CONACYT
Consejo Nacional de Ciencia y Tecnología

GH 2015: Forming and Fueling Supermassive Black Hole Seeds

July 6-24, 2015, Tonantzintla, Puebla

AGN-driven winds and ionized clouds moving along the jet in PKS 0521-365

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Outline

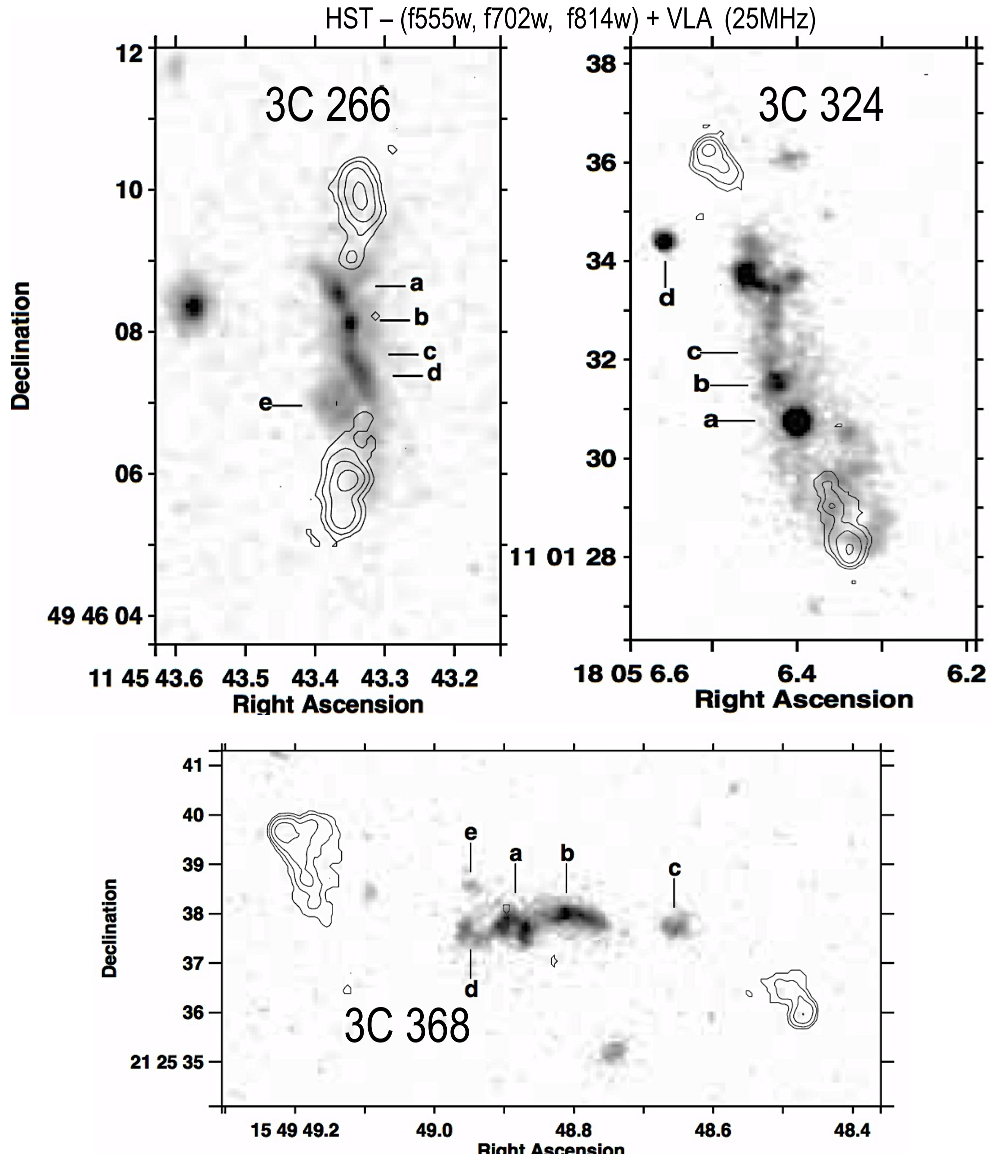
- Extended emission line regions in radio galaxies
- PKS 0521-365, an historical overview
- Observations (VLT/FORS2, HST/WFC)
- The central engine (BH mass)
- Outflow along the jet
- Summary

EELR in RG

Extended emission line regions (EELR) are often observed around radio galaxies (**preferentially at z>0.7**).

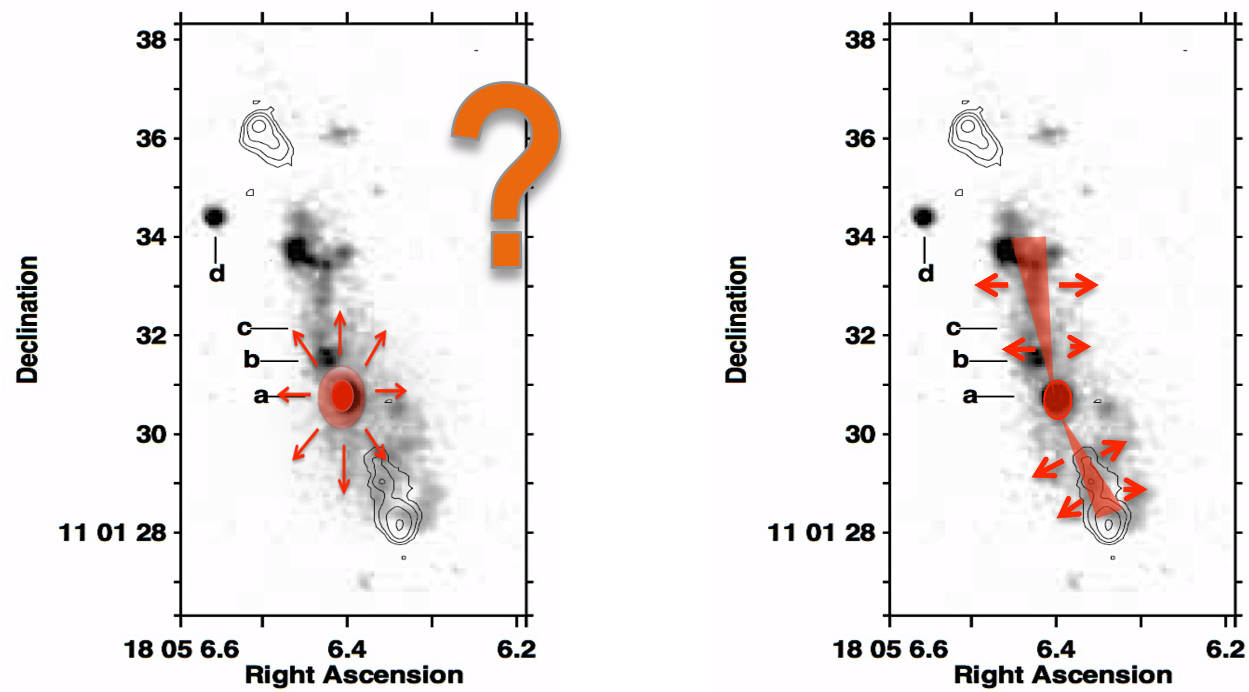
The emission-line profiles of EELR reveal disturbed kinematics and high-velocity motions, ~1000km/s (e.g. Chambers et al. 1990; McCarthy, Baum & Spinrad 1996, Solórzano-Inarrea et al. 2001)

These EELR can be up to 100 kpc in size and are often elongated and aligned along the radio jet axis (e.g. Best et al. 1996, Armus et al. 1998).



Best et al. (1997)

Such precise alignments, EELR - radio axes, are contrary to what would be expected for illumination of a central source…



HST – (f555w, f702w, f814w) + VLA (25MHz)

The passage of the radio jet through the ISM drives strong shock waves into warm clouds of gas embedded in the hot halo of the galaxy. ➔ the shocked gas is likely to be a strong source of line emission (e.g. Inskip et al. 2002).

EELR in RG

The very large distances of high-redshift radio galaxies make their study difficult.

Detailed studies of nearby radio galaxies that share many of the properties of high-redshift radio galaxies have been made (e.g. Tadhunter et al. 1991, Clark et al. 1998, Villa-Martín et al. 1999) .

In particular, valuable information are derived from **long-slit spectra** of these low-z objects.

