

# AGN outflows in the emission-line region of the GW recoiling BH candidate 3C 186

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# Supermassive black hole growth

1. Accretion of matter
2. SMBH Mergers

Accretion of matter onto SMBH



AGN

SMBH Mergers



Gravitational wave detections

## Galaxy Merger

Black hole pairs lose energy via

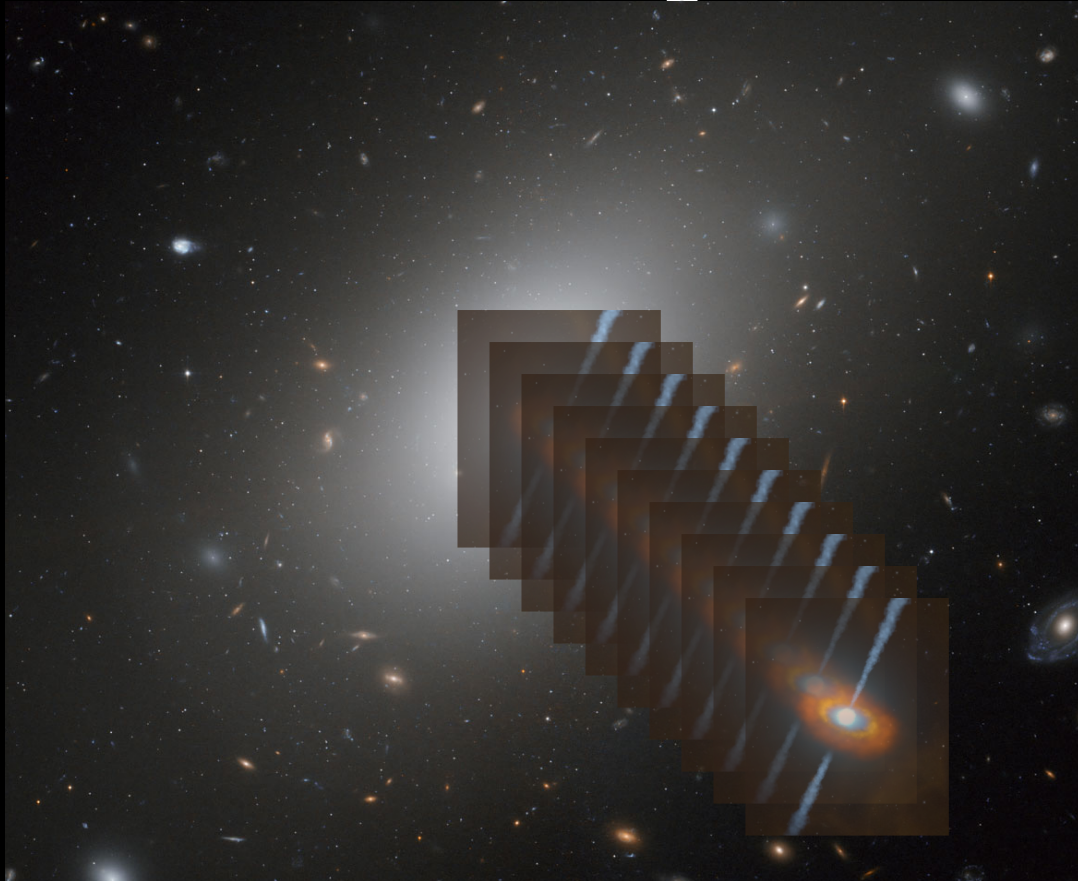
1. dynamical friction
2. 3-body interaction
3. Gravitational wave emission

*Begelman et al. 1980*

$T_{\text{in}} \sim T_{\text{Hubble}}$  Final Parsec problem  
*Merritt 2000*  
*Milosavljević & Merritt 2003*

but see also *Kahn et al. 2016*  
and *Gualandris et al. 2017*

# The merged BH may get a kick from anisotropic emission of gravitational waves



Prediction: kicked active BHs will show  
offset broad lines w.r.t. narrow lines  
AND spatial offset w.r.t. the host galaxy center

*Peres 1962, Bekenstein 1973  
Campanelli et al 2007,  
Lousto et al 08, 11, 12  
Loeb 2007, Volonteri & Madau 08*

