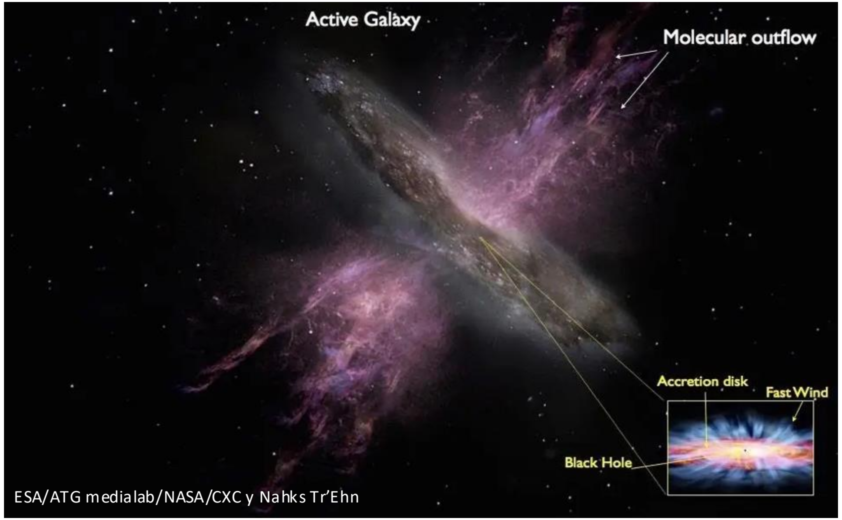
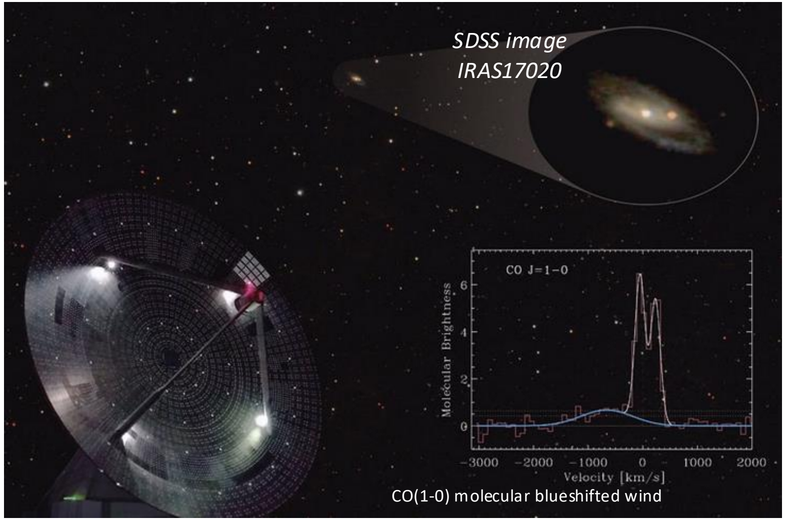
“The MEGARA/GTC Optical Perspective on the X-ray Ultra-Fast Outflow (UFO) in IRAS17020+4544"



ESA/ATG medialab/NASA/CXC y Nahks Tr’Ehn



CO(1-0) molecular blueshifted wind

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“IV IPARCOS congress”, 10th Dec 2025

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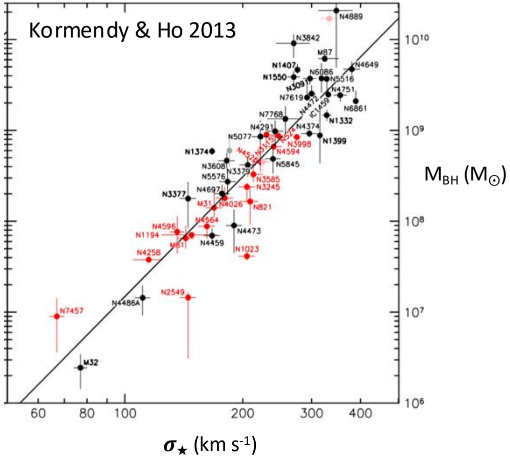
Why AGN outflow are so important?