EELR in RG

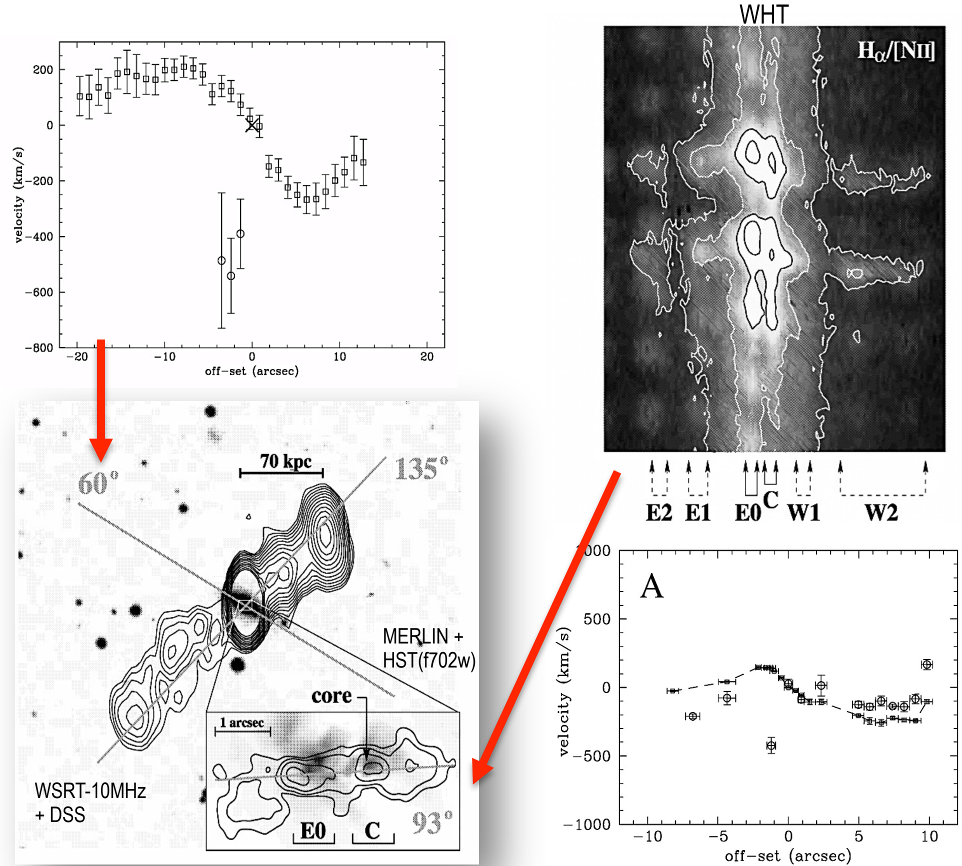
A jet-induced outflow in 3C293 (z=0.045)

With long-slit spectroscopy allows to estimate the **spatial extent and kinematics** of EELR.

In 3C293 a fast outflow of ionized gas was identified (with v~1000 km/s).

The outflow is located about 1kpc east of the nucleus, in a region of enhanced radio emission due to the presence of a distorted jet.

A rotating ionized gas disc (30 kpc in extent) was identified along the major axis of the host galaxy.



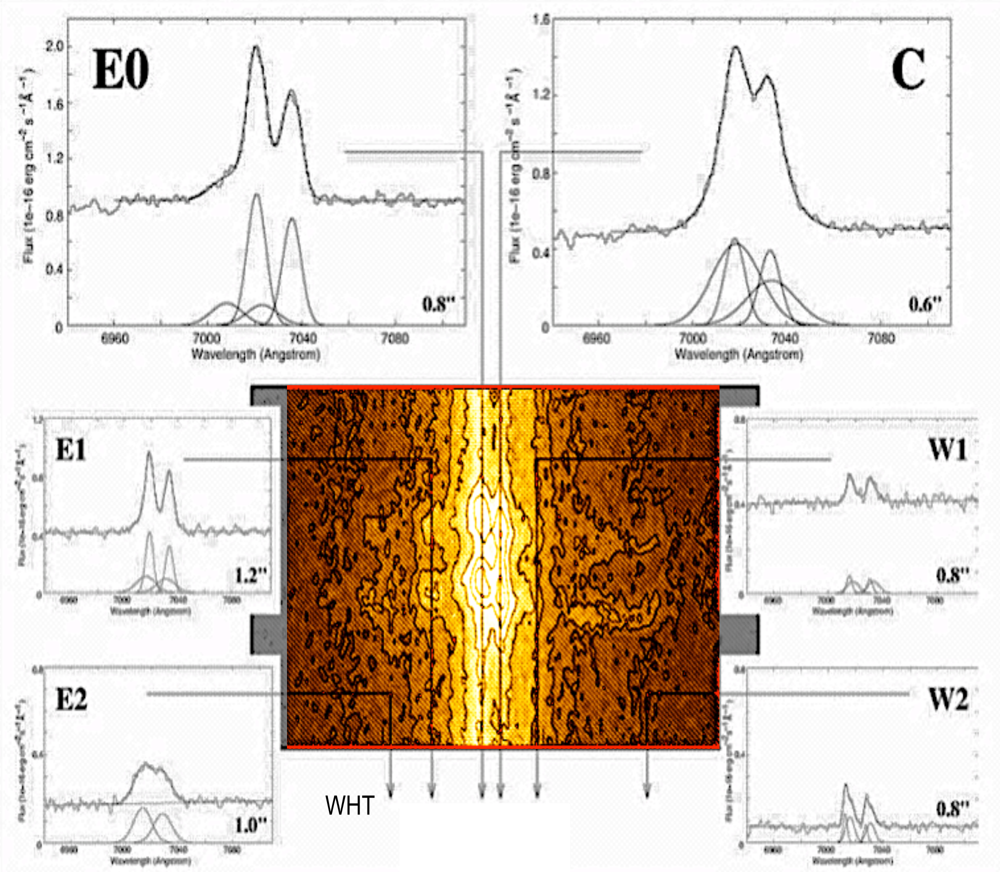
Emonts et al. (2005)

A jet-induced outflow in 3C293 (z=0.045)

Also, the **ionization state** can be studied.

Density, Temperature

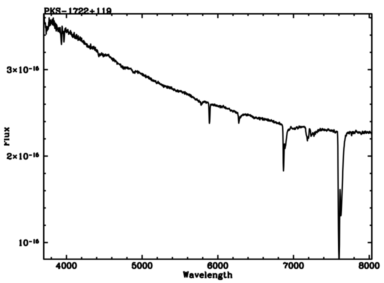
Mass of the gas outflow ($\sim 10^5 M_\odot$)



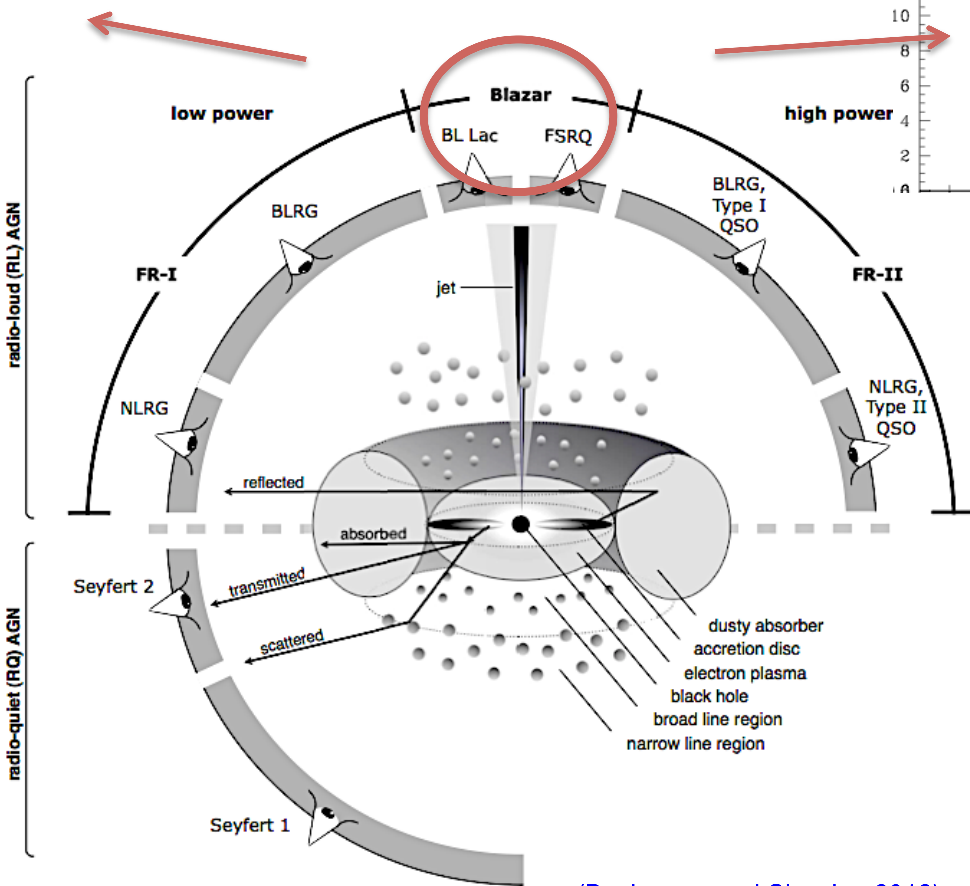
Emonts et al. (2005)