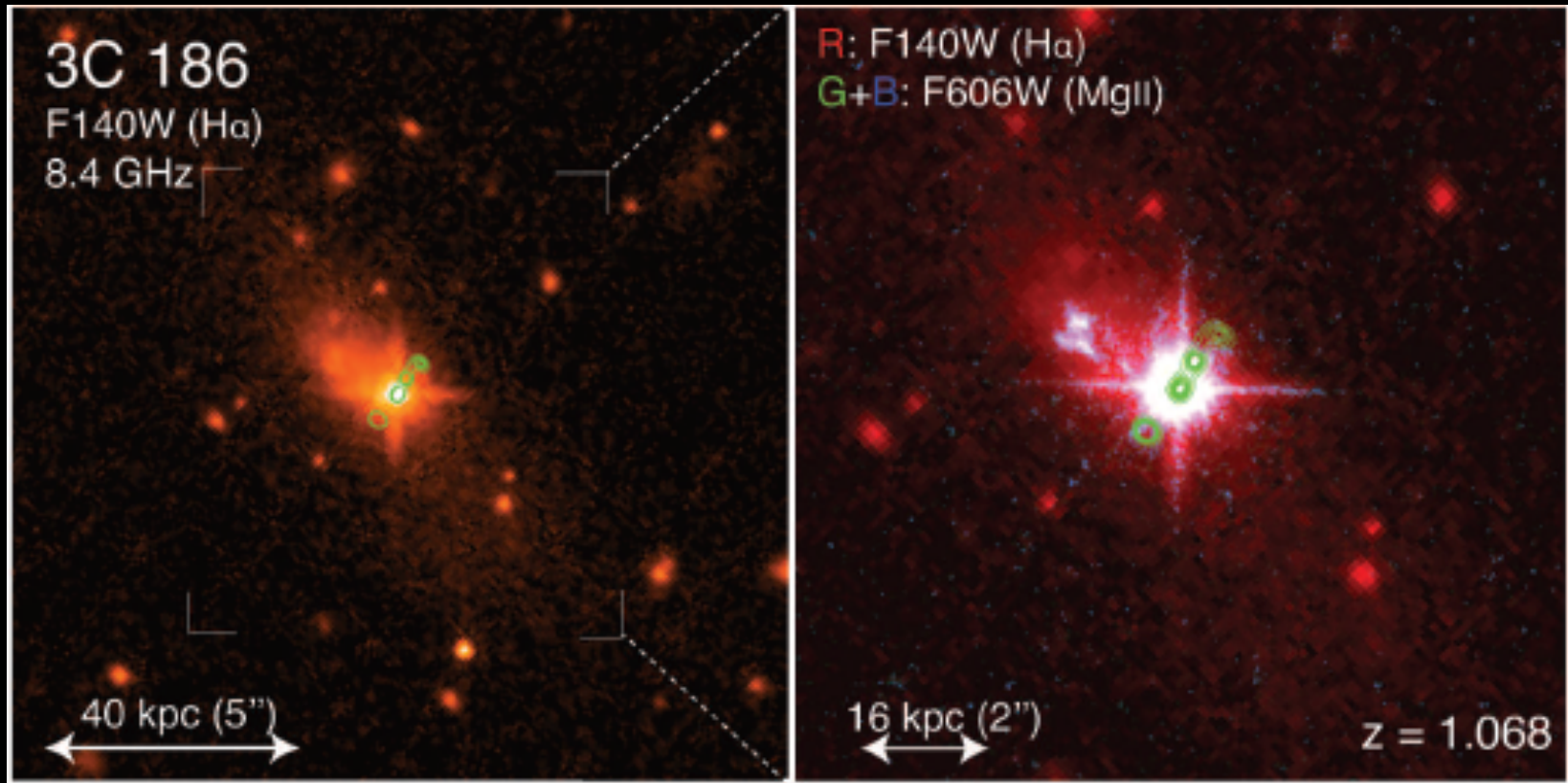
## GW recoiling black hole candidates

SDSS 0927	$z=0.7$	Komossa et al. 2008	$M_{\text{BH}}=6 \times 10^8 M_{\odot}$	? <i>Decarli et al. 2014</i>
CID-42	$z=0.36$	Civano et al. 2010	$M_{\text{BH}}=10^6 M_{\odot}$	Dual AGN? <i>Comerford et al. 2009</i>
NGC 3718	$z=0.003$	Markakis et al. 2015	$M_{\text{BH}}=10^8 M_{\odot}$	Merger. No v offset?
SDSS 0956	$z=0.7$	Steinhardt et al. 2012	$M_{\text{BH}}=4 \times 10^8 M_{\odot}$	Eccentric disk?
SDSS 1133	$z=0.008$	Koss et al. 2014	$M_{\text{BH}}=10^6 M_{\odot}$	LBV star + SN
SBS 1421	$z=0.28$	Sun et al 2016	$M_{\text{BH}}=2 \times 10^7 M_{\odot}$	Bipolar outflow?
Mrk 1018	$z=0.04$	Kim et al. 2018	$M_{\text{BH}}=1 \times 10^8 M_{\odot}$	Binary BH?

How can we confirm GW recoiling BH candidates?

# HST-3CR: Cycle 20 SNAP of the $z > 1$ 3CR RGs and QSO

## 3C 186 $z=1.07$



Type 1 QSO (broad and narrow lines)  $L_{\text{bol}} \sim 10^{47} \text{ erg s}^{-1}$   
In a cluster of galaxies (*Siemiginowska et al. 2010*)

