflow v~-1400 km/s (Fischer et al. 2010)
- Wide angle, kpc scale neutral gas outflow with v~-1100 km/s (Rupke & Veilleux 2011)



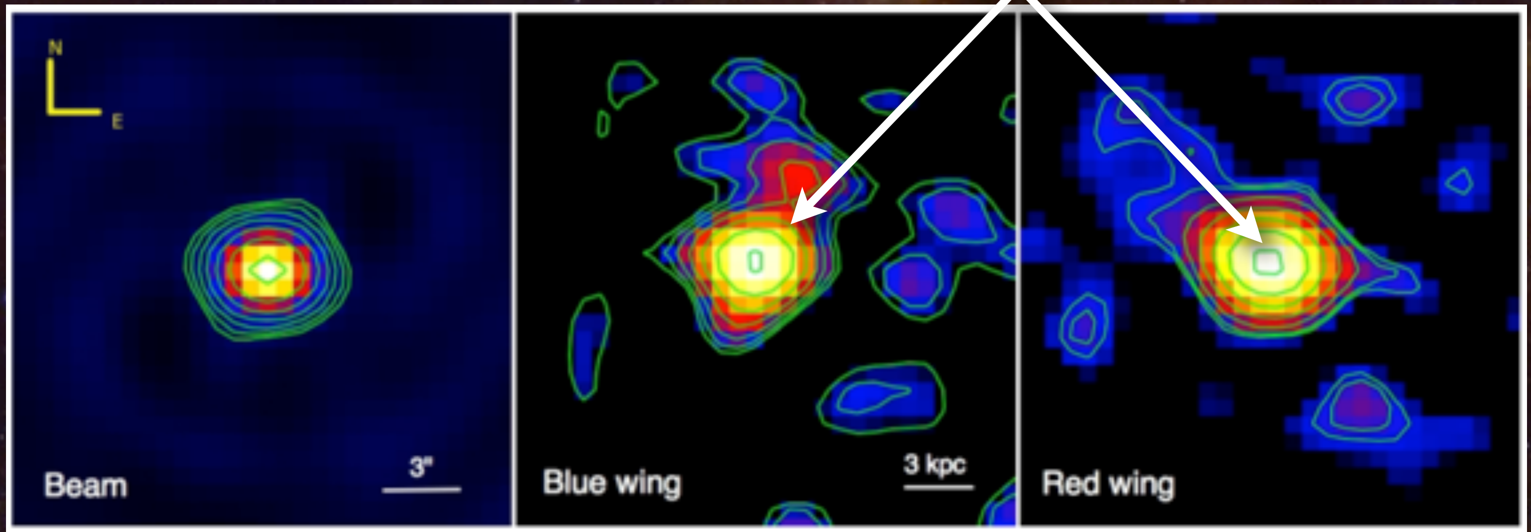
Outflow rate: 700 M☉/yr

Gas will be depleted and star formation will end in ~10Myr !



(Fischer et al. 2010)

Spatially extended (0.6-4 kpc) and coincident



(Feruglio et al. 2010)

.....more evidence needed !

A radio jet can entrain the gas and carry it outside of the galaxy, but only 10% of AGN are radio-loud.

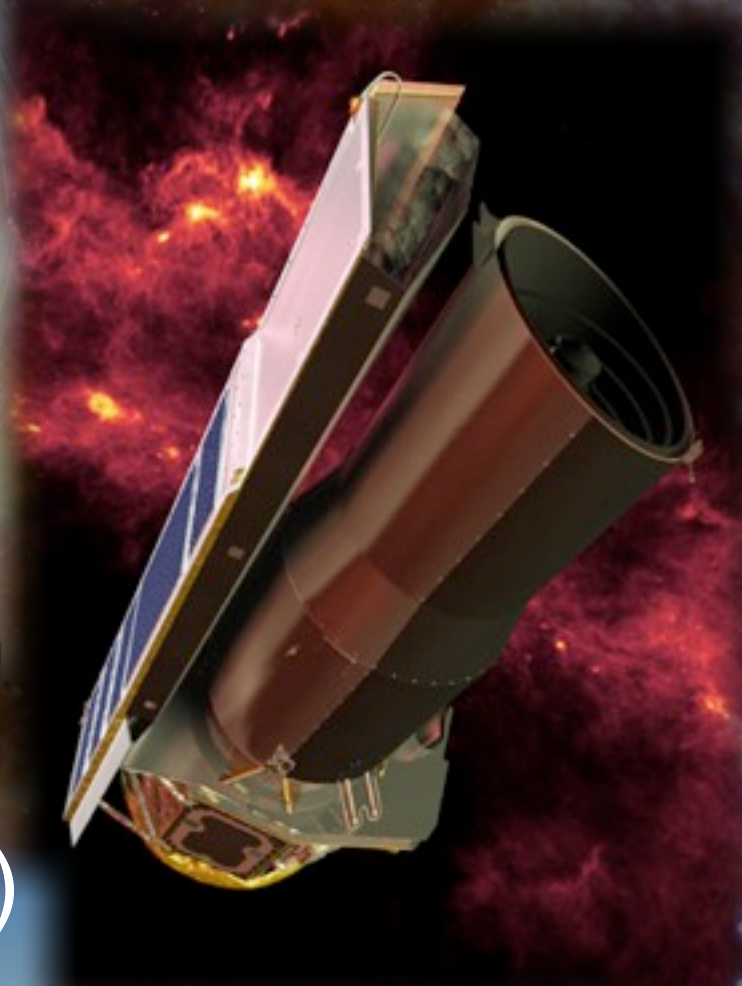
What about the rest of the AGN ?
Can radiation pressure drive the gas outside the galaxy ?

➫ Need to trace the ISM in high-z massive starburst galaxies with a powerful and NON RADIO-LOUD AGN

An army of telescope to find good candidates and look for feedback signatures

CFHT (optical)

Spitzer (IR)



IRAM: MAMBO (mm)

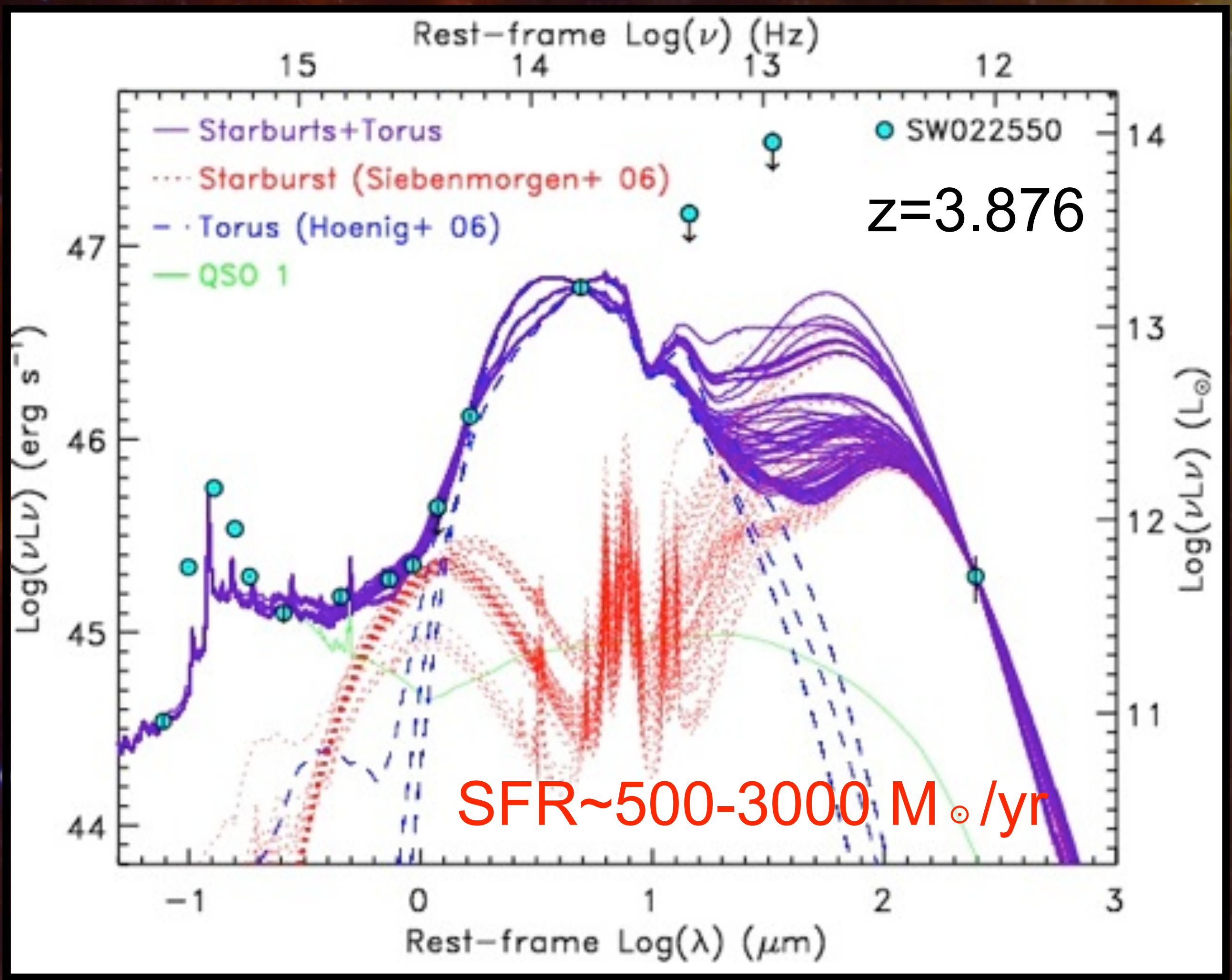
Plateau de Bure
(CO - molecular gas)