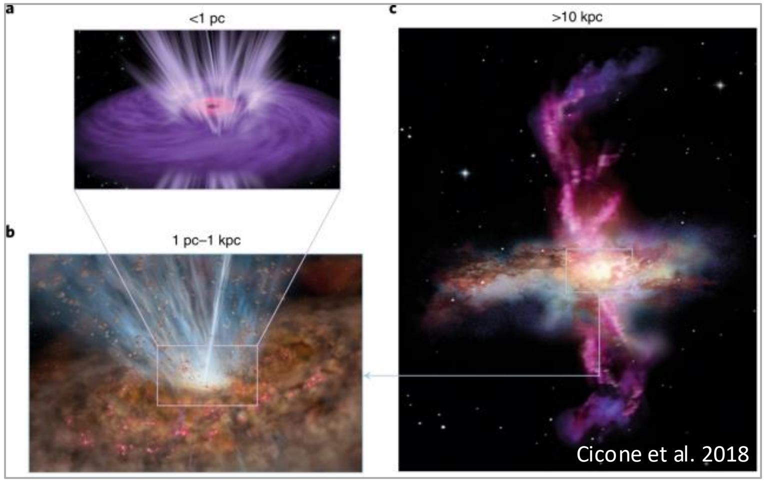
- M_{BH}-$\boldsymbol{\sigma}_\star$ (Kormendy & Ho 2013): nuclear and galaxy scale relation (King et al. 2003) supported by theoretical models and hydrodinamical simulations of galaxy formation and evolution (e.g., Di Matteo et al. 2005, Hopkins & Elvis 2010) → **tight coupling** between the growth of the central BH & the bulge of its host Galaxy

  → Feedback by AGN as key ingredient for regulating star formation and clearing up the gas in galaxies (Zubovas & King 2012)



- If this material eventually leaves the AGN, then outflows might carry significant mass out of the AGN and, as a consequence, give a substantial contribution to the chemical **enrichment** of the IGM

- Outflows may provide the connection between BH and host galaxies required to reconcile theory & observations → they carry out mass and energy out to larger scales

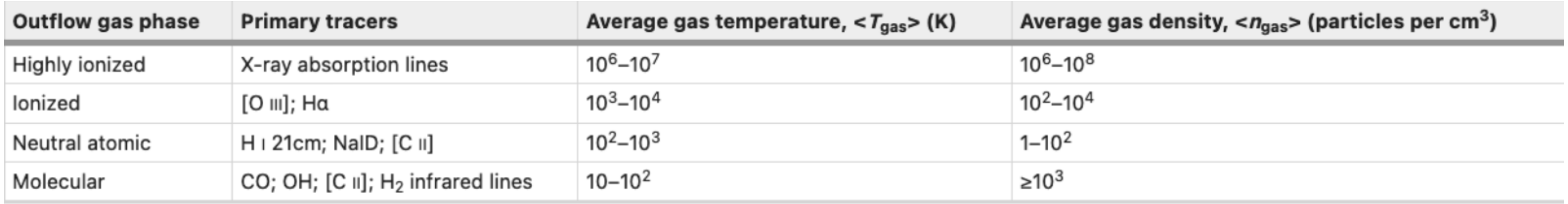


Cicone et al. 2018

The activity of the BH influences the life of the galaxy !
(Silk & Rees 1998; King 2003**)**

Outflows can be:

Multi-phase → highly ionized, warm ionized, neutral atomic and molecular



Outflow gas phase	Primary tracers	Average gas temperature, <T_{gas}> (K)	Average gas density, <n_{gas}> (particles per cm^3)
Highly ionized	X-ray absorption lines	10^6–10^7	10^6–10^8
Ionized	[O III]; Hα	10^3–10^4	10^2–10^4
Neutral atomic	H I 21cm; NaID; [C II]	10^2–10^3	1–10^2
Molecular	CO; OH; [C II]; H_2 infrared lines	10–10^2	≥10^3

Cicone et al. 2018; Harrison et al. 2017, 2018

Ultra Fast Outflow (UFO): These outflows are characterized by mildly relativistic speeds (v ~ 0.1-0.3 c), high ionization states, and prominent blueshifted X-ray absorption lines (Fe K band)

Tombesi et al. 2010a, b, 2015; Chartas et al. 2014; Nardini et al. 2015, Matzeu et al. 2017, 2019;
Parker et al. 2017; Reeves et al. 2020; Laurenti et al. 2021 …

Kew questions:

1) What are the mechanisms responsible for launching UFOs?
2) Are the different gas phases connected?
3) How does the nuclear X-ray wind transfer its energy from nuclear to galaxy-scale?