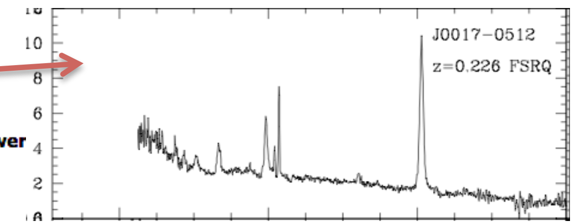
PKS 0521-365

PKS 0521-365 was classified as a BL Lac (Danziger et al. 1979)

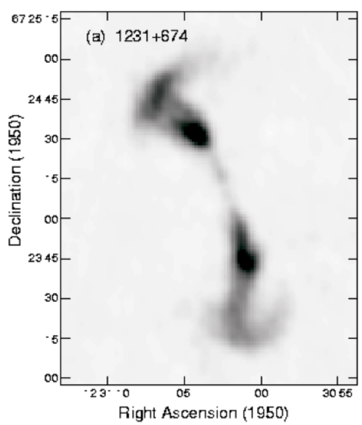


(Sbarufatti et al. 2006)



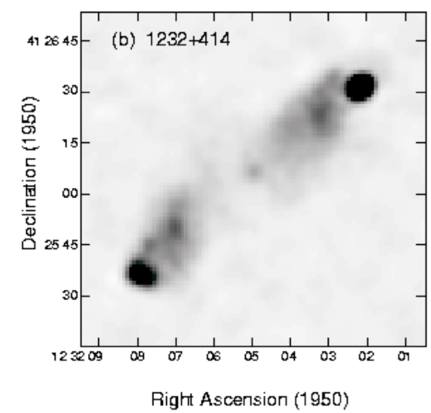


(Shaw et al. 2012)



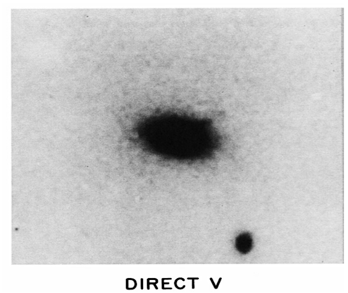
(Urry and Padovani, 1995)

(Beckmann and Shrader, 2012).



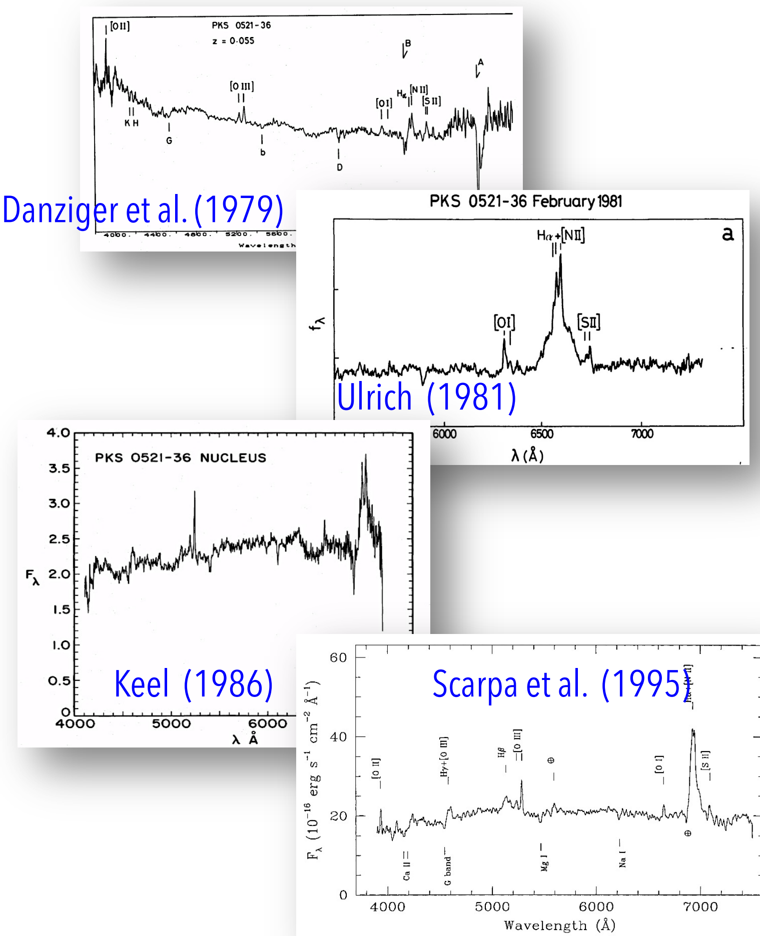
PKS 0521-365

PKS 0521-365 is among the most remarkable objects in the southern hemisphere.



This objects display two striking characteristics:

a) This is multi-faceted active galaxy



Danziger et al. (1979)

Ulrich (1981)

Keel (1986)

Scarpa et al. (1995)

Elliptical host galaxy at z=0.055.

Detected in X-rays by Chandra and in γ-rays by EGRET (Birkinshaw et al. 2002, Lin et al . 1995).

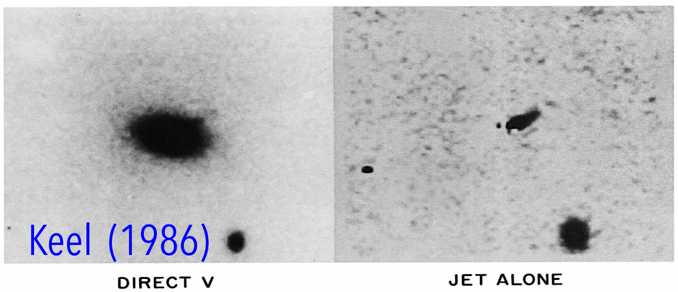
On 2010 June 17, a γ-ray flare was detected by the Large Area Telescope (LAT) on board the *Fermi Gamma-ray Space Telescope* (Iafrate et al. 2010).

Swift follow-up observation confirmed the high activity of the source in optical, UV, and X-rays (D'Ammando et al. 2010).

PKS 0521-365

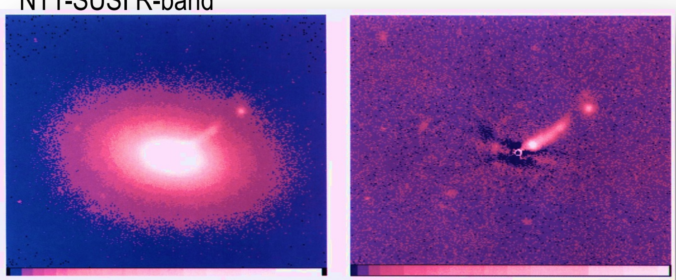
b) It has an optical jet.

In fact, the morphology of the jet is very similar at radio, near-IR, and optical frequencies.