VLT: SINFONI
(NIR - ionized gas)

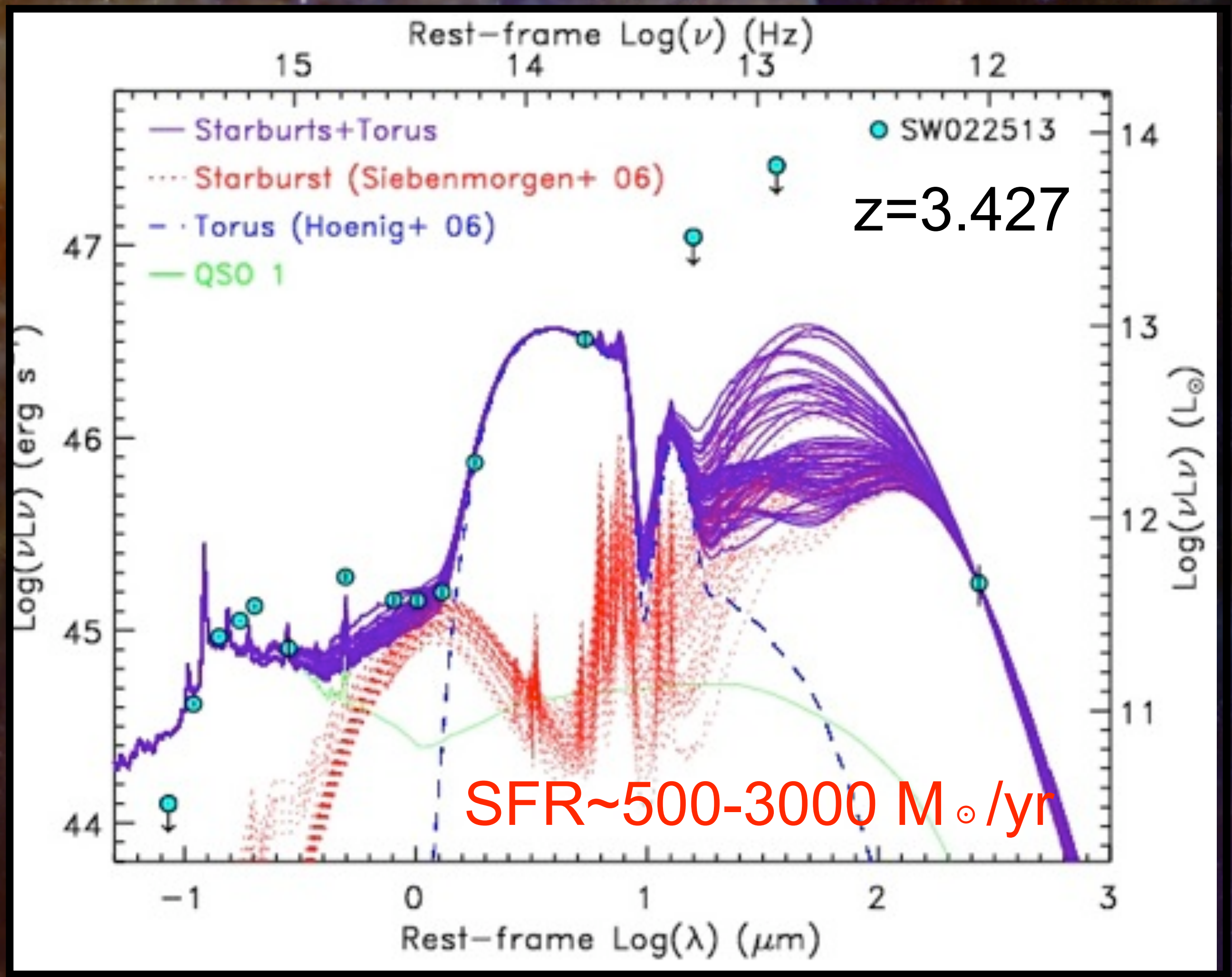
Obscured QSO hosted by powerful starbursts at z≥3.5

Massive host with intense starburst and AGN activity

SW022550



SW022513



L(AGN) ~ 10^{46} erg/s & L(SB) ~ $10^{46\text{-}46.8}$ erg/s → L_{bol} ~ 10^{47} erg/s

(Polletta et al. 2008)

Plateau de Bure Interferometer Observations

PdBI:

interferometer with 6 antennnas

3 bands: 1.3mm, 2mm & 3mm

D configuration with the 3mm band

Exposure times:

- 5.3 hrs per SW022550
- 8.9 hrs per SW022513

Beam size:

- 8.4″×4.8″ for SW022550
- 6″×4″ for SW022513

GOAL: detect the CO(4-3) line (ν_{rest} = 461 GHz)

SINFONI Observations

SINFONI on VLT:

Image slicing integral field spectrograph

FOV = 8″× 8″

Pixel scale = 0.25 ″× 0.25 ″

HK = 1.45-2.45μm (observer-frame)

H = 3300-4100Å (rest-frame)

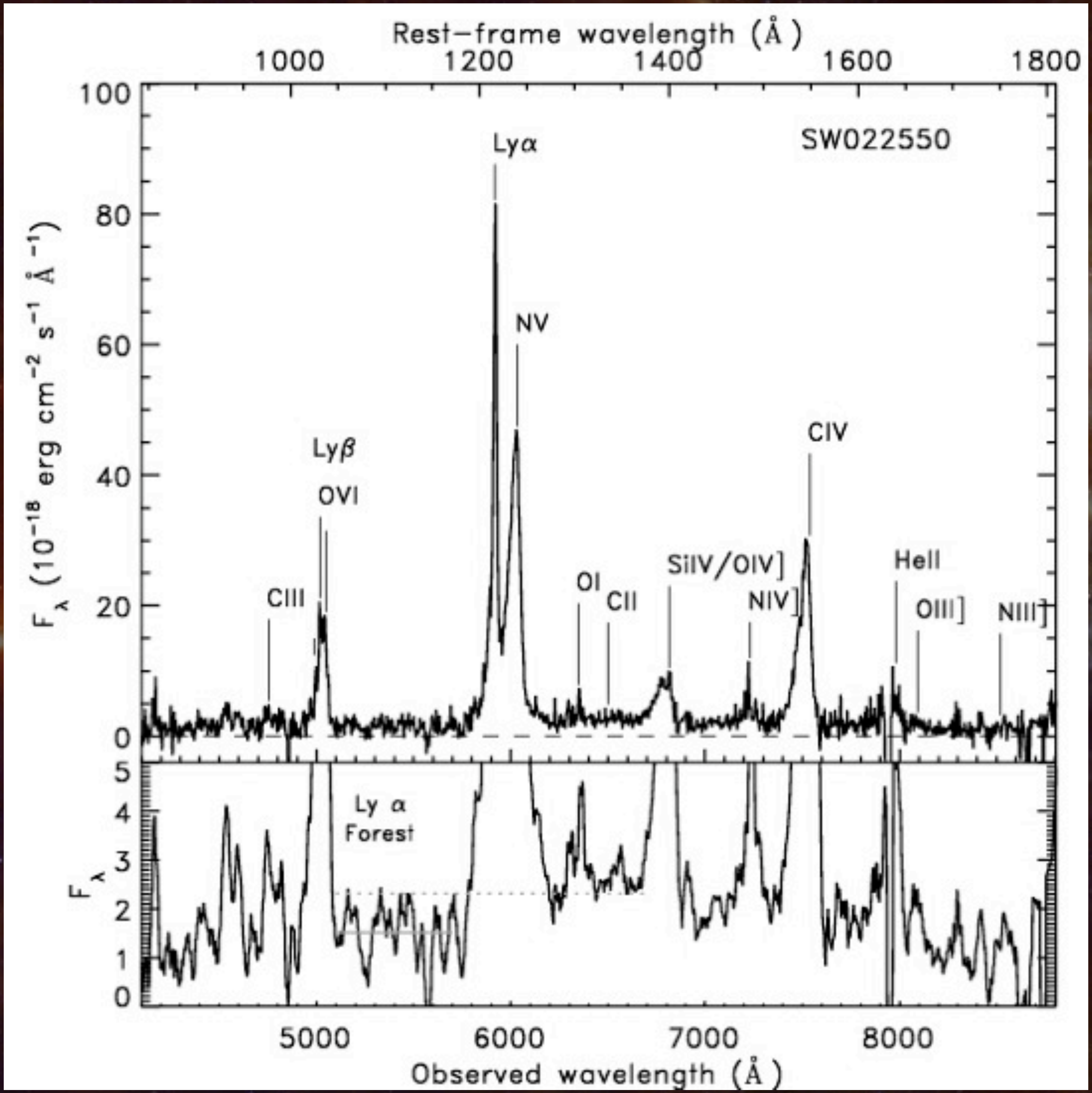
K = 4400-5400Å (rest-frame)