Transfer of wind energy to large scales

The nuclear, ultra fast X-ray wind ($v_{out} \geq 10^4$ km/s) interacts with the galaxy ISM in shock processes

- In the <u>momentum-driven case</u>, the narrow shocks rapidly cool to become effectively isothermal, leading to very low kinetic energy.
- In the <u>energy-driven outflow</u>, the shocked regions are much wider and do not cool → Their adiabatic expansion transfers most of the kinetic energy of the wind to the *<u>large scale outflow</u>*

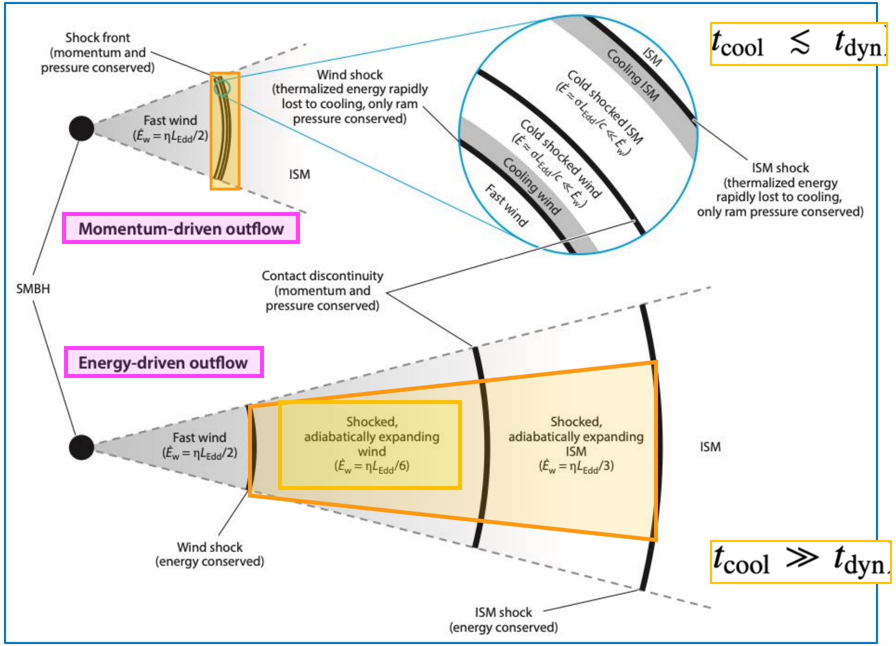
$$\dot{P} = \dot{M}_{out}\, v_{out}$$

→ Outflow momentum rate

$$\frac{\dot{P}^{[ion,mol]}}{\dot{P}^{[UFO]}} = \frac{v_{out}^{[UFO]}}{v_{out}^{[ion,mol]}}$$

→ Momentum boost in the "energy conserving" regime

Zubovas & King 2012 (Faucher-Giguere+2012, King & Pounds 2015)



→ *"The cooling of the shocked wind, rather than the shocked ambient medium, that determines whether the outflow is energy- or momentum conserving (King+2011)".*

Multi-wavelength campaign can help:

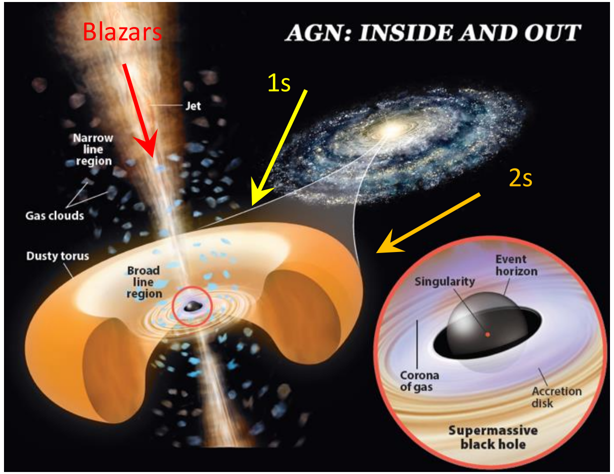
→ to understand the effect of a powerful nuclear X-ray wind during its encounter through the ISM

→ to follow the evolution of the shocked outflow initiated by this wind in its propagation at larger scale

Our targets are Narrow Line Seyfert 1 (NLSy1) Galaxies hosting an UFO

- Sy1 Galaxies with exceptionally narrow Balmer lines (Osterbrock & Pogge 1985)
- FWHM Hβ<2000 km/s, [OIII]5007/Hβ <3, strong FeII lines
- Strong X-ray variability & Steep X-ray power law continua
- Smaller M_{BH} (~10^6 - 10^8 $M_\odot$)
- High Accretion Rates $\dot{M} = L_{Bol}/L_{EDD}$ related to high radiative efficiency drives disk winds