# 3C 186 $z = 1.07$

*Chiab et al., 2017*

WFC3-IR ima

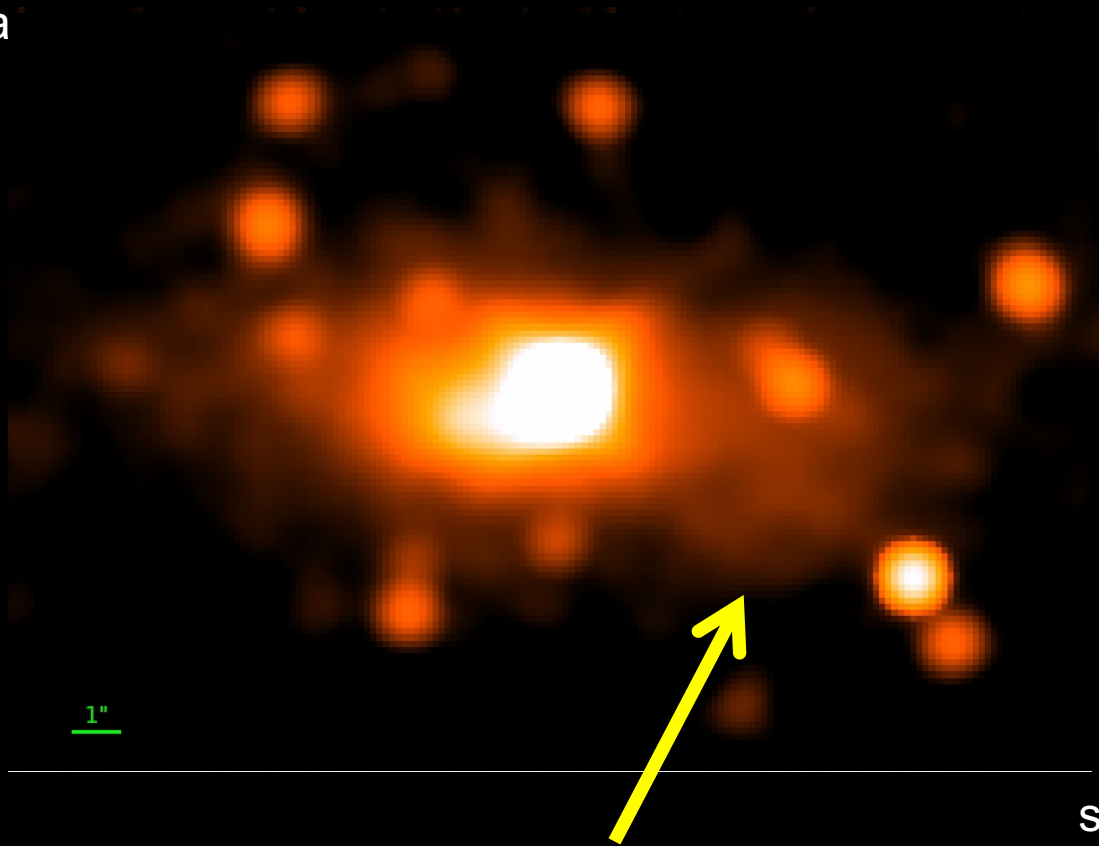
Galfit model

residuals

smoothed image

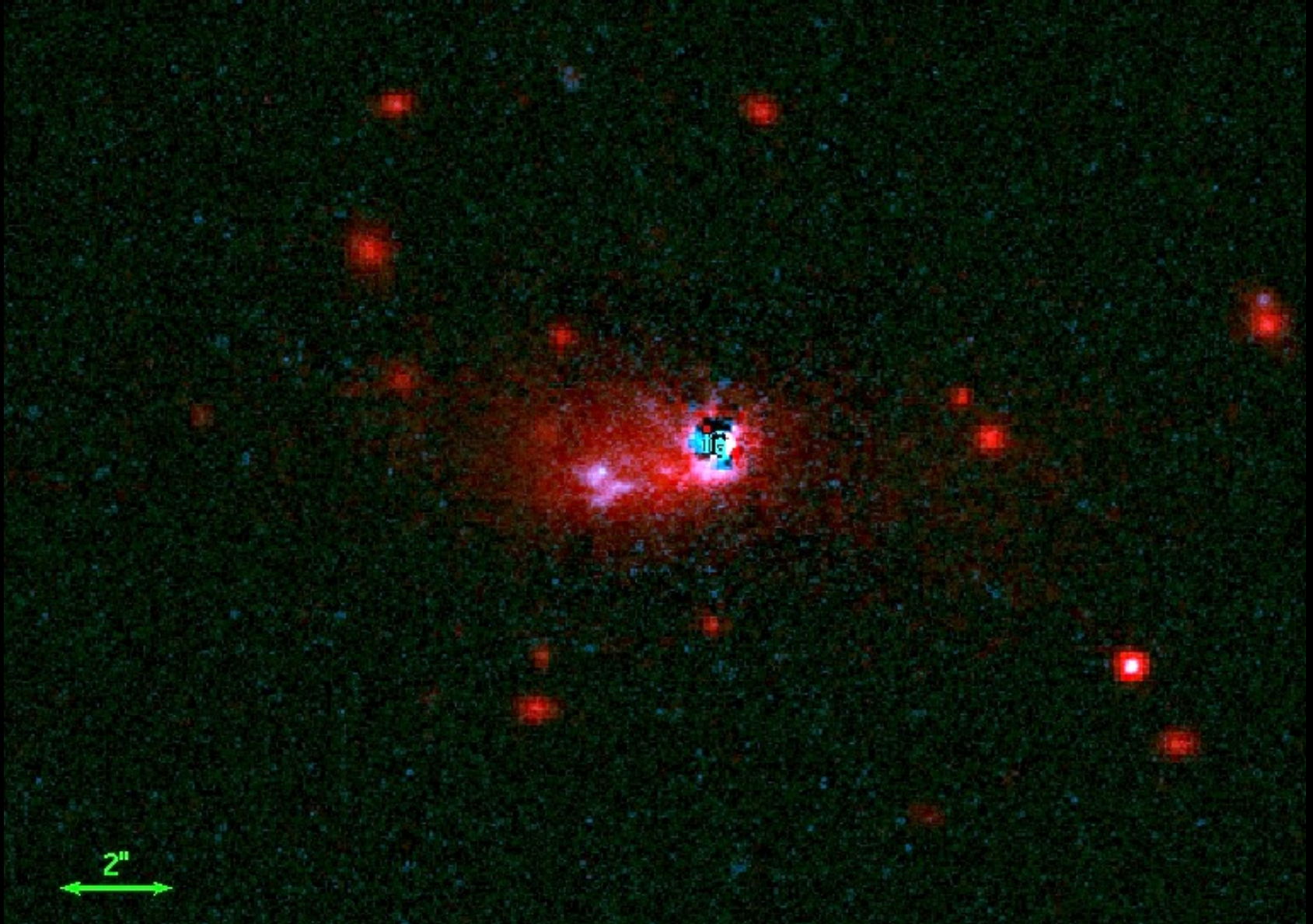
1".3 (10kpc) projected offset between the galaxy photo-center and the QSO

Tidal arcs or shells – merger remnant ~1-2Gyr old

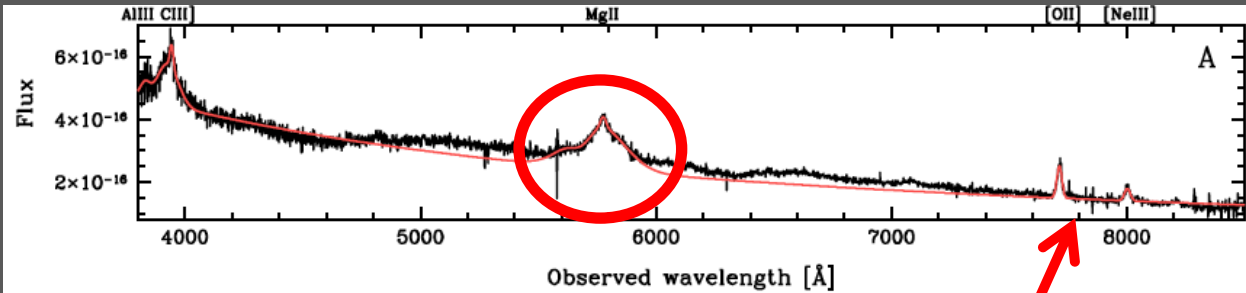




3C 186  $z = 1.07$

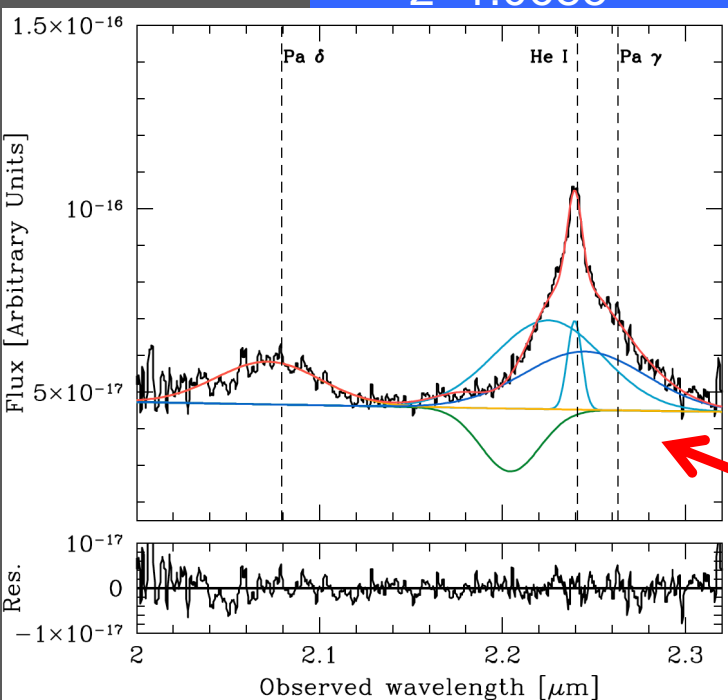


# SDSS and Palomar TripleSpec spectra

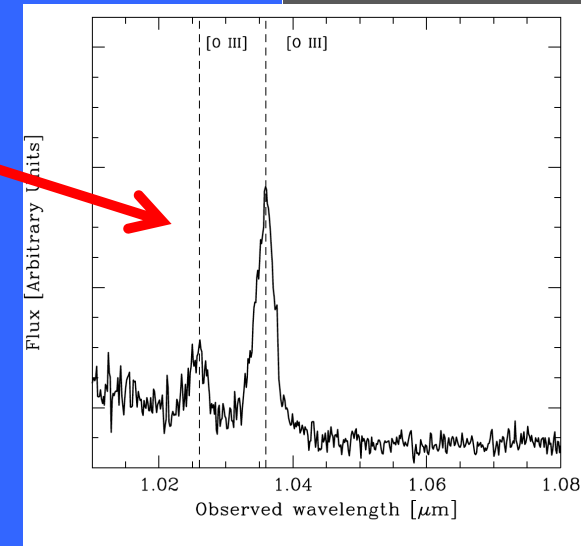


Isolated narrow lines [OII], [NeIII], [OIII]