Exposure ~ 3h/target

GOAL: kinematics of the warm gas

SW022550

Ultraviolet rest-frame spectrum of SW022550

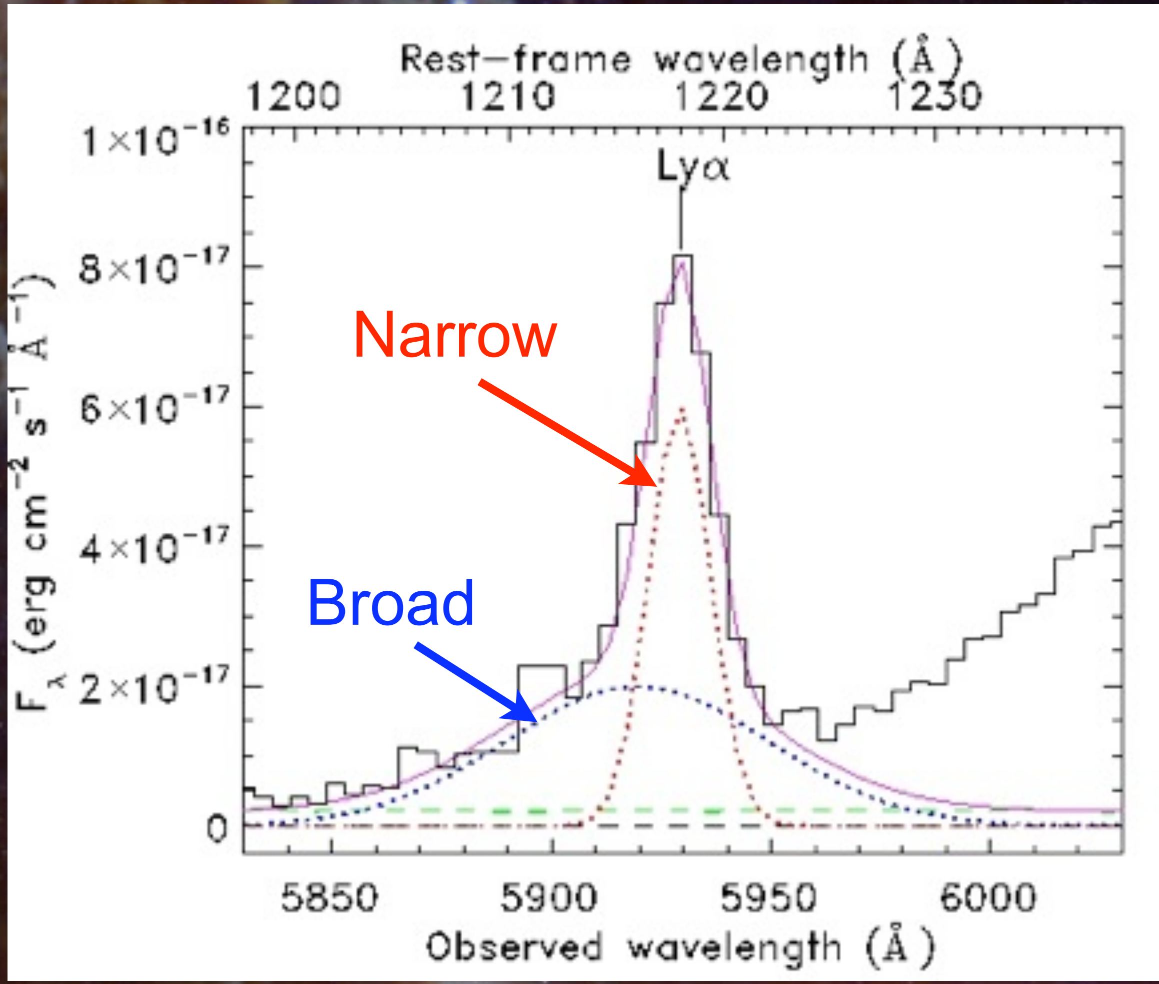


VLT/ISAAC (Polletta et al. 2008)