(e.g. Komossa et al. 2018, Boroson et al. 2011, Panessa et al. 2011, Berton & Järvelä 2021)



❑ NLSy1s are one of the key AGN subclasses in investigating the origin of the M_{BH}-$\boldsymbol{\sigma}_\star$ relation because of their high accretion rate and significantly low M_{BH}

→ these two characteristics may imply that NLS1s are young phases of AGNs (Mathur et al. 2001; Véron-Cetty et al. 2001; Boroson 2002, Woo+2015)

❑ What do we know about NLSy1 with UFO? Not much… (e.g., Marasco et al. 2020, Tozzi et al. 2021…)

The case of the NLSy1 IRAS17020+4544

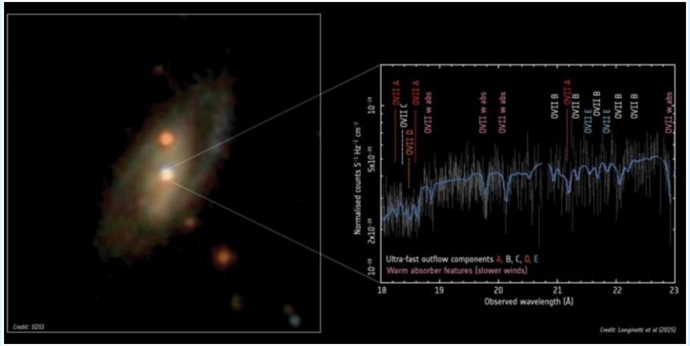
- Host galaxy is a (barred) Sp
- z ~ 0.0612 (1.181 kpc/arsec)
- Small M_{BH} ~ 6 ×10^6 $M_{\odot}$
- High $\dot{M} = L_{Bol}/L_{EDD}$~ 0.7

→ Multi-wavelength campaign in the last years (X-ray, sub-mm, radio bands…)

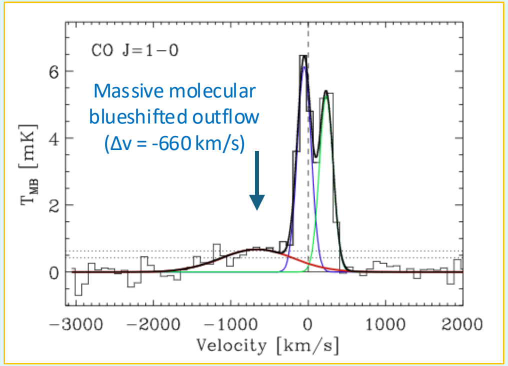
XMM-Newton X-ray spectrum: a stratified, multi-component wind

5 UFO distinct components wide range of ionization, NH outflowing and velocity range v ~ **0.1-0.3 c** → *UFO launched at the accretion disk scale*

❑ Fast + Slow winds with complex velocity pattern in IRAS17 (Longinotti et al. 2015, see also Sanfrutos et al. 2018)



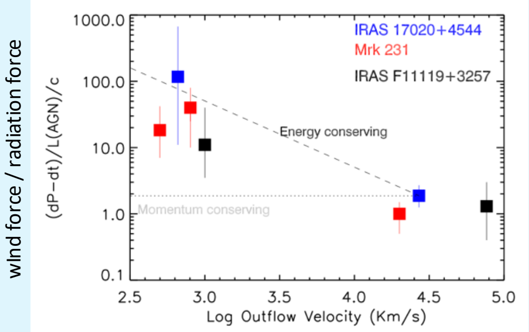
Large Millimeter Telescope (LMT): fast molecular outflow



$$\dot{P}_{out} = \dot{M}_{out} \times v_{out}$$

$$\dot{P}_{[CO]}/\dot{P}_{[X]} = v_{out\_X}/v_{out\_CO}$$

The molecular outflow follows the "energy-conserving" regime (Longinotti et al. 2018)