Systemic redshift of the NRL (host galaxy)  
 $z=1.0685$

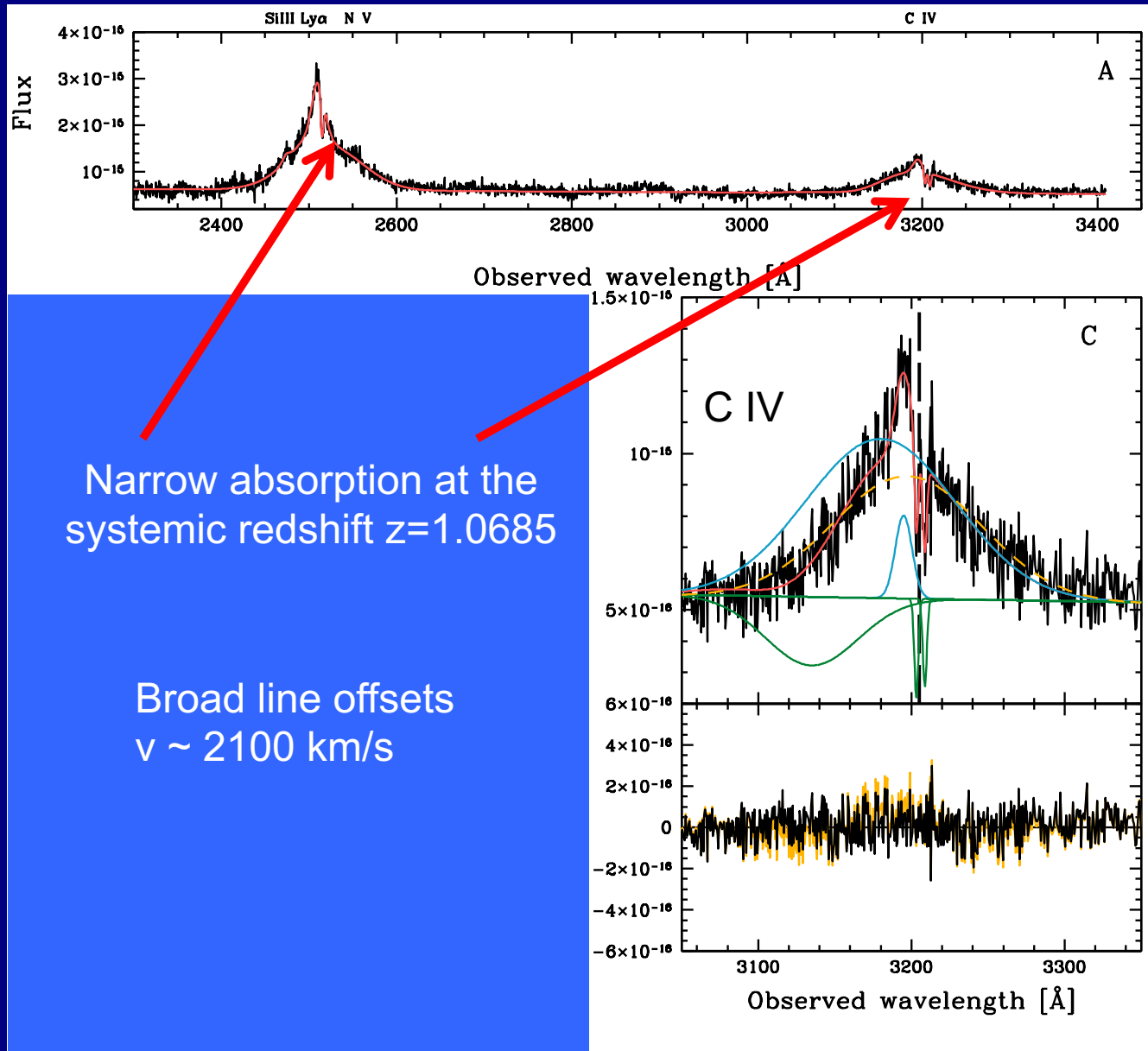


Broad lines:  
concave shape, broad absorption  
Em. Line offset  $v \sim -2100$  km/s





# HST/FOS UV spectrum of 3C 186 (1991)



# A GW RECOILING BH IN A RADIO-LOUD AGN

3c186

$z=1.07$

*Chiab et al. 2017*

$M_{\text{BH}} = 5 \times 10^9 M_{\odot}$

$L_{\text{bol}} \sim 10^{47} \text{ erg s}^{-1}$

## Time scales

Galaxy merger timescale (roughly) known from comparison with simulations:

1-2 Gyr

Time since the GW “kick” (from the velocity and the QSO offset):  
~5 Myr

We know the age of the AGN from radio observations:  
~1  $\times 10^5$  years (*Murgia et al. 1999*)