Broad (FWHM~2000km/s) lines at z = 3.868

Narrow (FWHM~500km/s) lines at z = 3.876

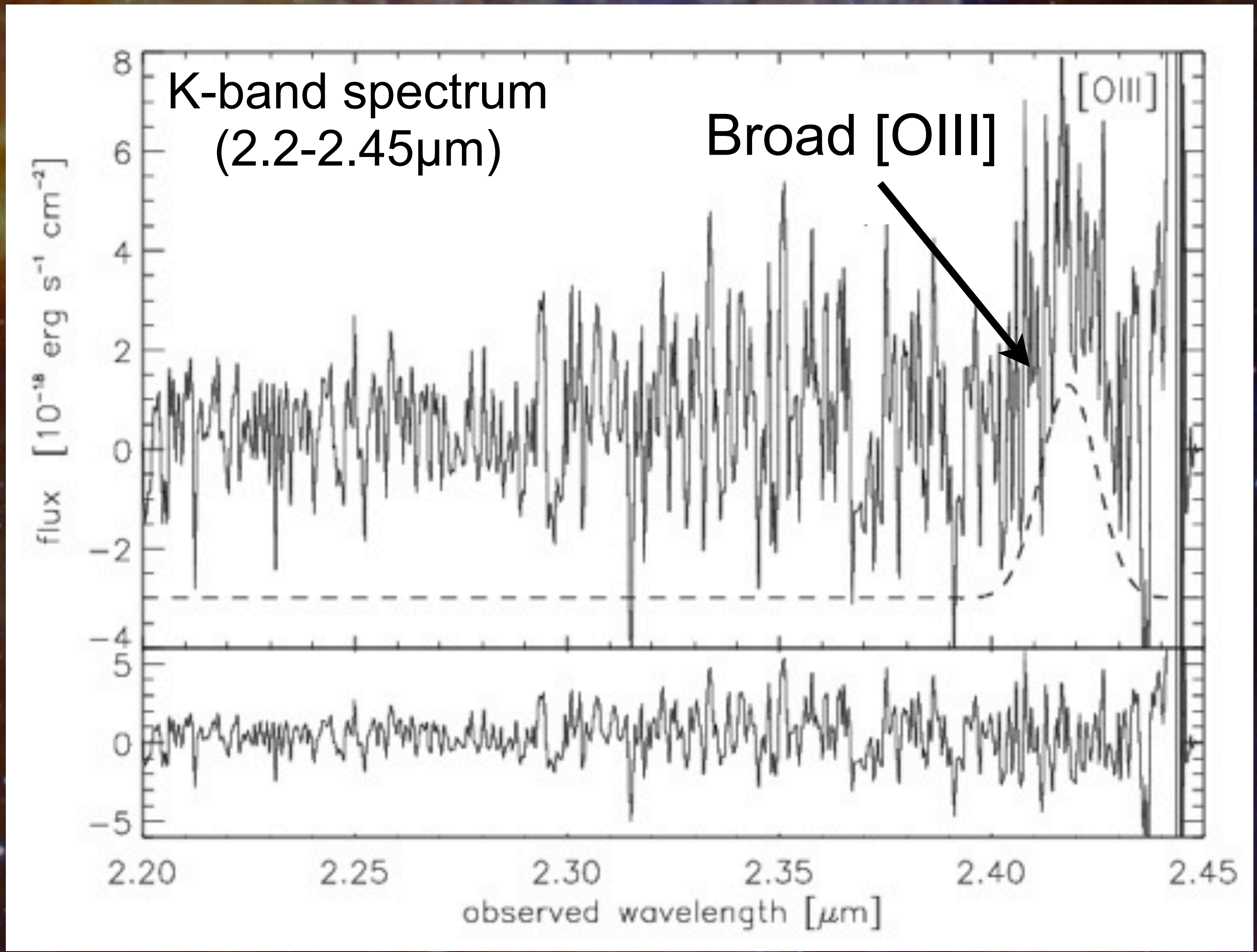
Velocity offset ~ -492 km s^{-1}



Broad blueshifted lines are commonly interpreted as outflowing gas

Optical rest-frame spectrum of SW022550

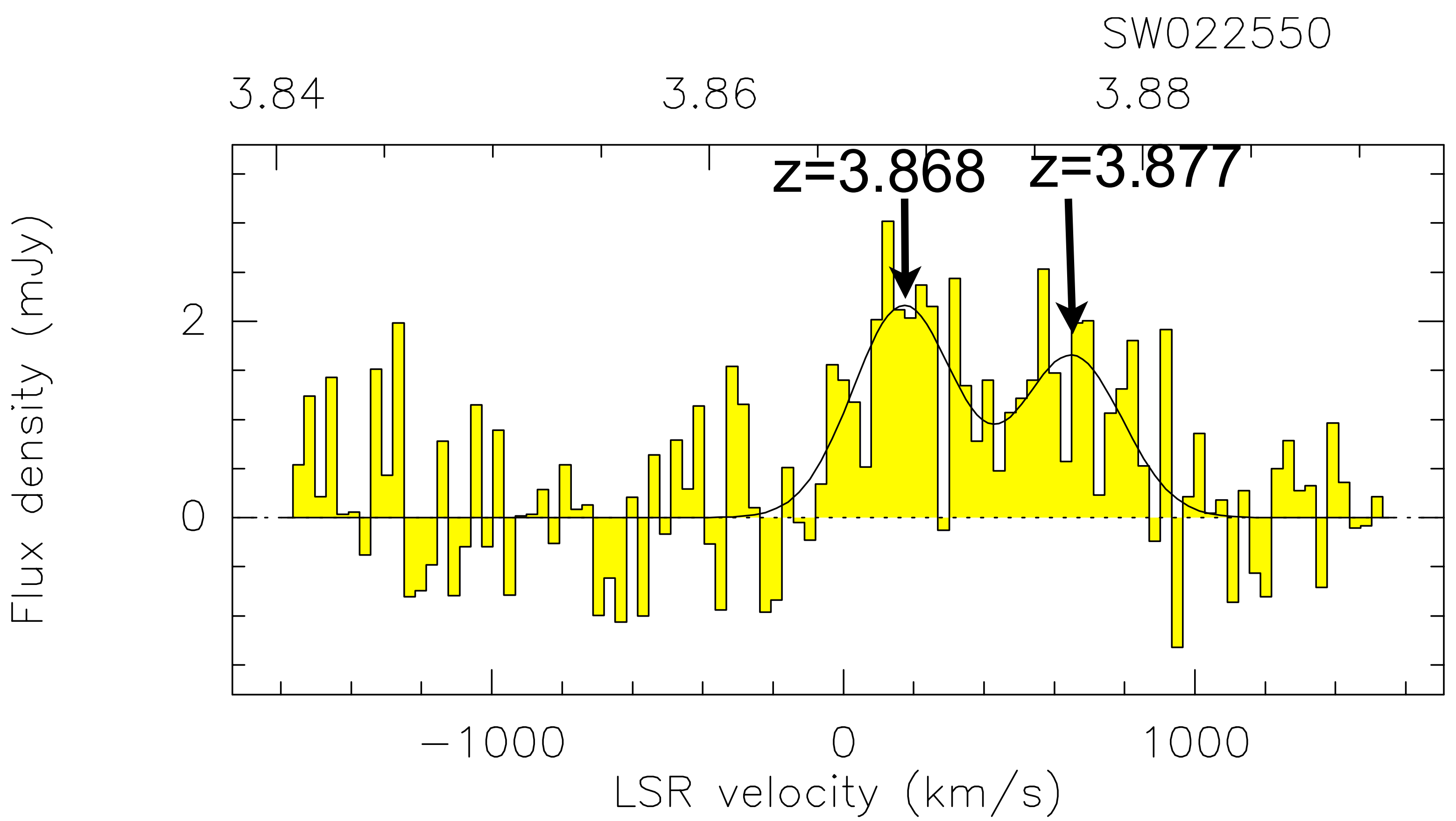
- Broad (FWHM=2212 km s^{-1}) [OIII] 4959 Å emission line at z=3.876
- Compact and associated with the continuum
- *z* consistent with UV lines



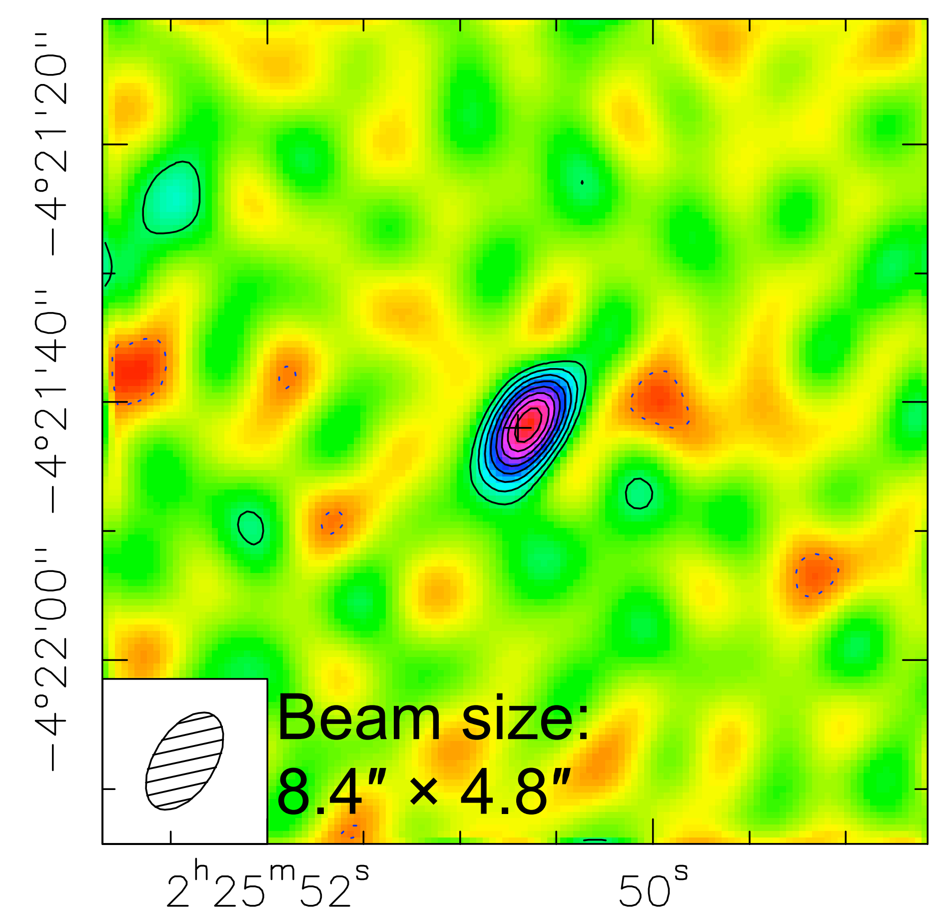
VLT/SINFONI (Nesvadba, Polletta et al. 2011)

Molecular gas kinematics in SW022550

Spectrum of CO J=4-3 emission



Velocity-integrated Map



Double peak profile
$FWHM_1 = FWHM_2$ = 340 km/s
Δv = 500 km/s
z_1=3.868
z_2=3.877

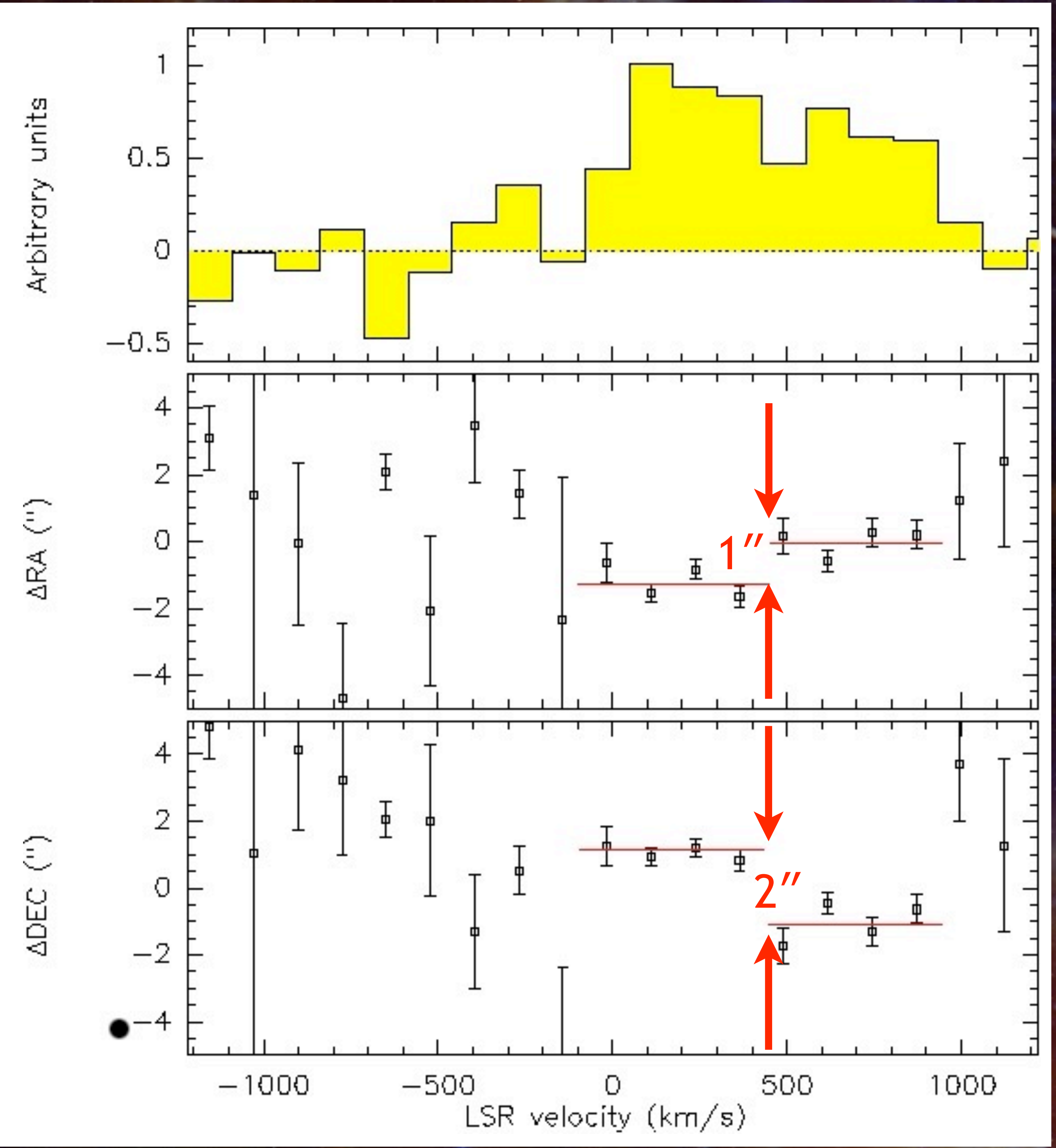
CO J=4-3:
I_{CO}=1.4 ± 0.16 Jy km/s
Compact
$M_{gas}=4.3\times10^{10} M_{sun}$