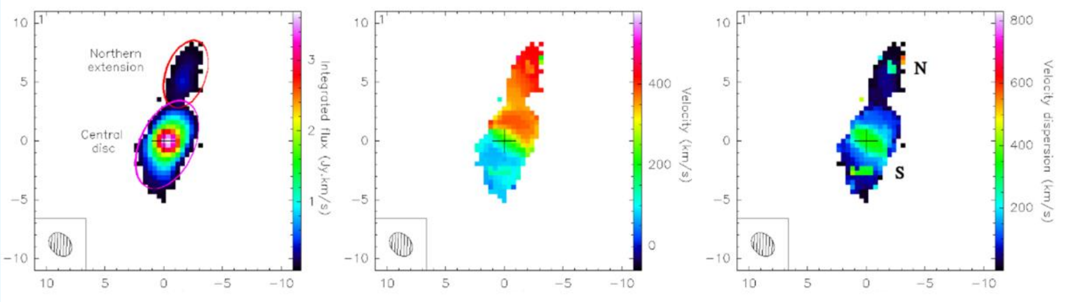
The case of the NLSy1 IRAS17020+4544

→ Multi-wavelength campaign in the last years (X-ray, sub-mm, radio bands…)

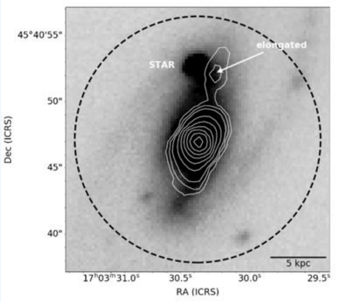
NOEMA (*NOrthern Extended Millimeter Array)* PdB Interferometry

Salomé et al. 2021

CO(1-0) systemic emission



Salomé et al. 2021 found that the molecular gas is distributed into a central disc-like structure of ~$10^9 M_\odot$ → Discovery of a companion toward the North located up to 8 kpc (possibly interacting with IRAS17, at the early phase of merger) with a molecular gas mass $M_{H2} \sim 10^8\ M_\odot$

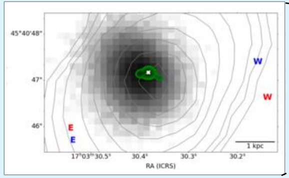


R-band image taken by the ALFOSC/NOT with CO contours (white)

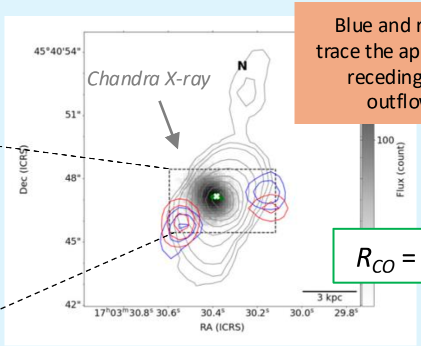
Longinotti et al. 2023

CO(1-0) outflow emission

radio emission VLBI
e-MERLIN @ 1.5 GHz

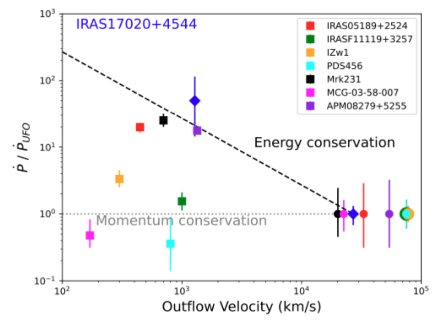


Giroletti et al. 2017



Blue and red contours trace the approaching and receding molecular outflowing gas

R_{CO} = 2.8 ± 0.3 kpc

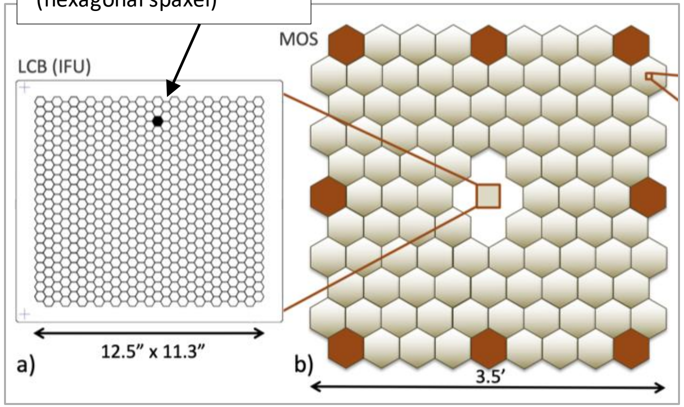


NOEMA results confirm the "energy-conserving" regime for the spatially resolved molecular outflow (Longinotti et al. 2023)