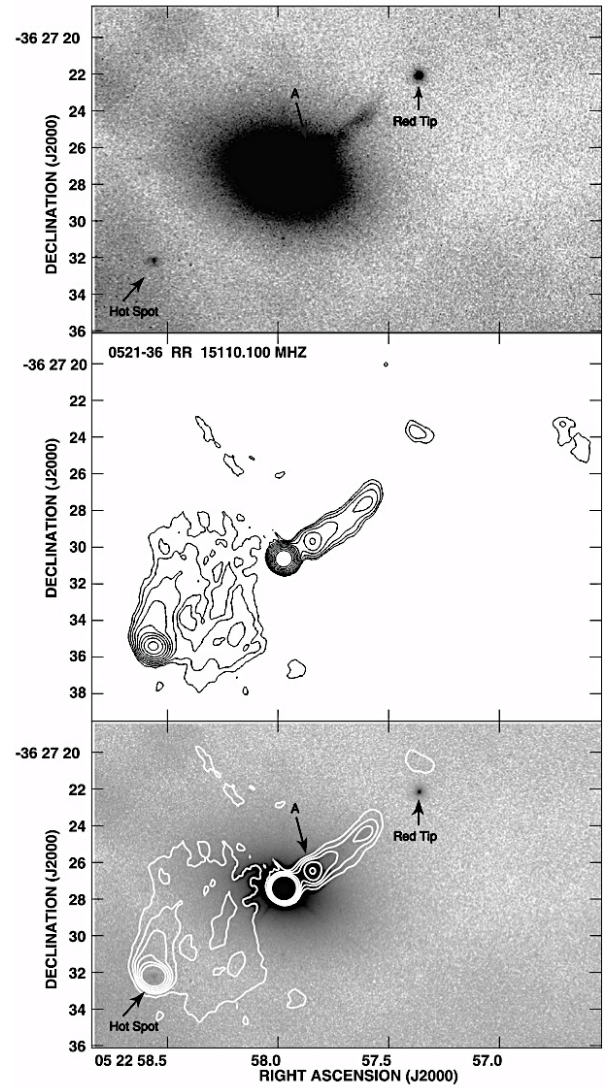
Keel (1986)

NTT-SUSI R-band



Falomo (1994)

MAD Ks-band and VLA 15GHz



Falomo et al. (2009)

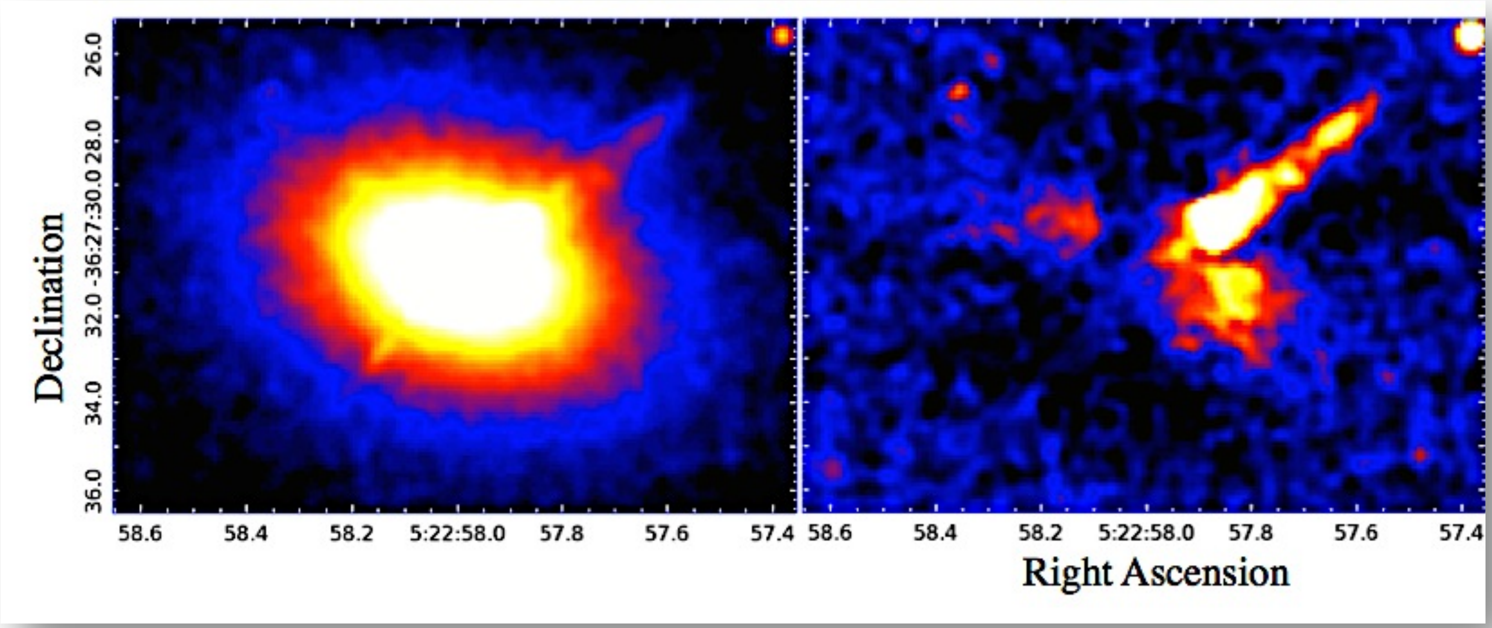
Viewing angle:

Pian et al. 1996	- 30°
Giroletti et al. 2004	- 21° - 27°
D'Ammando et al. 2015	- 6° - 12°

HST image

By modeling the host galaxy surface brightness distribution of PKS 0521-365, we are able to identify an optical jet and and two extended biconical-like structures.

GALFIT (Alejandro Olguín…)

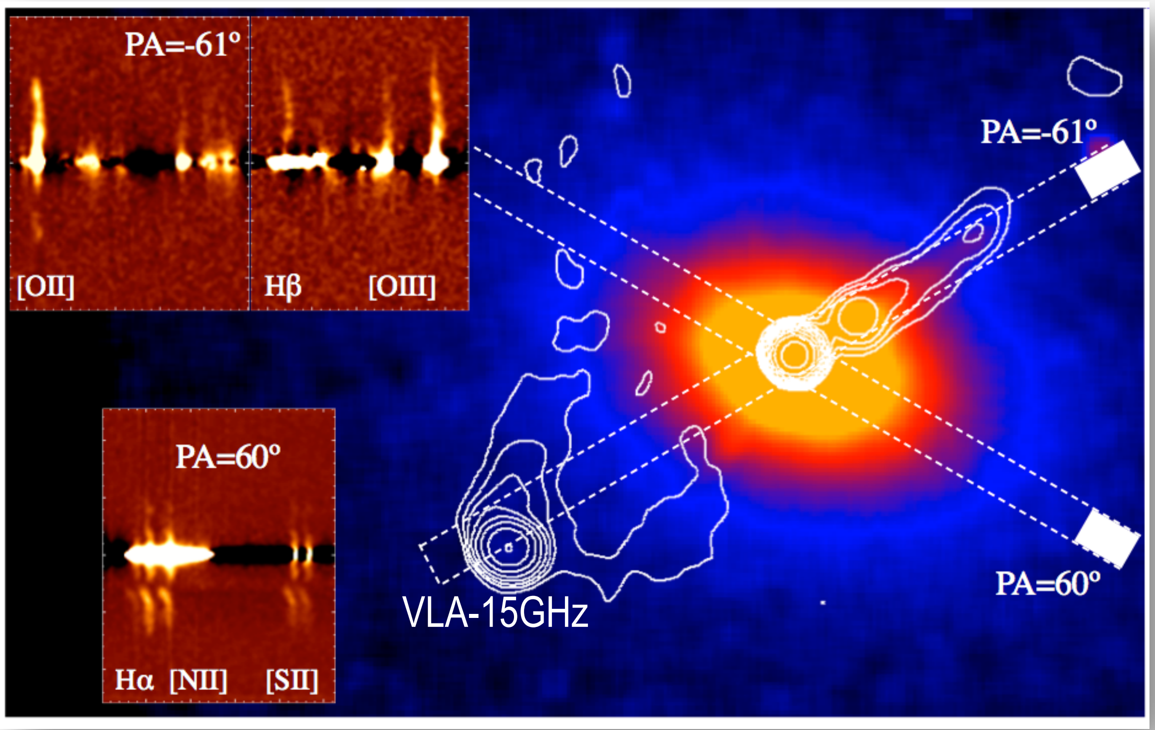


The latter structures are located at a distance of 3 kpc.

Observations

We obtained optical spectra with the VLT/FORS2, along the optical jet and the galaxy's optical major axis.