Numerical relativity modeling *Lousto et al. 2017*

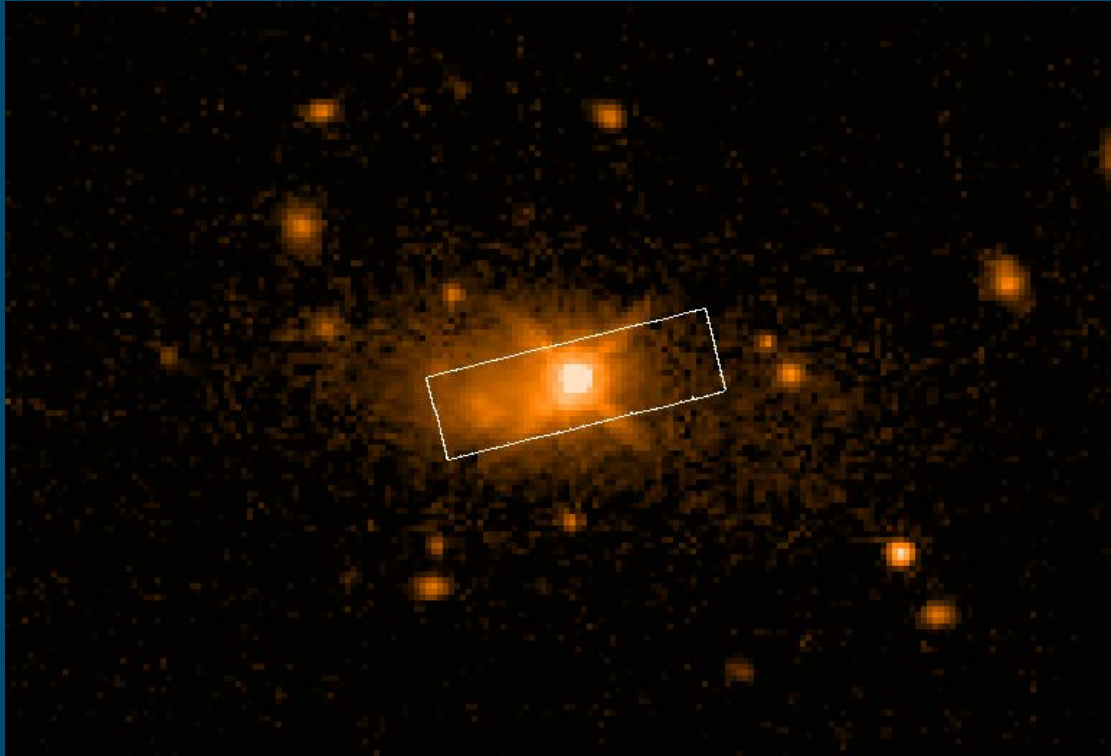
Gas-rich merger

$m_1 / m_2 \sim 0.58$   $\alpha_{\text{final}} = 0.91$   $\delta M = 8.6\%$

of the larger and smaller black holes were  $\alpha_1 = 0.93_{-0.31}^{+0.05}$  and  $\alpha_2 = 0.93_{-0.10}^{+0.08}$ . We can also estimate the final recoiling black hole spin  $\alpha_f = 0.91_{-0.05}^{+0.02}$  and that the system radiated  $8.6_{-1.8}^{+1.0}\%$  of its total mass, making the merger of those black holes the most energetic event ever observed.

$E_{\text{GW}} \sim 10^{62} \text{ erg}$

# Keck/OSIRIS Integral Field Spectroscopy of 3C 186



FOV 1.6" x 6.4"

Scale 0.1"/pixel

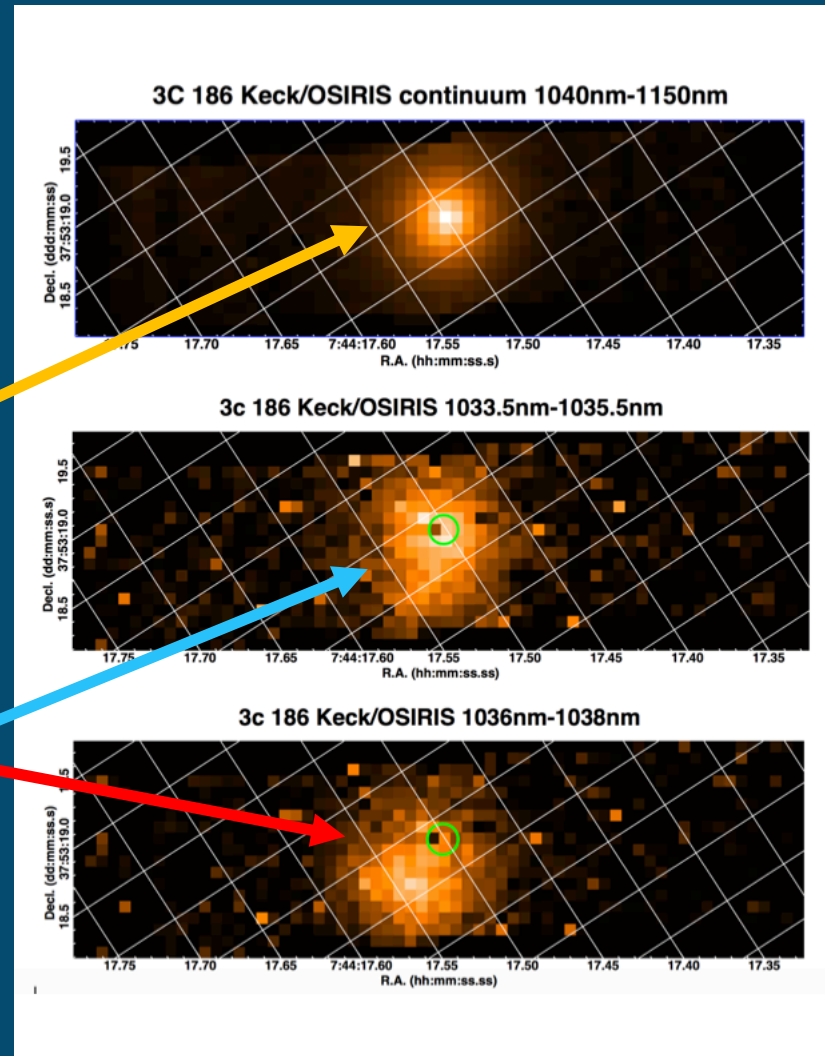
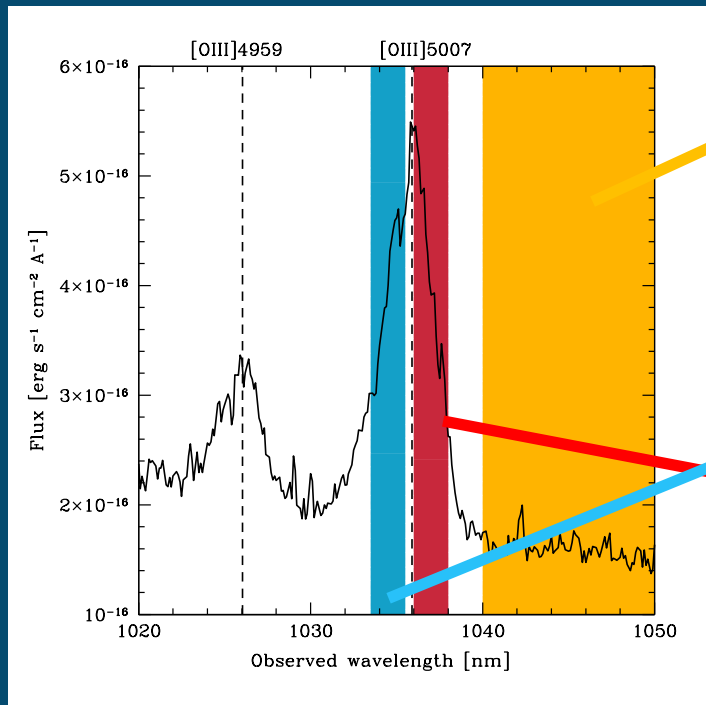
Wavelength coverage  
999nm – 1176nm