Multi
Espectrógrafo en
GTC de
Alta
Resolución para
Astronomía

Within the framework of the "<u>MATRIOSKA</u>" Project ***[M**ultiphase n**A**ture of ul**T**ra-fast outflows in na**R**row l**I**ne seyfert 1: the **O**ptical **S**urvey and **K**inematic **A**nalysis]* → we present the analysis of *IRAS 17020+4544 using MEGARA/GTC*

MEGARA = Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía



spatial resolution 0.62"
(hexagonal spaxel)

Gil de Paz, A. et al. 2018
Carrasco et al. 2018
Castillo-Morales, A. et al. 2020

In this work we used MEGARA/GTC IFU to characterize the <u>ionized gas phase</u> in the optical band as traced by the Hα and [OIII] emission lines

- ✓ We use MEGARA/GTC data at low- (LR, R=6000) and medium-resolution (MR; R=12,000), with FWHM~1") to characterize the ionized outflow, which covers the region encompassed by the resolved, powerful molecular outflow
- ✓ Multi-Gaussian line fit allowed us to derive its kinematics and energetics (velocity, mass, kinetic power, and momentum), we evaluate the outflow's energy budget and compare it with that of the molecular and X-ray phases and check if the ionized gas phase also follows an "energy-conserving" regime, as previously found for the molecular phase (Longinotti et al. 2023)

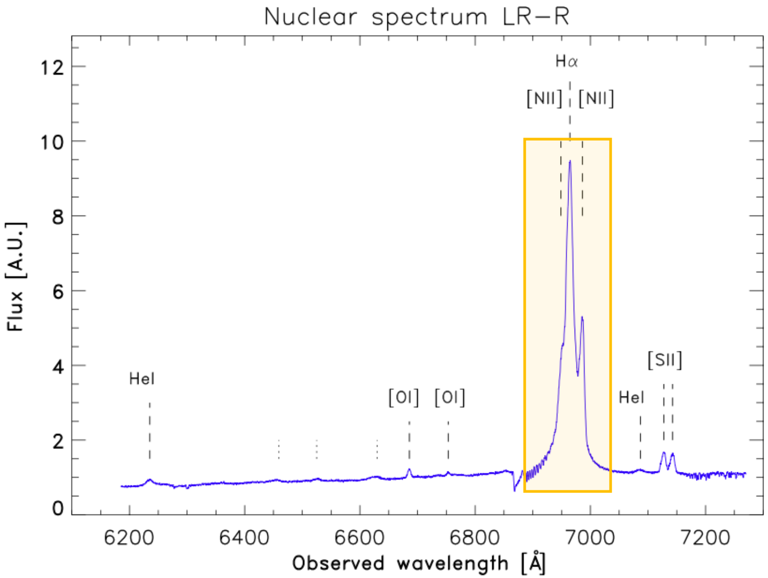
Bellocchi et al. submitted to A&A

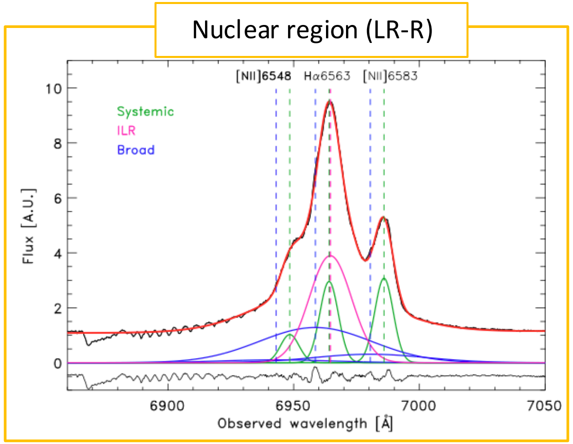
PI: Longinotti A.