VLT-FORS2

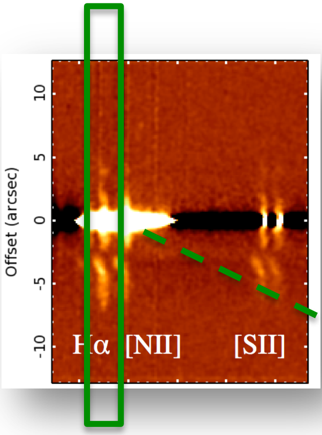


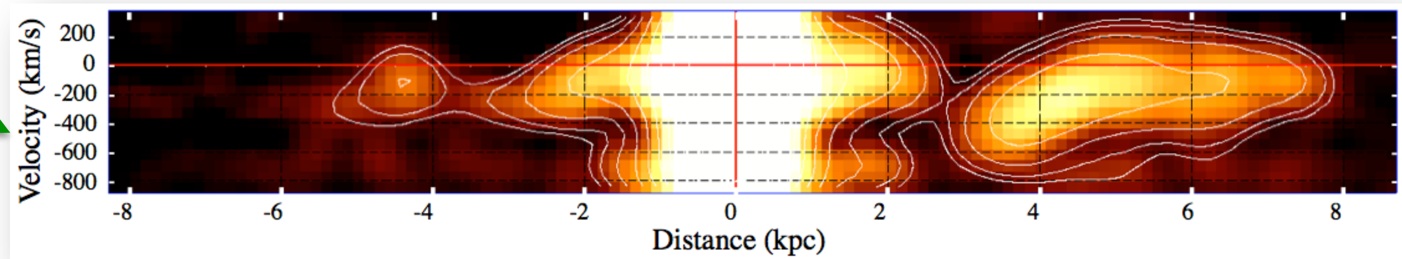
HST-f702w

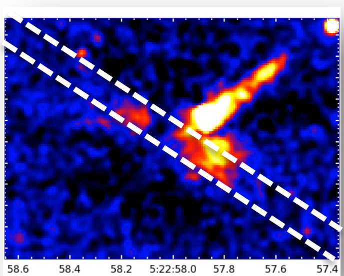
PA	Grism	Wavelength range
-61º (jet)	GRIS 600B+22	3300 - 6200
+60º (major axis)	GRIS 600RI+19	5200 - 8400

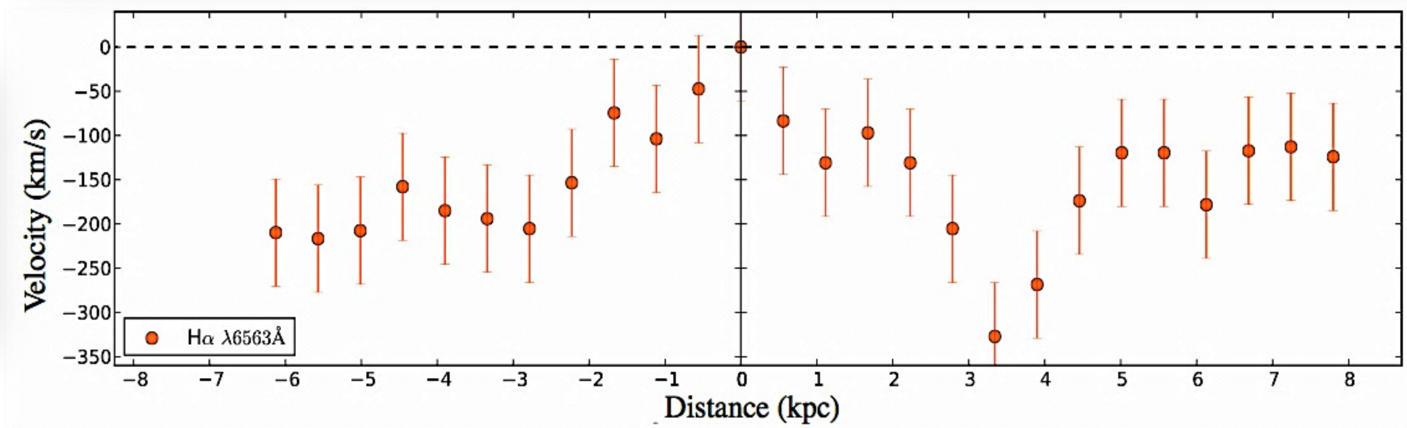
Velocity profiles

Rotation curve obtained from the Hα 6563 emission line observed in the long-slit spectrum taken along the galaxy's optical major-axis.





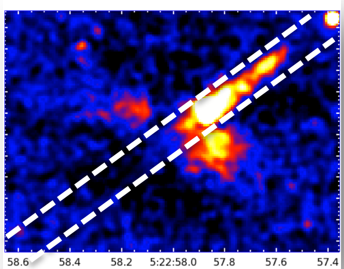


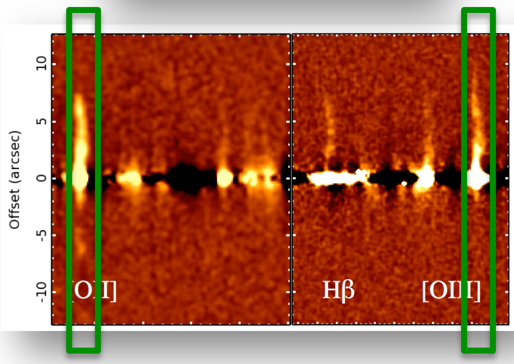


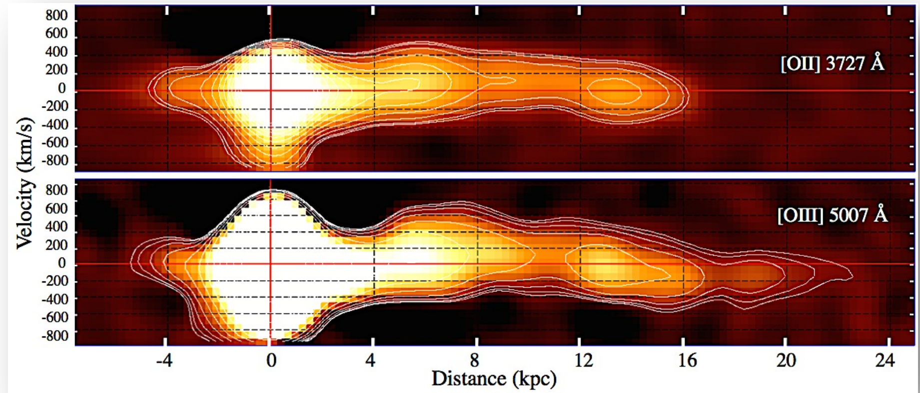
We found tentative evidence of an **outflow** moving with a maximum projected **velocity of -350 km/s** (toward us) **at 3 kpc** from the galaxy nucleus.

Velocity profiles

Velocity profile along the optical jet frame at PA=-61.0 obtained from the [OII,III] 3727, 5007 lines.

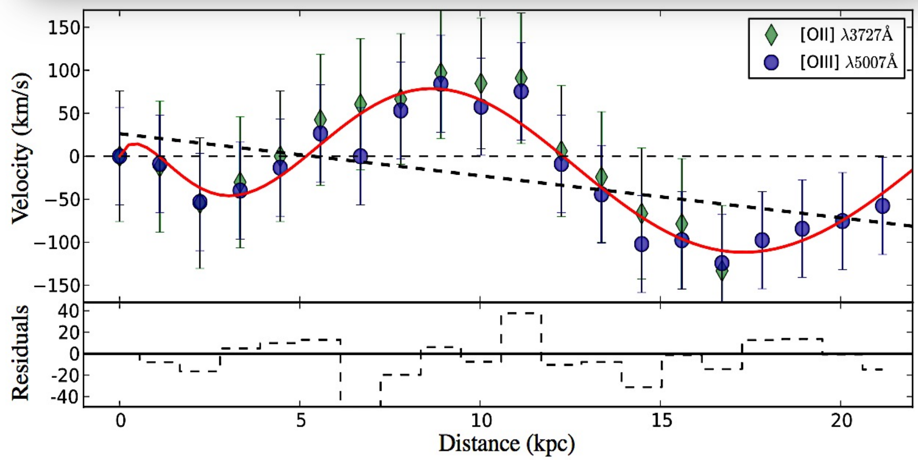






Linear fit: p-value=0.02, r^2=0.26.