## Goals

1. Spatial location of the NRL
2. Is the blue "blob" due to emission lines?
3. Is broad H $\beta$  offset? No offset implies  $\lambda = 1006\text{nm}$

# Keck/OSIRIS Integral Field Spectroscopy of 3C 186

Aperture =  $0''.6$   
Centered on the QSO



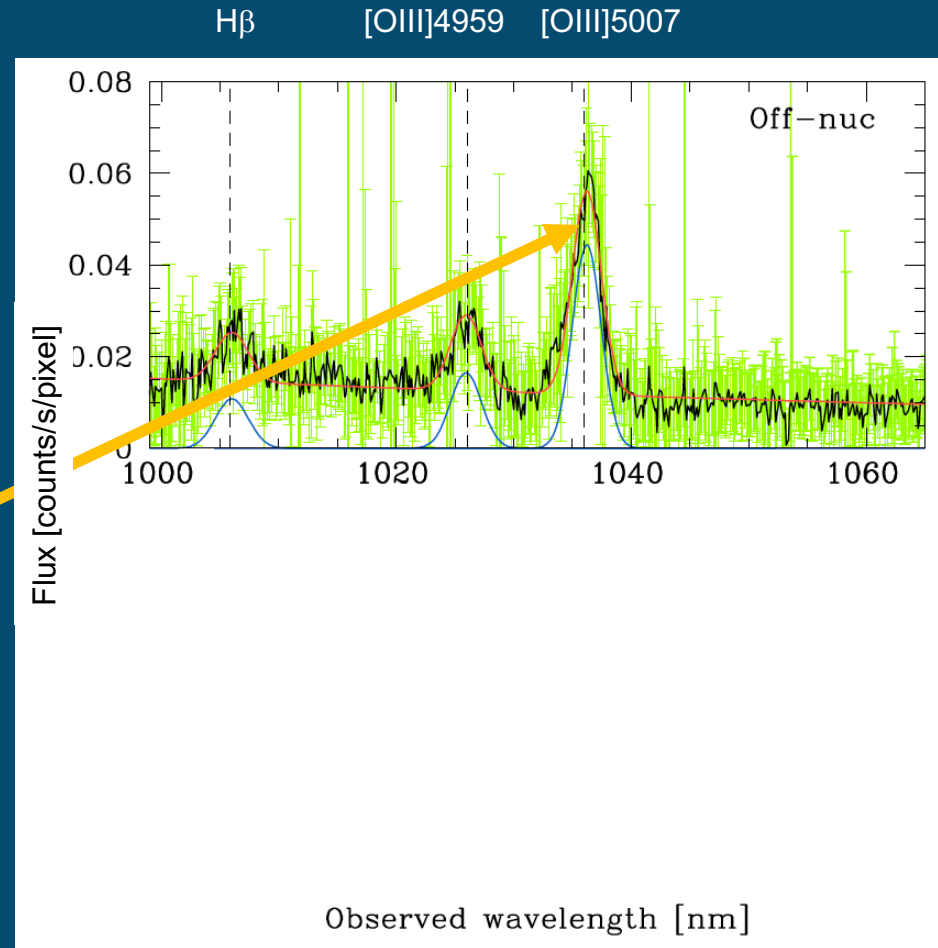
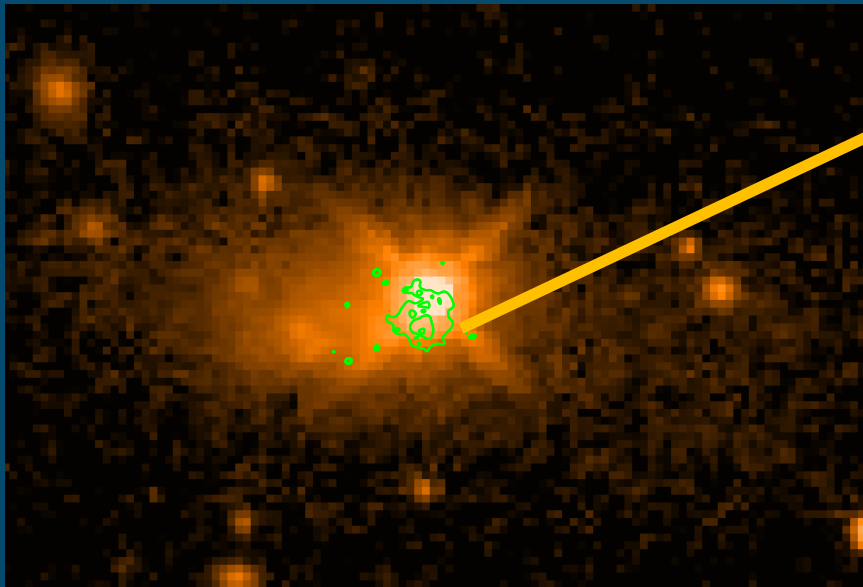
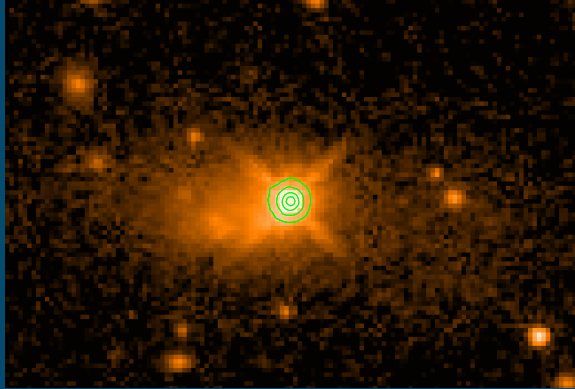
Unresolved  
FWHM  
 $=0''.59$

Resolved  
FWHM  
 $=1''.6$

$d=0''.5$

# Keck/OSIRIS Integral Field Spectroscopy of 3C 186

Continuum: point source (contours from Keck)