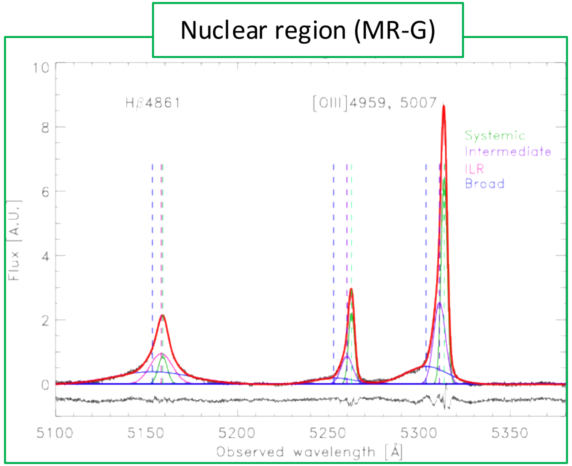
Program (1)	Grism (2)	Spectral coverage [Å] (3)	R. L. D. [Å pix^{-1}] (4)	R (5)	Observing Date (6)	t_{exp} [s] (7)	Airmass (8)	Seeing ["] (9)	Atm. Conditions (10)
GTC8-20AMEX	LR-R (VPH675_LR)	6100-7300	0.32	6100	23 June 2020	3×1000	1.31	1.2	Clear
GTC8-20AMEX	MR-G (VPH521_MR)	4970-5445	0.13	12035	23 June 2020	3×1000	1.16	1.2	Clear
GTC1-24AMEX	LR-V (VPH570_LR)	5140-6170	0.27	6080	11 May 2024	6×1120	1.05	0.9	Clear

Multi
Espectrógrafo en
GTC de
Alta
Resolución para
Astronomía

Multi Gaussian (3c) line fit using MEGARA/GTC data


Nuclear spectrum LR−R

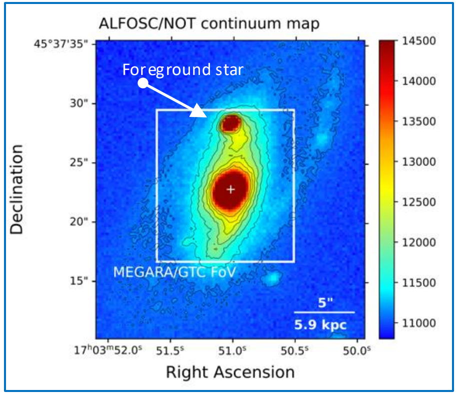

Nuclear region (LR-R)


Nuclear region (MR-G)

Program (1)	Grism (2)	Spectral coverage [Å] (3)	R. L. D. [Å pix^{-1}] (4)	R (5)
GTC8-20AMEX	LR-R (VPH675_LR)	6100-7300	0.32	6100
GTC8-20AMEX	MR-G (VPH521_MR)	4970-5445	0.13	12035
GTC1-24AMEX	LR-V (VPH570_LR)	5140-6170	0.27	6080

→ [OI], Hα+[NII], [SII]
→ Hβ-[OIII]
→ Hβ-[OIII]

2D kinematic maps: Hα – [NII] complex from the LR-R setup



Contours:
Continuum emission (IRAS17+star)
CO emission in white

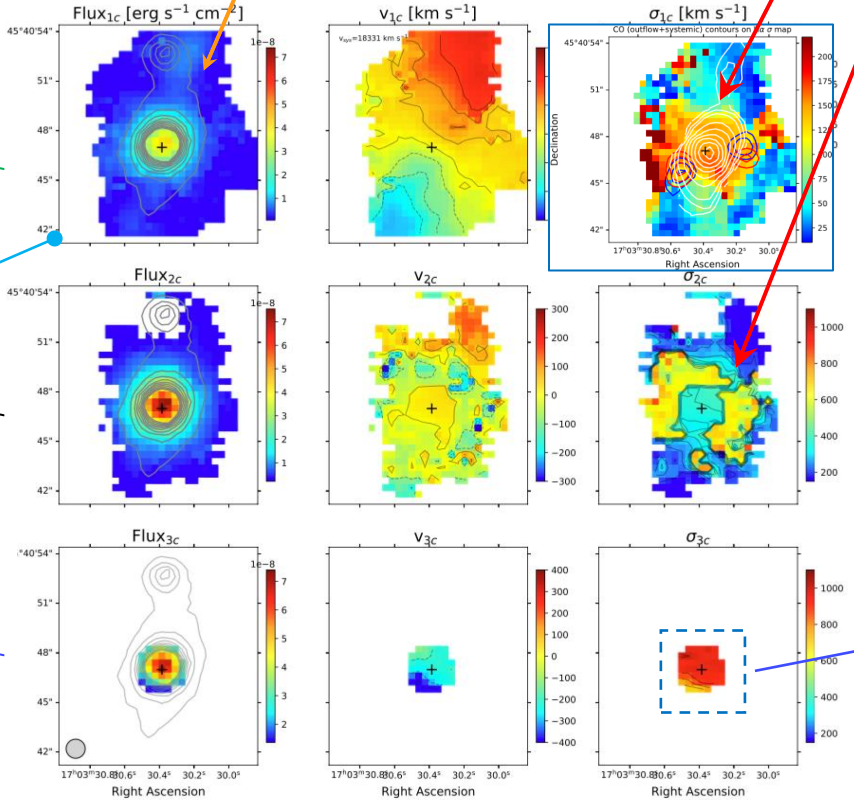
Companion Galaxy (CO+Hα)