The kinematics of the broad and narrow UV lines match the two CO peaks

(Polletta et al. 2011)

The origin of the two CO peaks

Two components separated by 2.2″ (~ 10 kpc)



(Polletta et al. 2011)

What drives the kinematics of the ionized and of the molecular gas in SW022550 ?

FACTS:

- CO line profile (double) and width (300-400km/s) ➩ merger or rotating disk
- broad and luminous [OIII] ➩ the AGN affects the warm ionized ISM : outflow ?
- CO extended over 10 kpc and [OIII] from compact nuclear region ➩ different origin

CO

1. merger **MAYBE**

   but only one point source in the multi-λ images

2. single rotating galaxy **UNLIKELY**

   implies high velocities and is hard to reconcile with UV spectrum

[OIII]

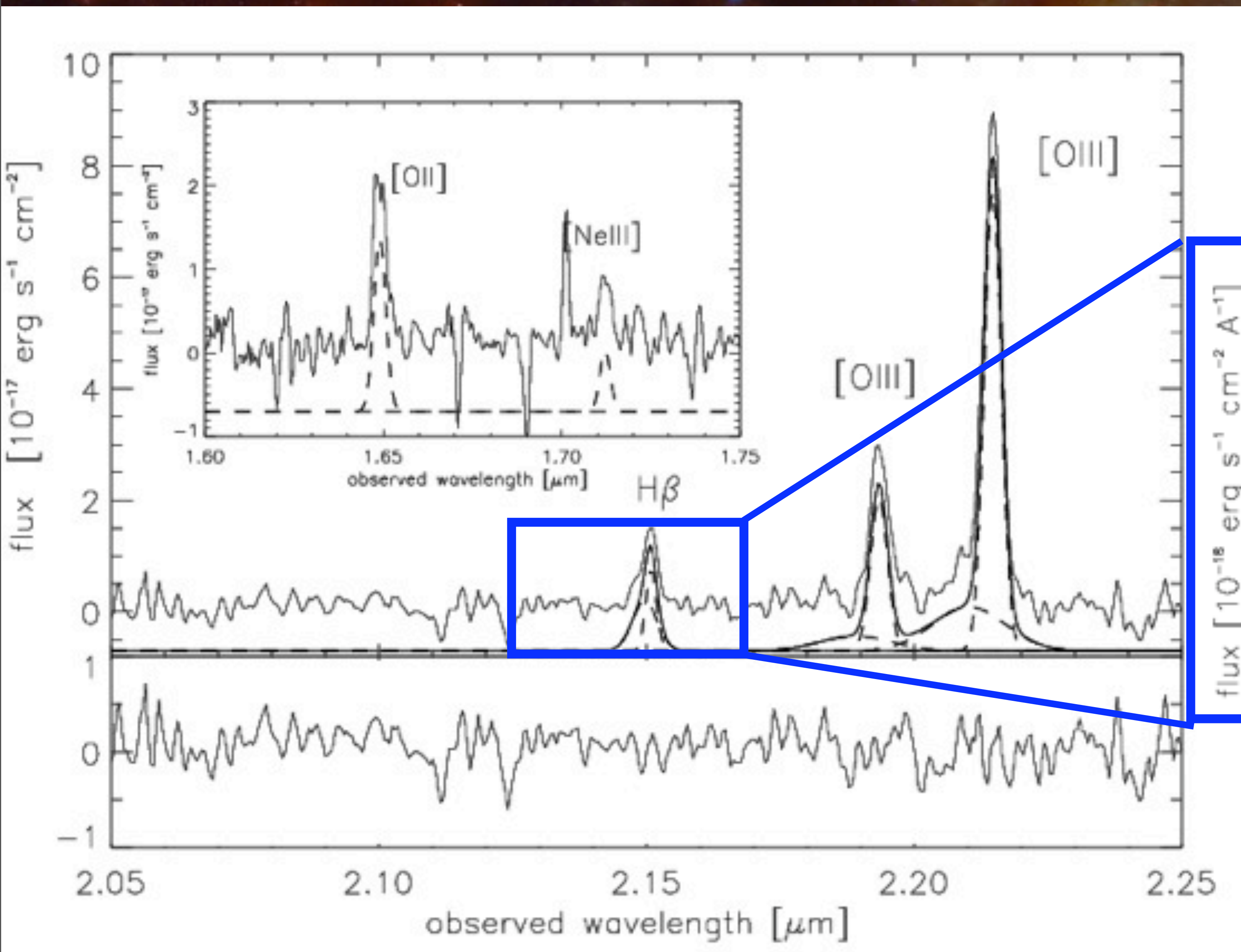
AGN-driven warm gas outflow **LIKELY**

supported by the width of the [OIII] line

AGN-driven warm gas outflow (perhaps in a merger)