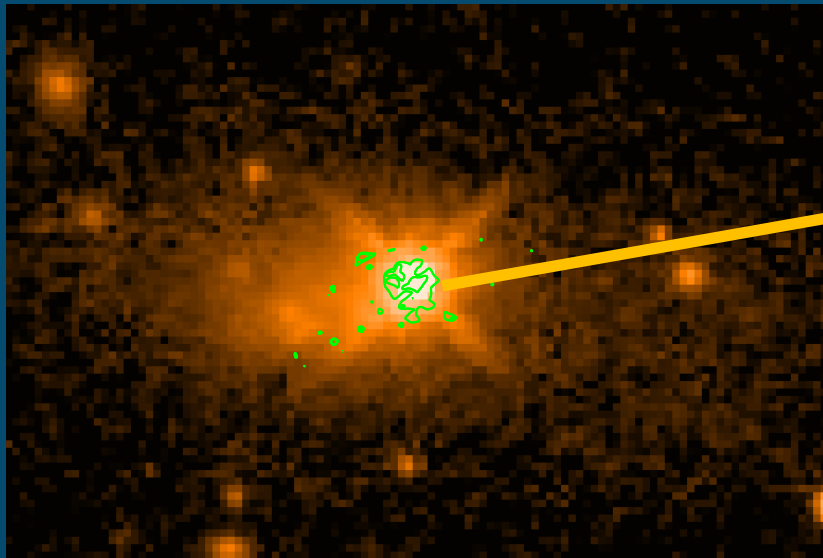
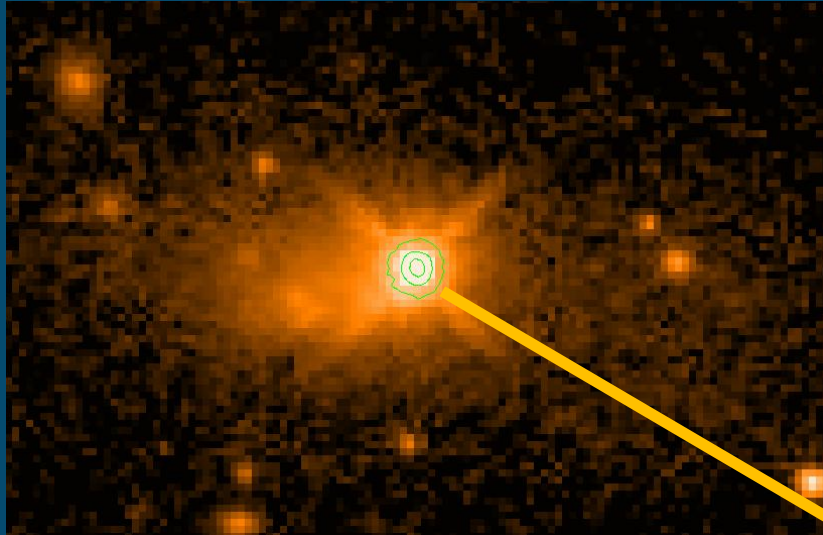
Line emission: off-nuclear (contours from Keck)  
[OIII] offsets = +75 km/s redshifted!

Blue *blob* has no line emission  
Star formation?



# Keck/OSIRIS Integral Field Spectroscopy of 3C 186

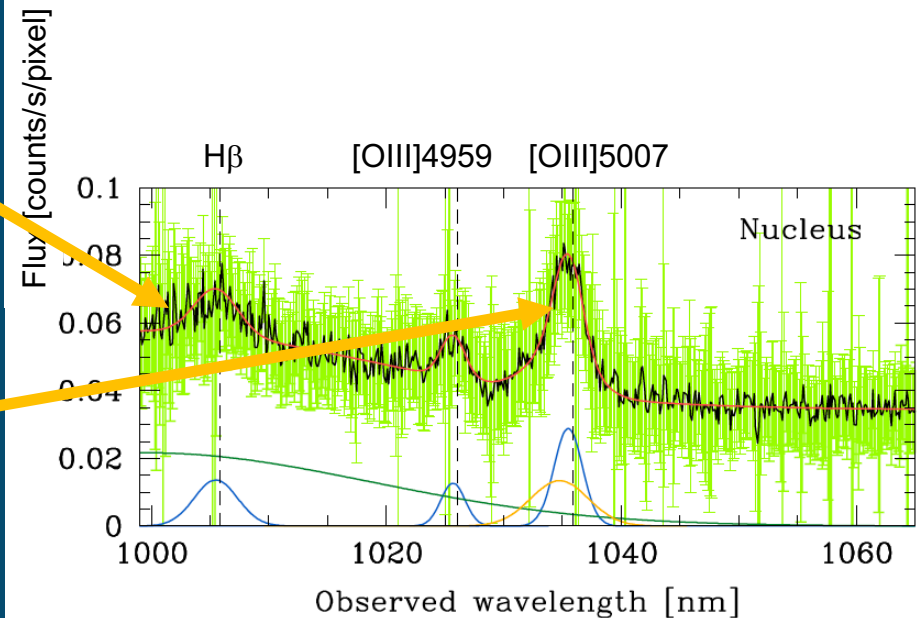
QSO nucleus: contours from Keck



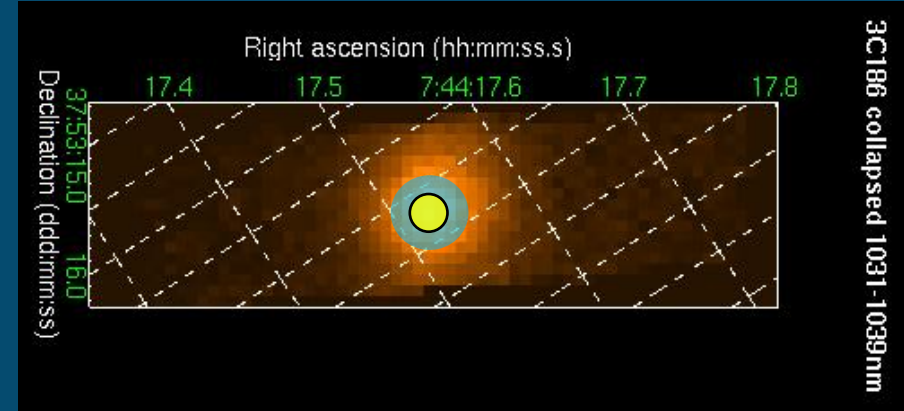
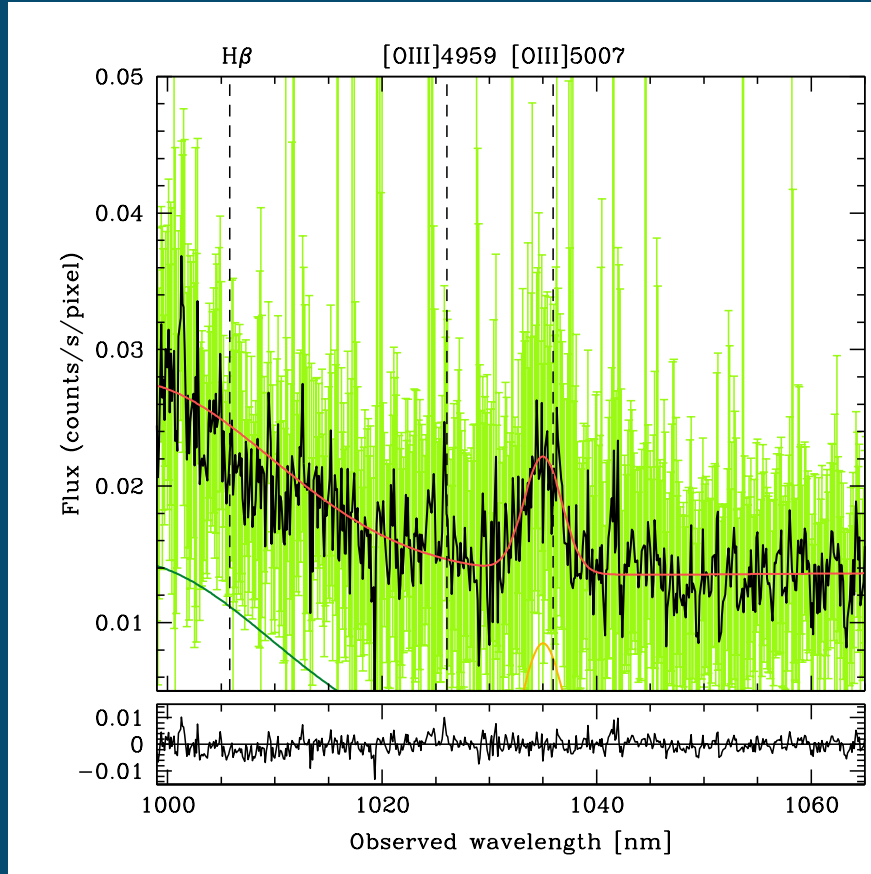
**Broad-ish [OIII] offset = - 670 km/s**