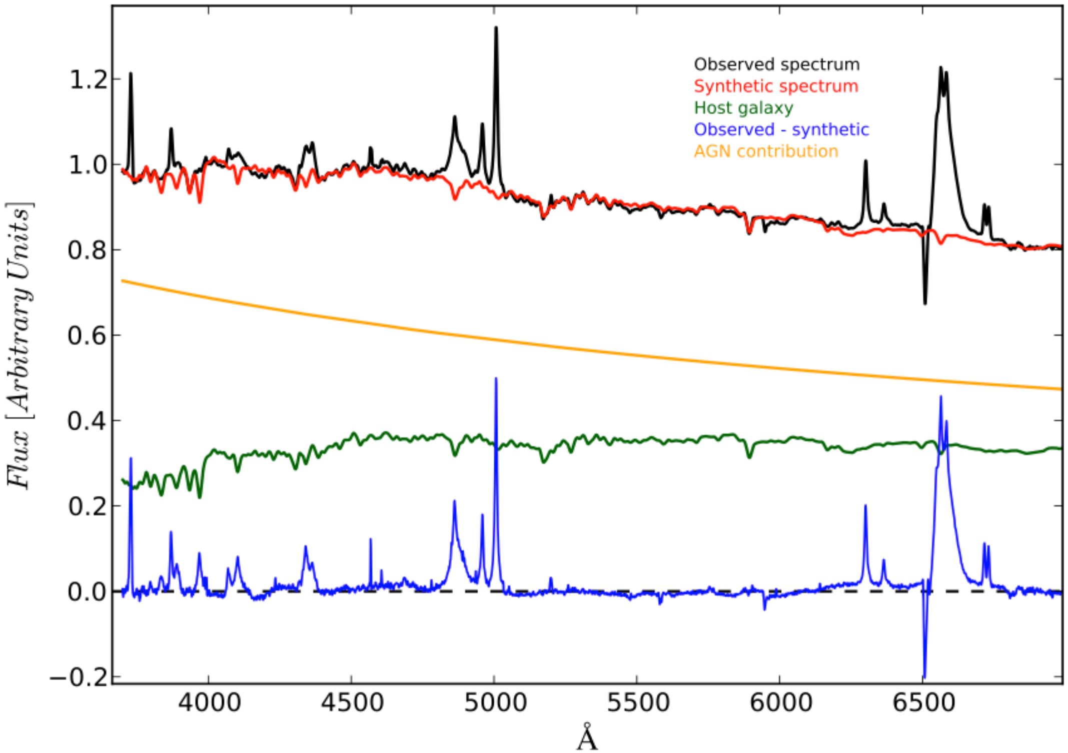
$$v(r) = Ar^{1/2} sin(Br^{1/2} + C)$$

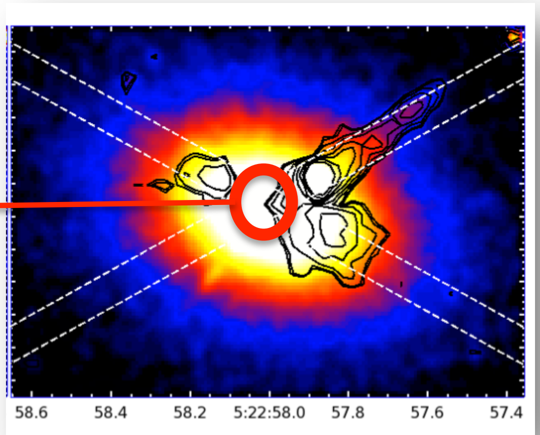


This function describes **a sinusoidal movement of ionized matter along the jet**. The farthest detected emission lies **at 24 kpc** and the velocity reaches a maximum of 100 km/s.

The central engine

We extracted one 1D spectrum from the nuclear region (with an aperture of 1 arcsec ~ 1 kpc) to assure that the information in both spectra are coming from the same region.

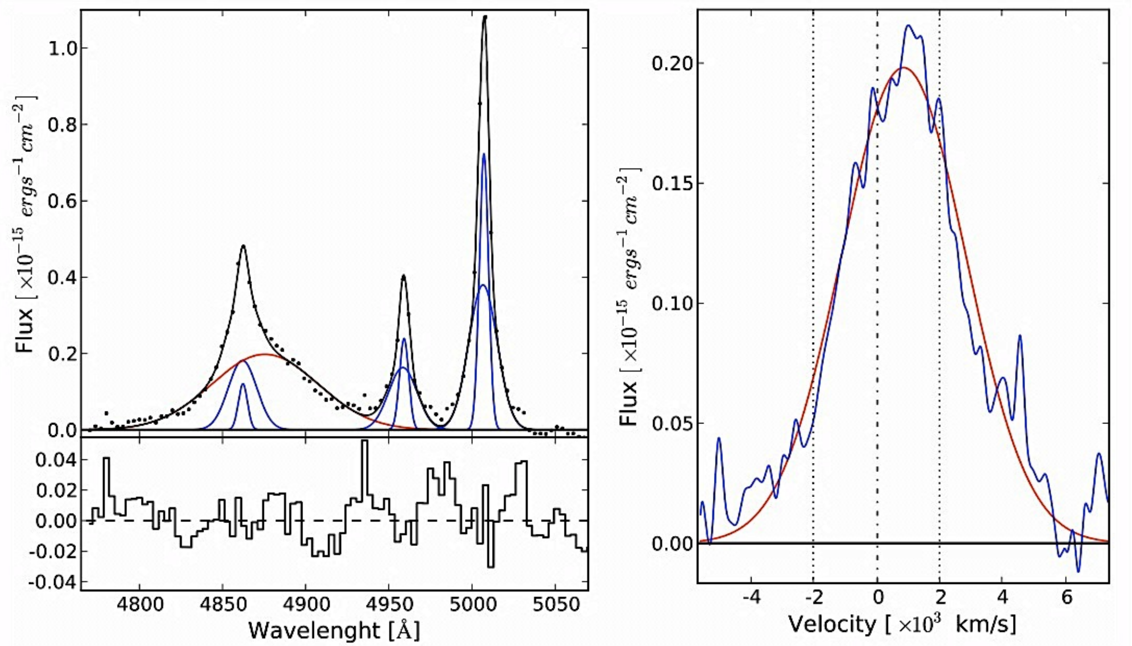




We applied the Starlight code (Cid-Fernandes et al. 2005) in order to model the observed spectrum and subtract the host galaxy contribution.

The central engine

A multi-Gaussian model is fit to the H β +[OIII] complex using a χ2 minimization routine to obtain the best-fitting parameters.



The Gaussian decomposition indicates that the narrow [O III] 4959,5007 emission lines are composed of more than one Gaussian component ➔ **NLR=NLR1+NLR2 (**FHWM~1250 km/s and FWHM~400 km/s respectively).

Also, the decomposition indicates the existence of a red-shifted broad component (FWHM of ~ 4600 km/s) ➔ **inflowing components.**

The central engine

We use the relations proposed by (Vestergaard and Peterson, 2006, VP06) to estimate the black hole mass using the H β 4862 and 5100 °A continuum luminosities.

$$\log(M_{BH}/M_{\odot}) = \log\left[\left(\frac{FWHM(H\beta)}{1000\ kms^{-1}}\right)^2\left(\frac{\lambda L_{\lambda}(5100\text{Å})}{10^{44}\ ergs^{-1}}\right)^{0.50}\right] + 6.91$$

$$\log(M_{BH}/M_{\odot}) = \log\left[\left(\frac{FWHM(H\beta)}{1000\ kms^{-1}}\right)^2\left(\frac{L(H\beta)}{10^{42}\ ergs^{-1}}\right)^{0.63}\right] + 6.67$$

$$\log(M_{BH}/M_{\odot}) = (8.12 \pm 0.08) + (4.24 \pm 0.41)\log\left(\frac{\sigma}{200\ kms^{-1}}\right)$$

Moreover, we employ the $M_{BH} - \sigma$ relation proposed by (Gültekin et al. 2009, G09) to estimate the black hole mass from the stellar velocity dispersion.

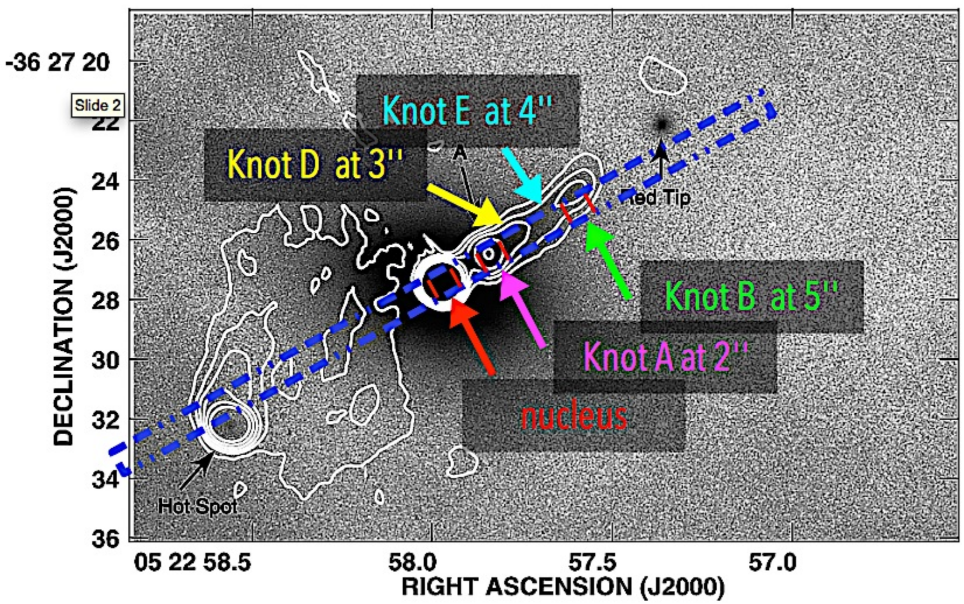
Method	$\log(M_{BH}/M_{\odot})$	Reference
$M_{BH} - \sigma$	9.0 ± 0.5	G09
$FWHM_{H\beta}, L_{\lambda}(5100\text{Å})$	8.1	VP06
$FWHM_{H\beta}, L(H\beta)$	7.4	VP06
$f \times FWHM_{H\beta}, L_{\lambda}(5100\text{Å})$	≥ 8.4	VP06+D08
$f \times FWHM_{H\beta}, L(H\beta)$	≥ 7.7	VP06+D08