SW022513

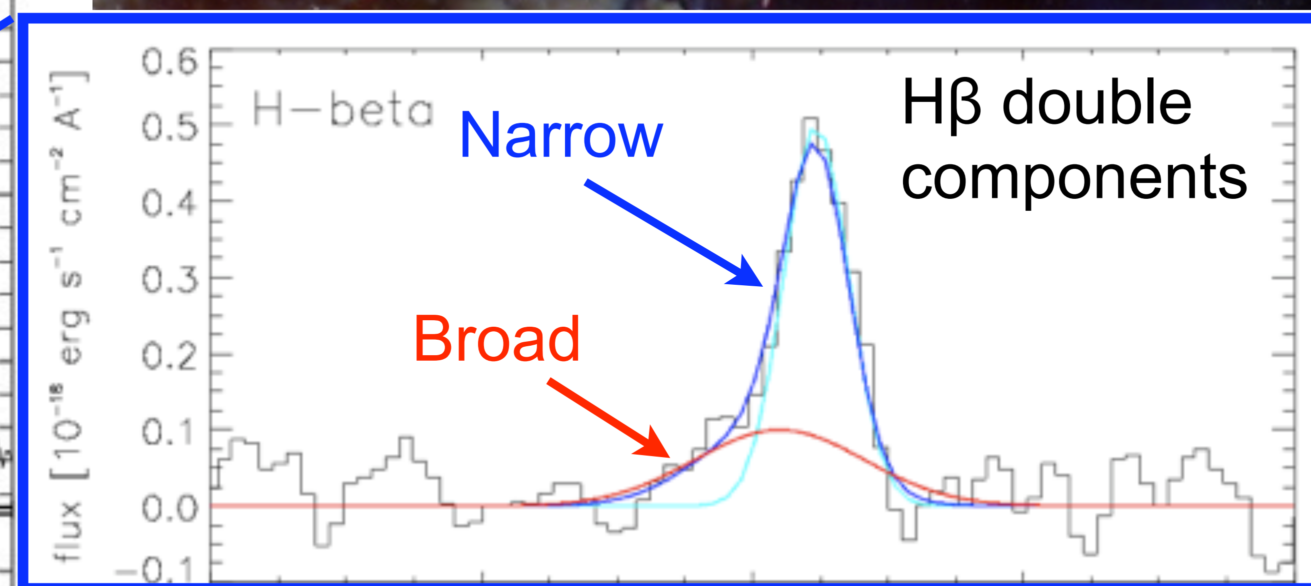
Optical rest-frame spectrum of SW022513



Broad (FWHM~1000km/s) lines at z = 3.422

Narrow (FWHM~369km/s) lines at z = 3.4247

Blueshifted by Δv ~ -183 km s^{-1}



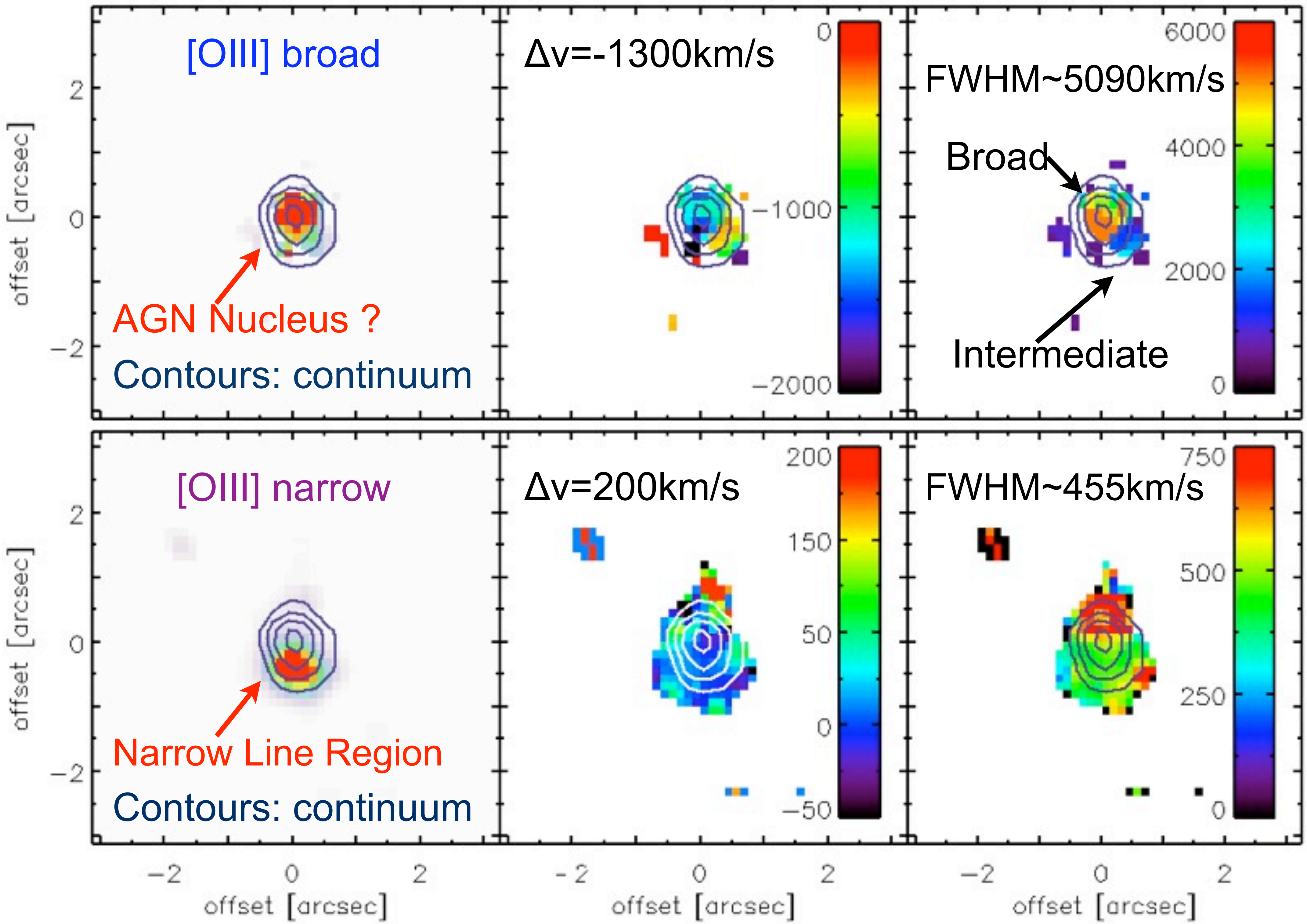
Broad blueshifted lines likely trace outflowing gas

Ionized gas in SW022513

Compact & coincident with the continuum

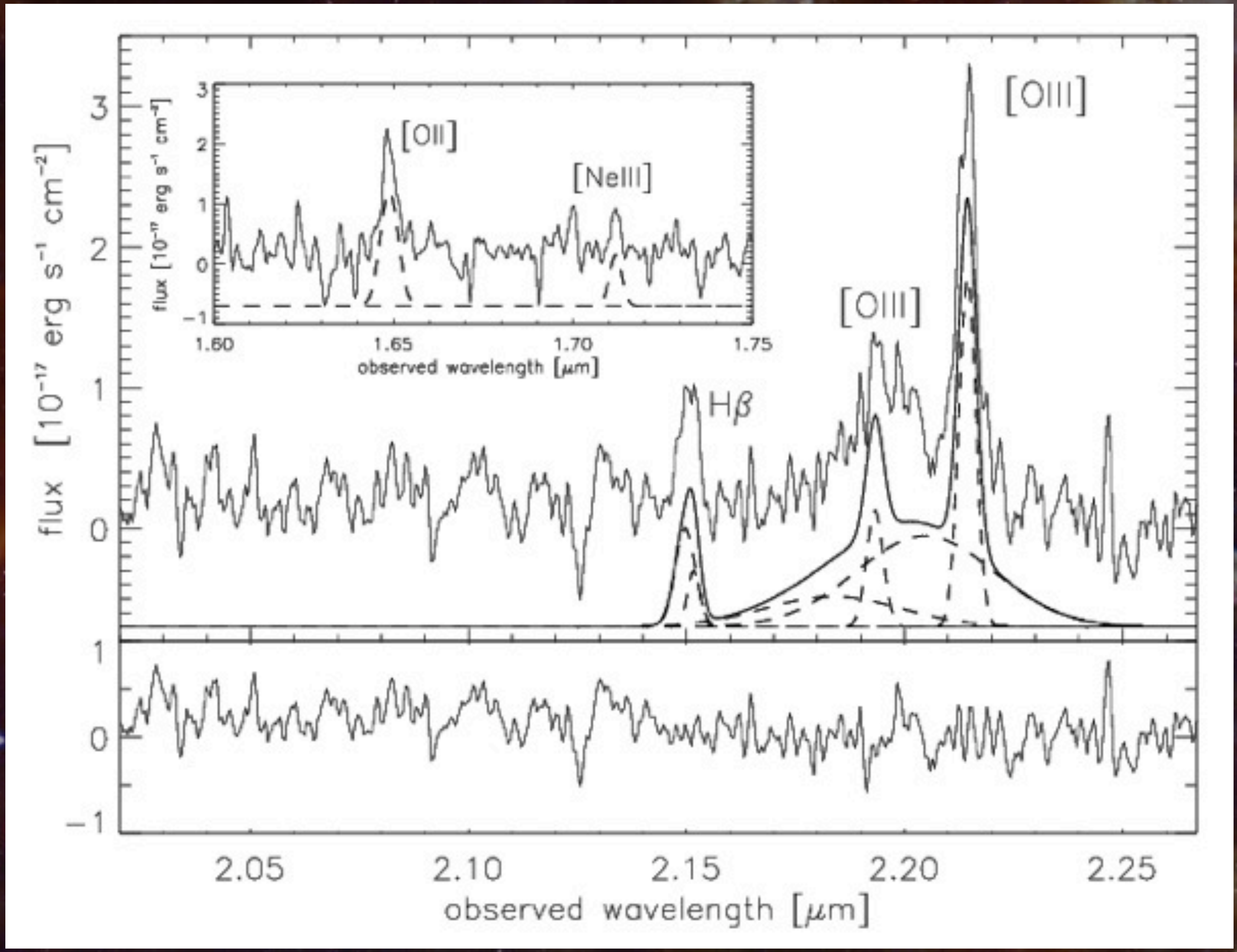
Spatially offset (0.75″~5kpc) from the nucleus

Morphology   Relative velocity [km/s]   FWHM [km/s]



(Nesvadba, Polletta et al. 2011)

Spectrum from the nucleus (continuum peak)