**Narrow [OIII] offset = -100 km/s**

**Broad H $\beta$  offset  $>\sim$  -1800 km/s**



# Keck/OSIRIS Integral Field Spectroscopy of 3C 186



The narrow lines are produced in extended regions

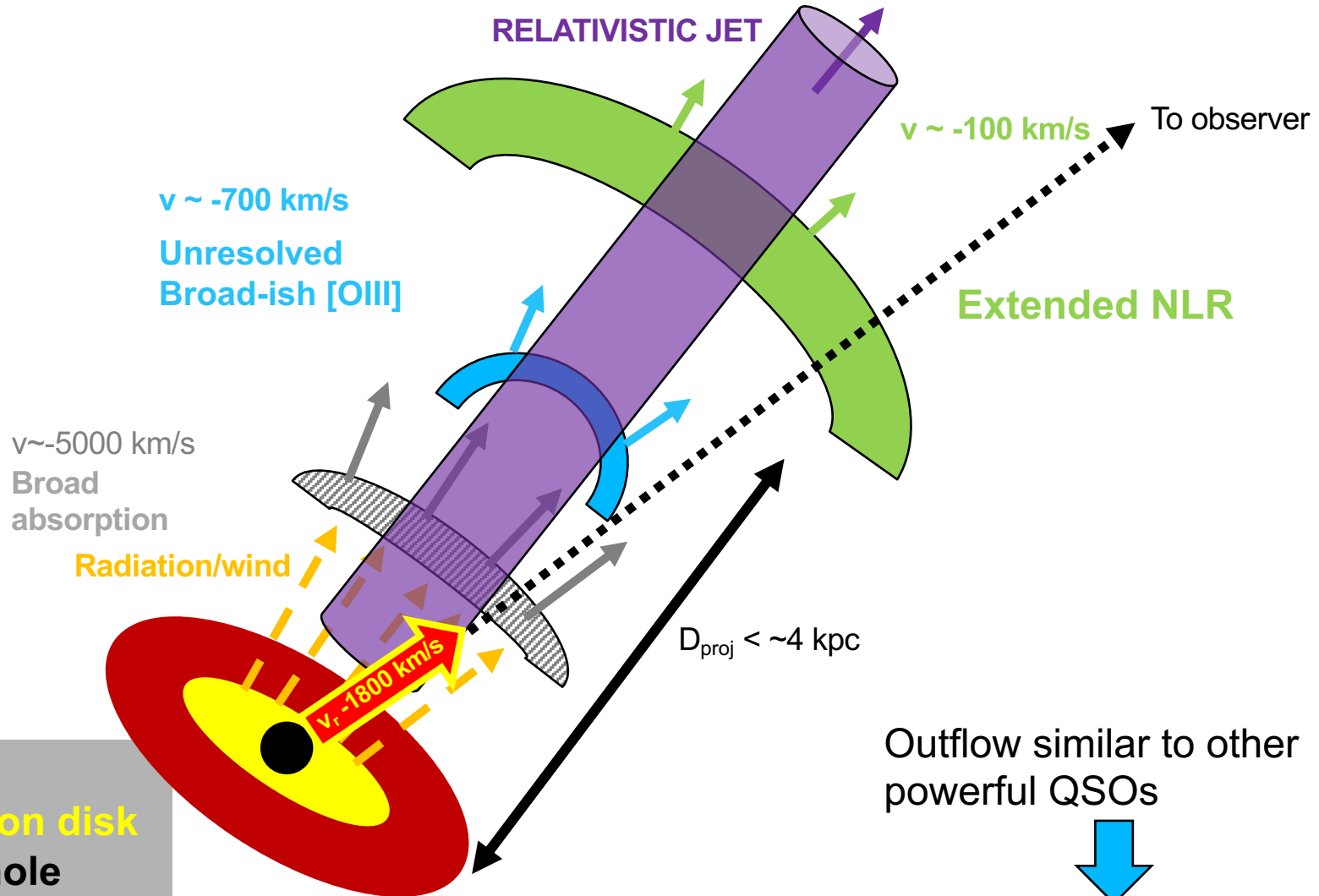
The broad-ish ( $\sim 1300$  km/s) outflow component of [OIII] is unresolved and co-spatial with the nucleus of the QSO

Outflow properties are consistent with other powerful QSOs (*e.g.* Bischetti et al. 2017)

$P_{\text{kin}} \sim 3 \times 10^{45} \text{ erg s}^{-1}$ ,  $\sim 4\%$  of the bolometric luminosity of the QSO

# Keck/OSIRIS Integral Field Spectroscopy of 3C 186

## Geometry of the source



Outflow similar to other powerful QSOs



Driven by radiation pressure?

# **SUMMARY**

## **Gravitational wave recoiling BH candidate in 3C 186**

**GW recoiling BHs: important observational evidence against the final pc problem  
Confirmed candidates are good news for LISA and PTA**

**Radio-loud AGNs are invariably associated with galaxy and BH mergers  
Excellent targets for recoiling BH (see also Lena et al. 2014)**

**The new Keck/OSIRIS IFU data supports the GW recoiling BH picture**

**Different components of [OIII] are produced at different locations**

**Very important for our understanding of the geometry of outflows!!!!**

**FUTURE: HST deep imaging coming up in January 2019(?)  
JWST for the full broad H $\beta$  line and to image the outflow at higher resolution  
ALMA: molecular gas  
and more...**