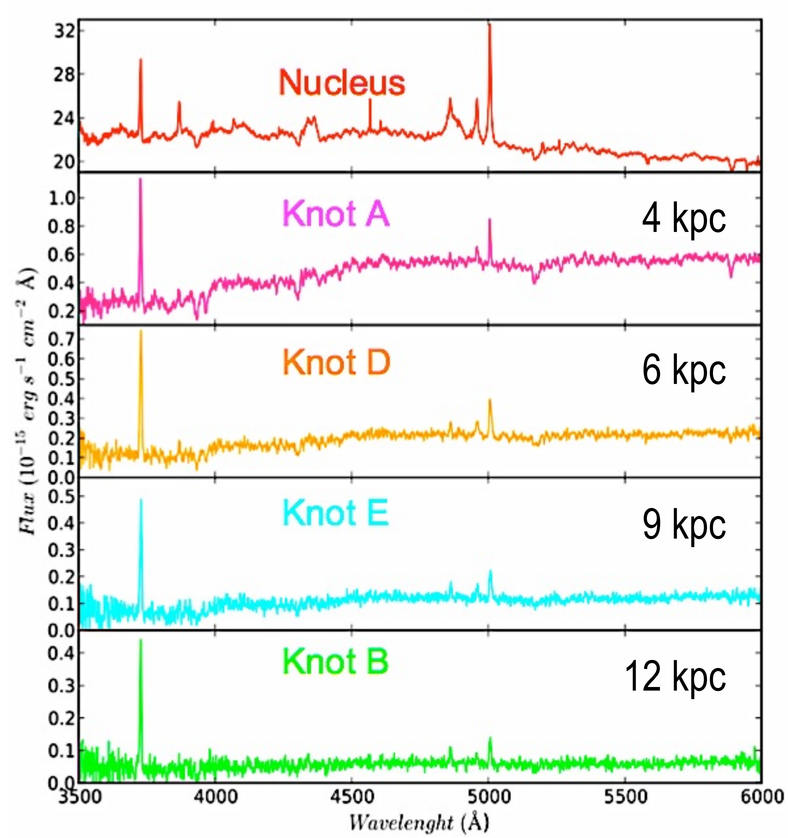
Since the BLR is complex (i.e. highly non- virialized gas) the values for $M_{\odot}$ are merely rough estimates.

Ionization source along the jet

Star formation along the jet?

Image of PKS 0521-36 observed in the Ks band (Falomo et al. 2009).

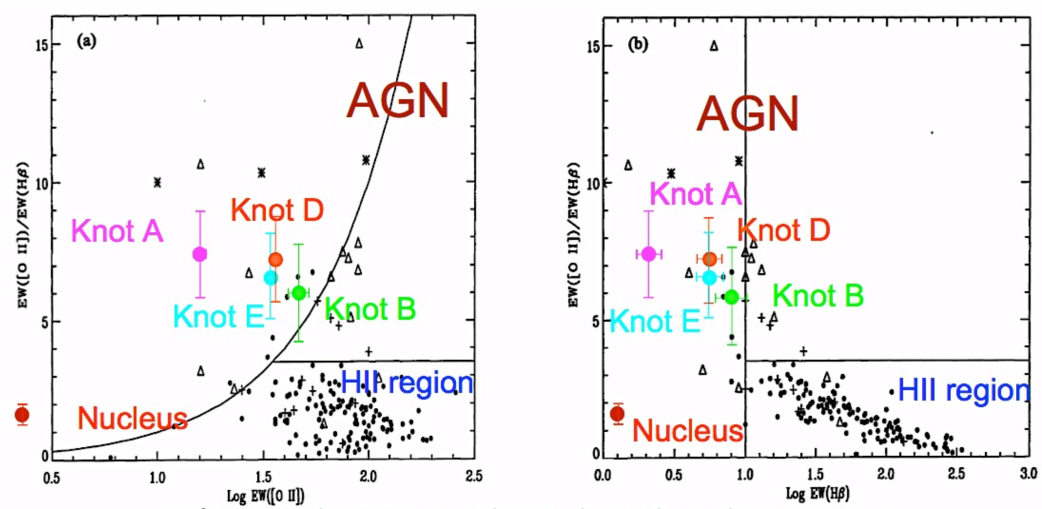




In the nuclear region we are observing a QSO like-spectrum. While the spectra taken from knots visible in IR and radio show narrow emission lines.

Ionization source along the jet

In order to segregate between HII region and AGN we are using diagnostic diagrams which involve the [OII] 3727 Å and H β 4862 Å relative equivalent widths (Rola, Terlevich & Terlevich, 1997). ➔ RTT diagram.



Seyfert 2 – triangles, LINERs – asterisks, H II galaxies – dots, ambiguous – crosses

Not a HII region

On the other hand, by applying the criteria proposed by Ho, Filippenko & Sargent (1997):

Class	[O III] λ5007/Hβ
H II nuclei	Any
Seyfert nuclei	≥ 3
LINERs	< 3
Transition nuclei......	< 3

Our results

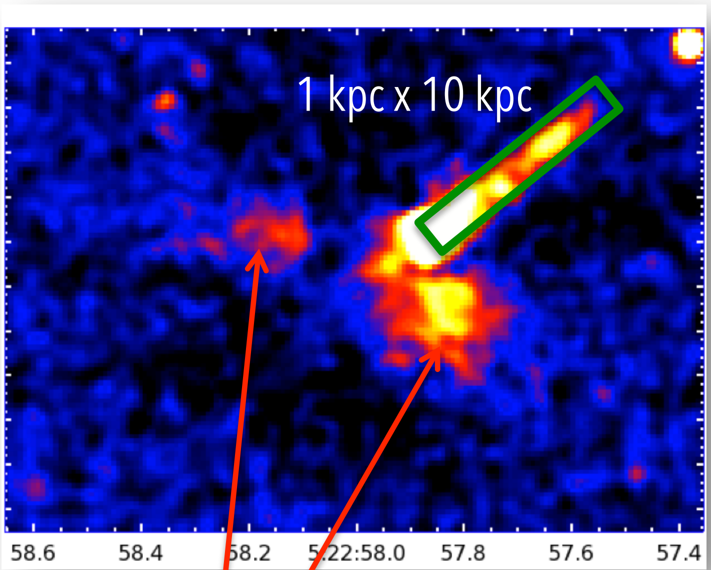
	$[OIII]$ $\lambda 5007$ Å$/H\beta$
knot A	2.0 ± 0.5
knot D	2.60 ± 1.0
knot E	1.80 ± 1.0
knot B	1.40 ± 0.7

?

If the gas in a line-emitting region is primarily photoionized, the mass can be derived from basic nebular photoionization theory (Osterbrock, 1989).

$$M_{gass} = m_p \frac{L(H\beta)}{n_e \alpha^{eff}_{H\beta} h\nu_{H\beta}}$$

?



n_e = 500 cm^{-3} which leads to a mass of $10^{4.7} M_\odot$.