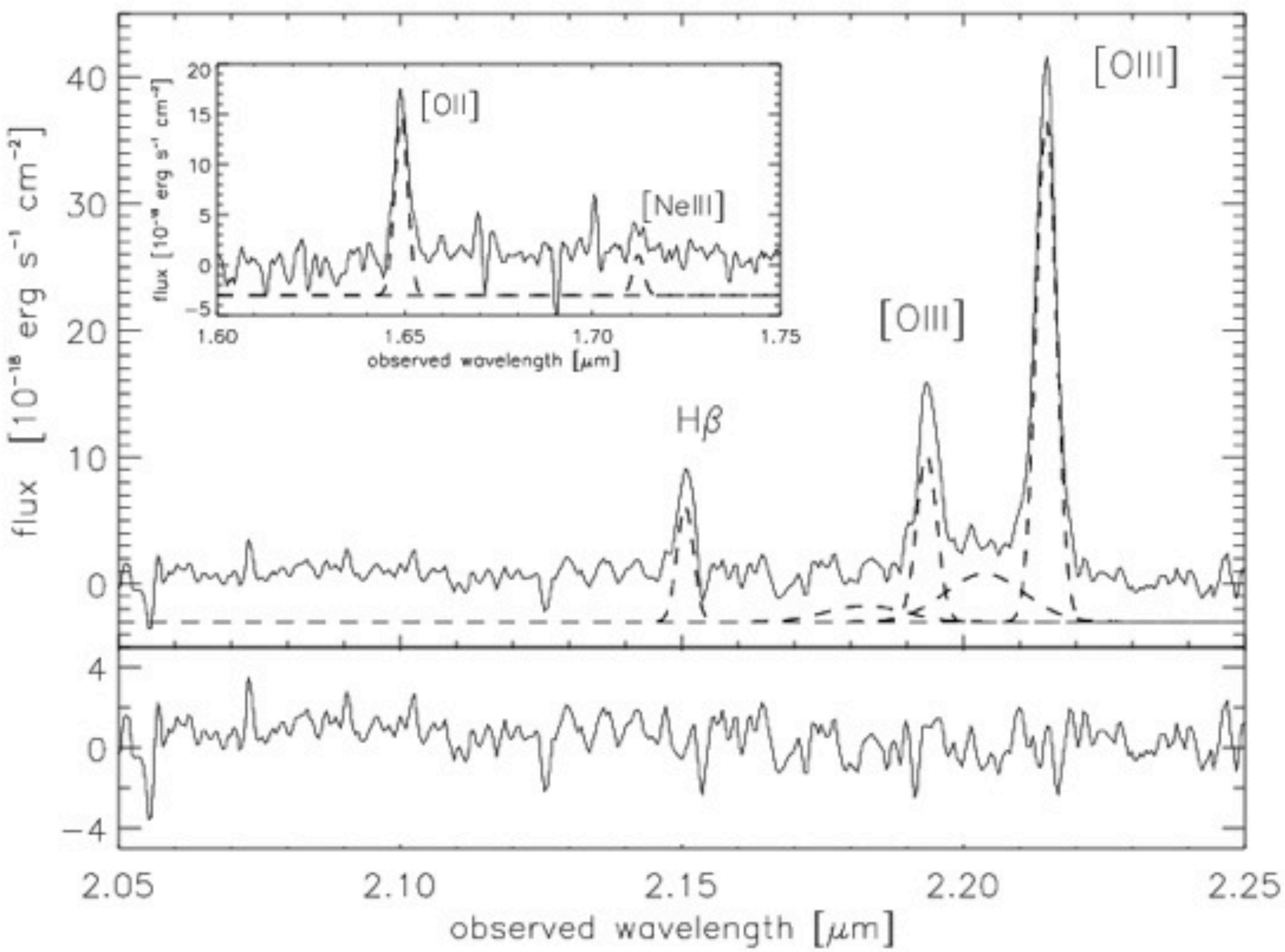
FWHM ~ 5090km/s
Δv = -1300km/s

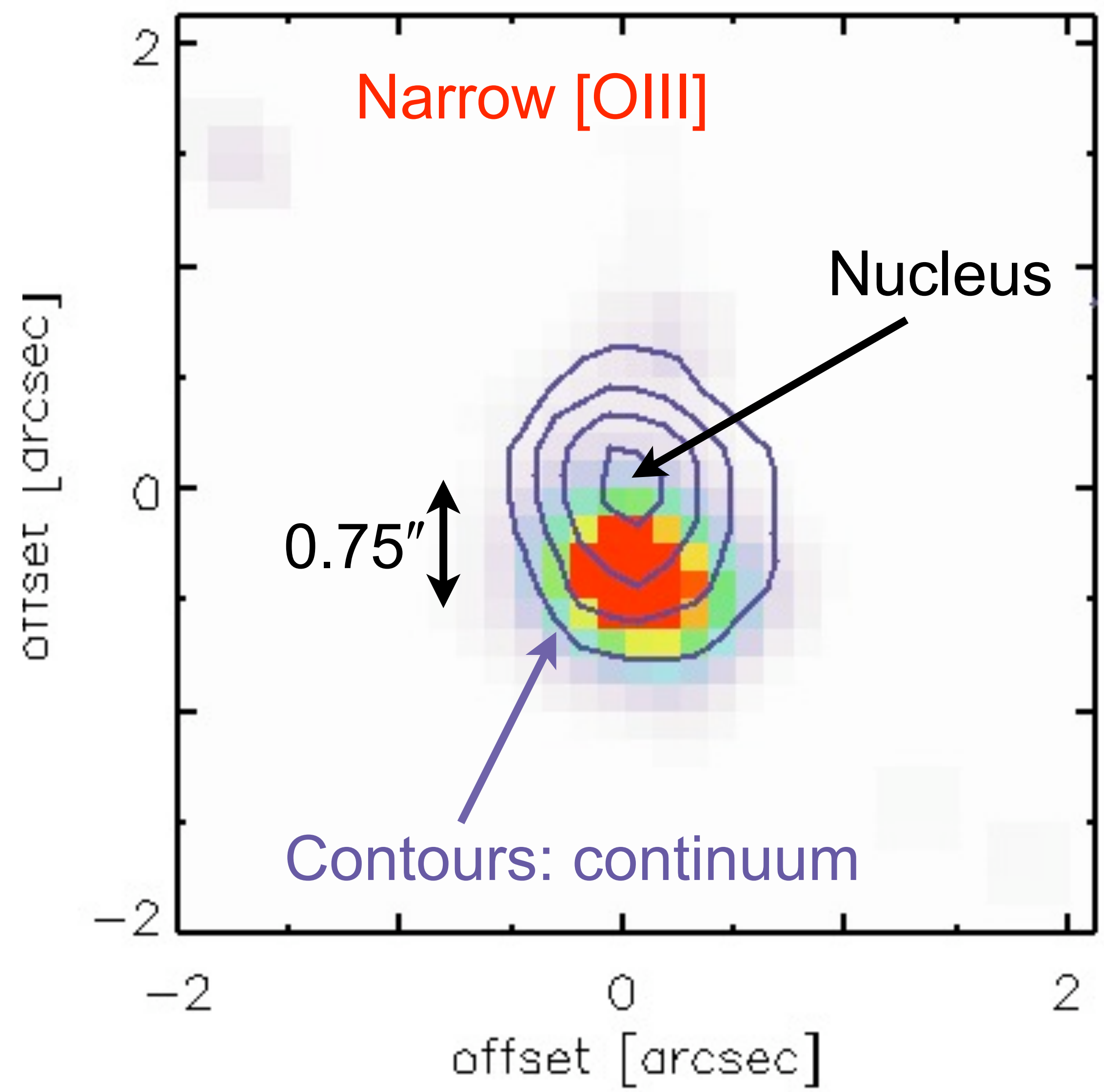
The broadest [OIII] components are around the continuum peak
→ spatially coincident

Large widths imply perturbations and blueshift suggests an outflow:
AGN driven outflow ?

Broad [OIII] (winds) also detected in compact radio galaxies and submm galaxies
(e.g. Nesvadba et al. 2008; Holt et al. 2008; Alexander et al. 2010)

Spectrum from the southern region ([OIII] peak)



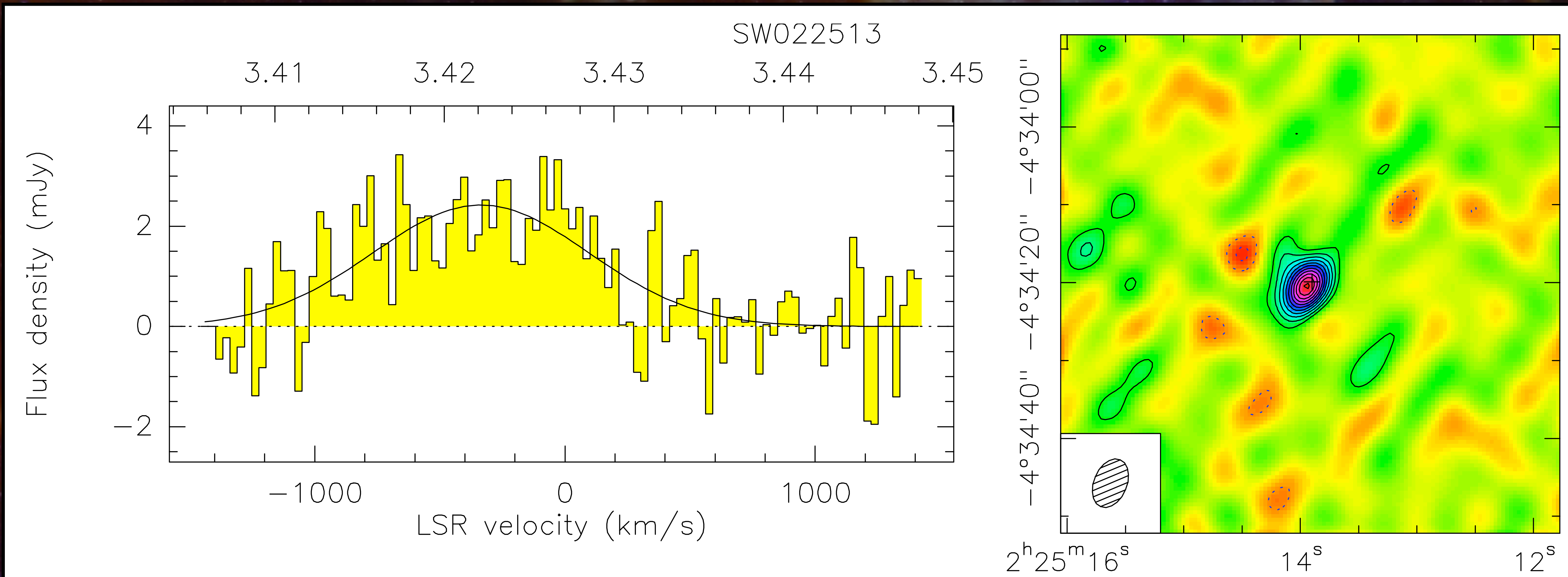


The strongest [OIII] component is narrow & spatially offset (5 kpc) from the nucleus