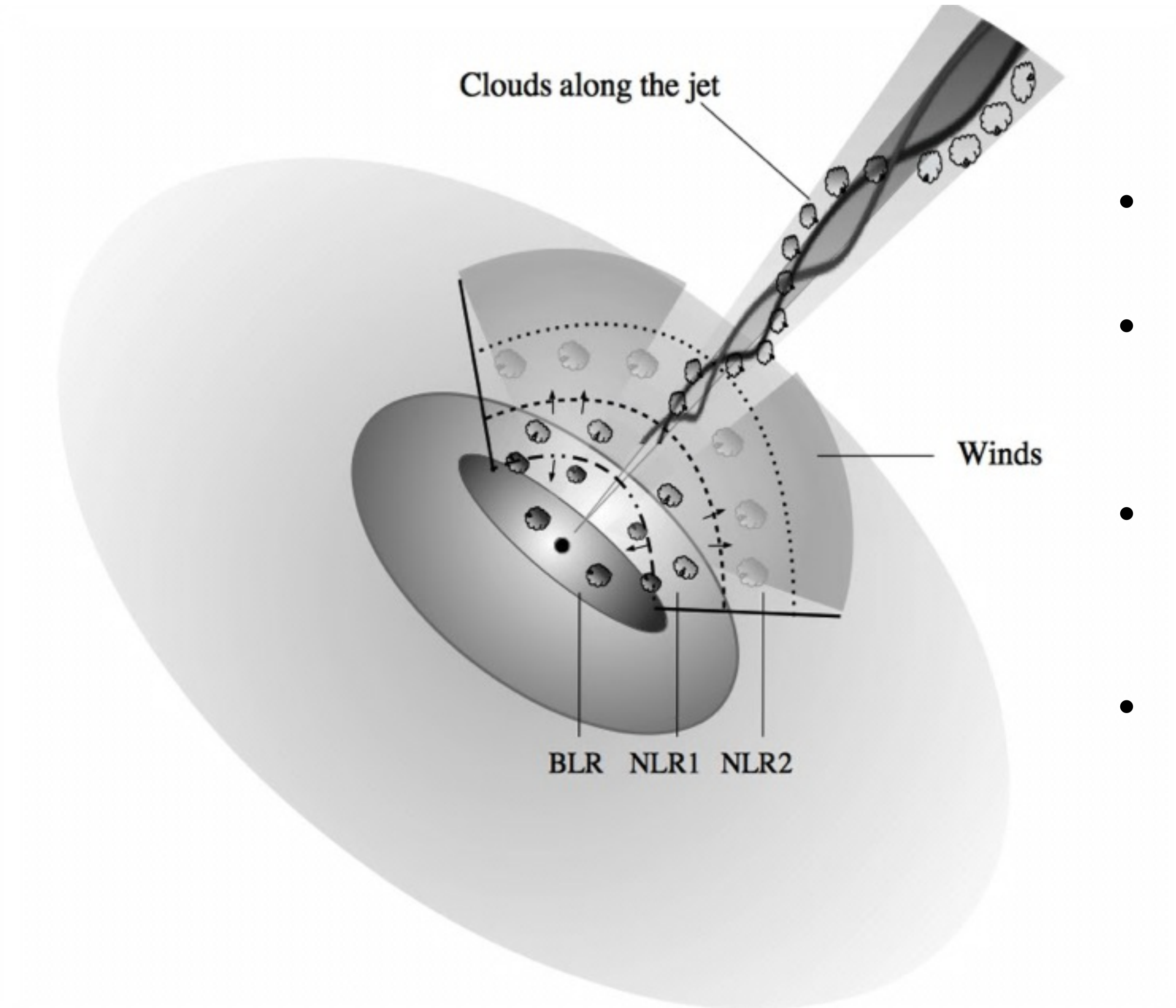
Reference	Density ($\times 10^2$ cm^{-3})	Object
Clark et al. (1997)	$1.7^{+0.5}_{-0.5}$	PKS 2250-41
Armus et al. (1998)	1.90 – 6.75	4C +19.71
Clark et al. (1998)	$2.7^{+0.3}_{-0.2}$	3C 171
Villar-Martín et al. (1999)	$1.9^{+0.8}_{-0.6}$	PKS 2250-41
Emonts et al. (2005)	2.0-3.0	3C 293
Nesvadba et al. (2006)	2.4-5.7	MRC1138-262 (winds)
Nesvadba et al. (2008)	5.0	MRC0406-244 (winds)
Rosario et al. (2010)	12^{+5}_{-3}	NGC 2110

Reported values for the density in jet-cloud interaction regions.

Derived values are in the range from 200–1000 cm^{-3}, which leads to a mass of **$10^5 M_\odot$ - $10^4 M_\odot$.**

In previous works of jet-induced outflows:
3C 293 – $10^5 M_\odot$ (Emmonts et al. 2005)
NGC 2110 – $1.5 \times 10^4 M_\odot$ (Rosario et al. 2010)

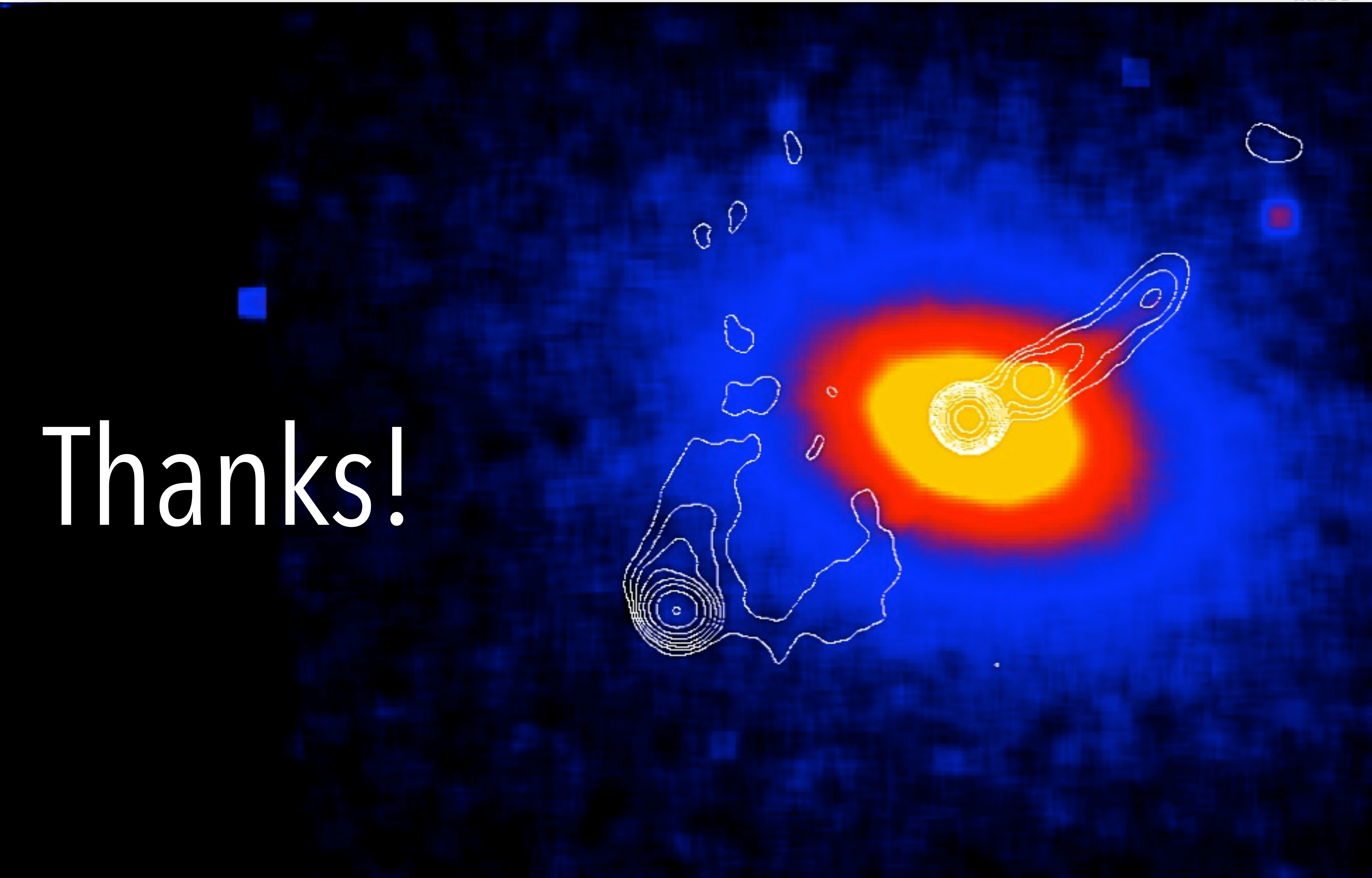
Summary



- SMBH mass: $10^{7.4}\,M_\odot$ - $10^{9}M_\odot$.
- Outflowing gas along the major axis extending beyond to 8 kpc.
- Outflow mass along the jet: $>10^{4}\,M_\odot$.
- Ionized clouds moving in a **helicoidal way** along the jet at distances beyond to ~20Kpc!

Future work

- We need to secure an optical spectrum covering the range from 3000-7000 angstroms to elaborate diagnostic diagrams and identify the ionization source, allowing also to estimate densities to further estimate the mass of the outflow.
- With IFS observations the physical conditions, gas dynamics and ionization state can be efficiently studied as function of position relative to the nucleus.
- High-resolution imaging in the CO lines would allow us to determine how much of it is infalling, and what kind of motions are present ➔ ALMA.



Thanks!