➙ extended narrow line region

(Nesvadba, Polletta et al. 2011)

Molecular gas kinematics in SW022513



Extremely broad non gaussian profile

z_{CO} = 3.422

FWHM = 1020 km/s

Δv = −183 km/s (z_{sys} = $z_{\text{narrow H}\beta}$ = 3.4247)

CO J=4-3:

I_{CO}=1.6 ± 0.13 Jy km/s

Unresolved & compact

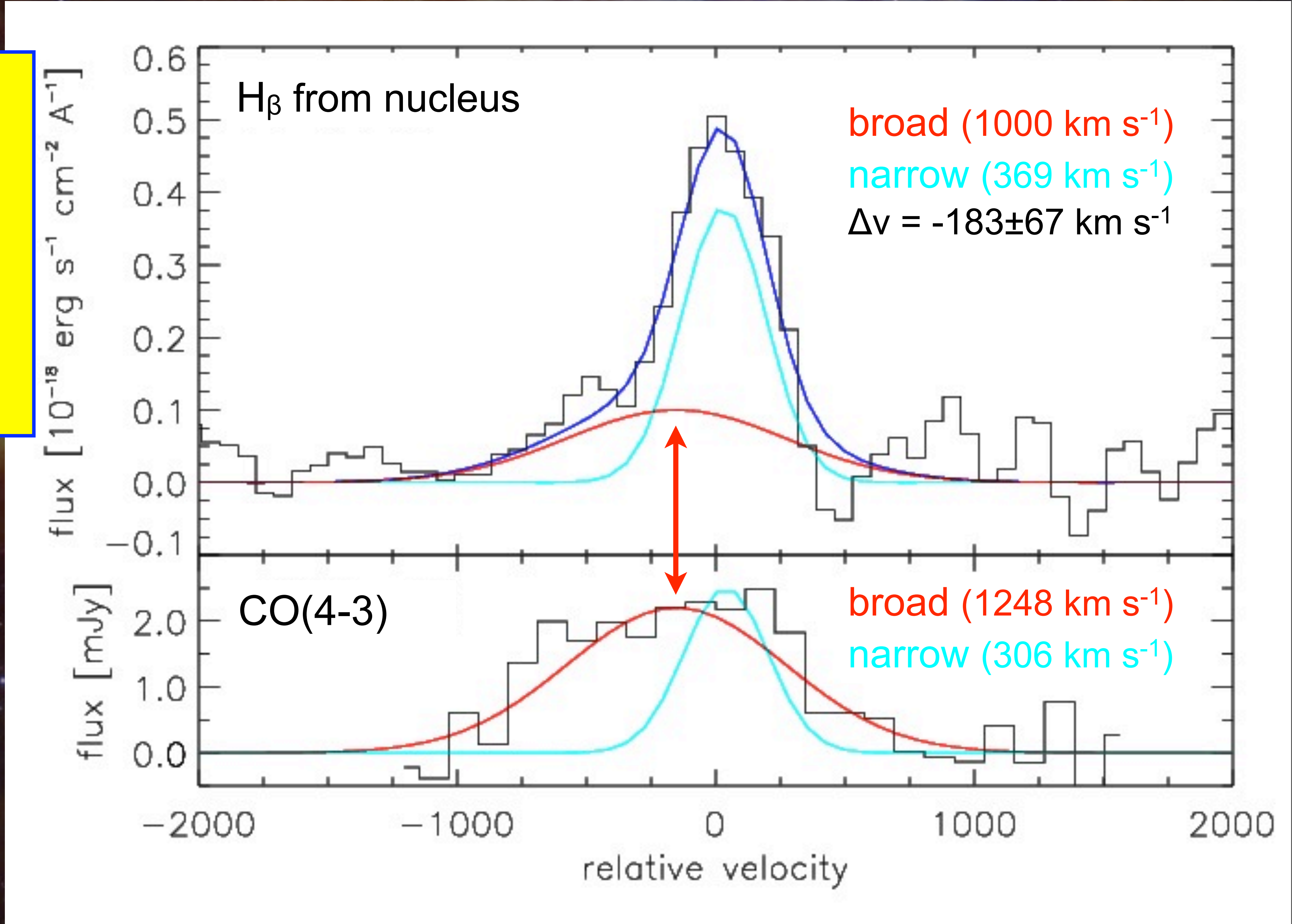
$M_{gas}=4.1\times10^{10} M_\odot$

Molecular (CO) vs Ionized (Hβ) gas in SW022513

Good match between the Hβ and the CO lines

Narrow components
⇨ systemic velocity

Blue wings ⇨ outflow of warm and cold gas



What powers the gas in SW022513 ?

FACTS:

- similar kinematics of the ionized and molecular gas ➯ common origin & power source
- line luminosity and ratios ➯ AGN photoionization
- large-scale velocity gradients ➯ never seen in mergers, starbursts galaxies, ULIRGs

⇩

1. merger **NO**

   difficult to explain the broad lines

2. single rotating galaxy **NO**

   inconsistent with line profile and velocity

3. AGN-driven outflow **YES**

   supported by simulations and observations

Significant amount of outflowing molecular gas at galactic scales

Outflowing gas kinetic energy

$$E_{kin} = \frac{1}{2} M v^2$$

M : outflowing gas mass (40% of mol. gas → $M(H_2) = 1.6 \times 10^{10}\ M_\odot$)

v : velocity relative to the systemic velocity (183 km/s)

⇓

$$E_{kin} = 5 \times 10^{57}\ \text{erg}$$

How does the AGN drive the outflow in SW022513 ?

Momentum-driven radiative pressure driven by the AGN

Outflow E:	AGN E:
$E_{kin} = 5\times10^{57}$ erg	$L_{bol}^{AGN} \times \tau_{AGN} \sim 10^{61}$ erg

✔

The luminosity necessary to launch a wind is :

$$L > L_M \cong 3\times10^{46} f_{g0.1} \sigma^4_{200} \text{ erg s}^{-1}$$

σ_{200}: vel. dispersion in 200 km s^{-1} (FWHM/2.4 ≅ 400 km s^{-1})

$f_{g0.1}$: gas fraction in 0.1 (0.1-0.2)

L_M : critical luminosity

(Murray et al. 2005)

$$L_M = 5\times10^{47} \text{ erg s}^{-1} > L_{AGN} \cong 5\times10^{46} \text{ erg s}^{-1}$$

The AGN radiation cannot launch such an outflow

How does the AGN drive the outflow in SW022513 ?

Mechanical energy injected through a radio jet

Outflow E:	Radio E:
$E_{kin} = 5 \times 10^{57}$ erg	$E_{mech} = L_{mech} \times \tau_{radio}$

$L_{1.4GHz} = 2.4 \times 10^{25}$ W Hz^{-1}

$L_{mech} = 3 \times 10^{38} f_W^{1.5} L_{rad,28}^{6/7}$ W $= 3 \times 10^{44}$ erg s^{-1}

$\tau_{radio} = 10$ Myr

→ 9×10^{58} erg ✔

(Willott et al. 1999; Nesvadba et al. 2011)

MECHANICAL ENERGY ASSOCIATED WITH THE RADIO POWER CAN ACCELERATE THE GAS !

Summary

Molecular and ionized gas observations of two obscured QSOs at z~3.4-3.9 with large SFRs (>500 M/yr) and large AGN luminosities

➙ good candidates to study the impact of powerful activity on the ISM

⇩

Extended narrow line region ➯ the AGN affects the gas at galatic scales (10 kpc)

Blueshifted, broad [OIII] line emission ➯ AGN-driven outflow with velocity of ~1000 km/s of warm gas

Large masses of molecular gas (CO) with blueshifted broad components matching the warm ionized gas (in 1 object) ➯ molecular gas outflow entrained by the AGN

The AGN luminosity cannot launch an outflow with the observed velocity, while the radio power can deposit enough mechanical energy ➯ radio powered outflow

Powerful radio quiet sources can power an outflow of warm and cold gas