3 Gaussian fit Hα line (LR-R)

systemic component

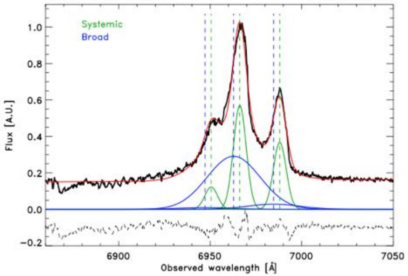
secondary component

third component

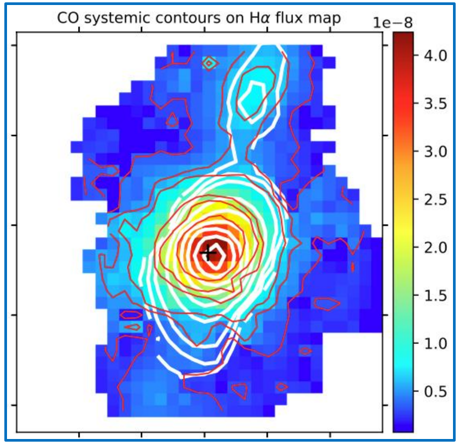


"Butterfly" or "X-shaped" region
→ high **σ** (turbulence) in the inner regions

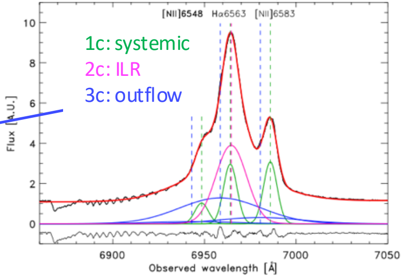
"Butterfly"



3c fitting for Hα and [NII] lines



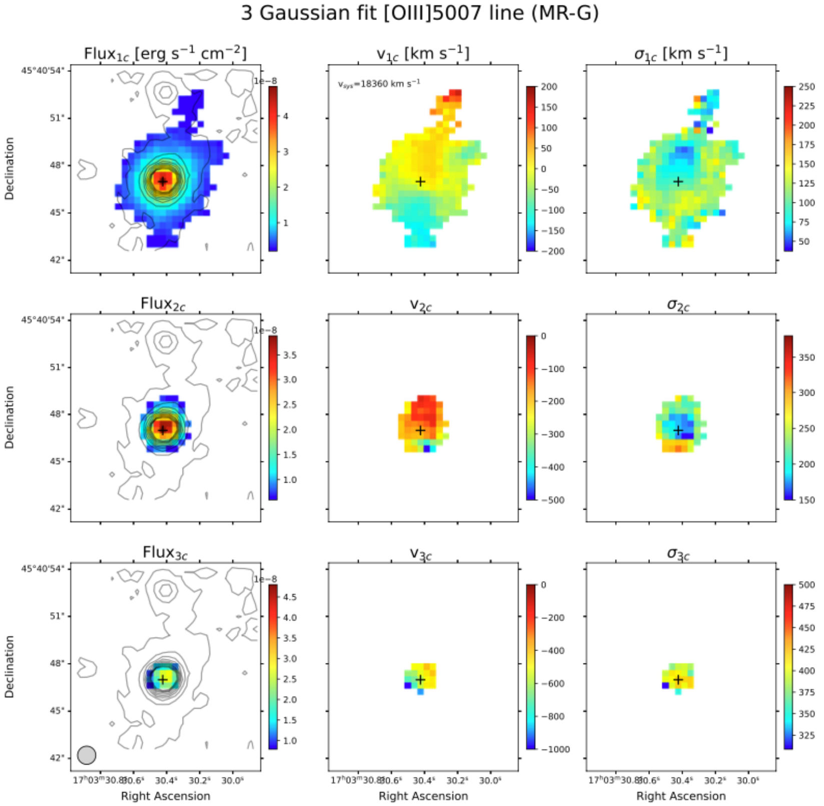
Nuclear region



1c: systemic
2c: ILR
3c: outflow

2D kinematic maps: [OIII]5007 emission from the MR and LR setups

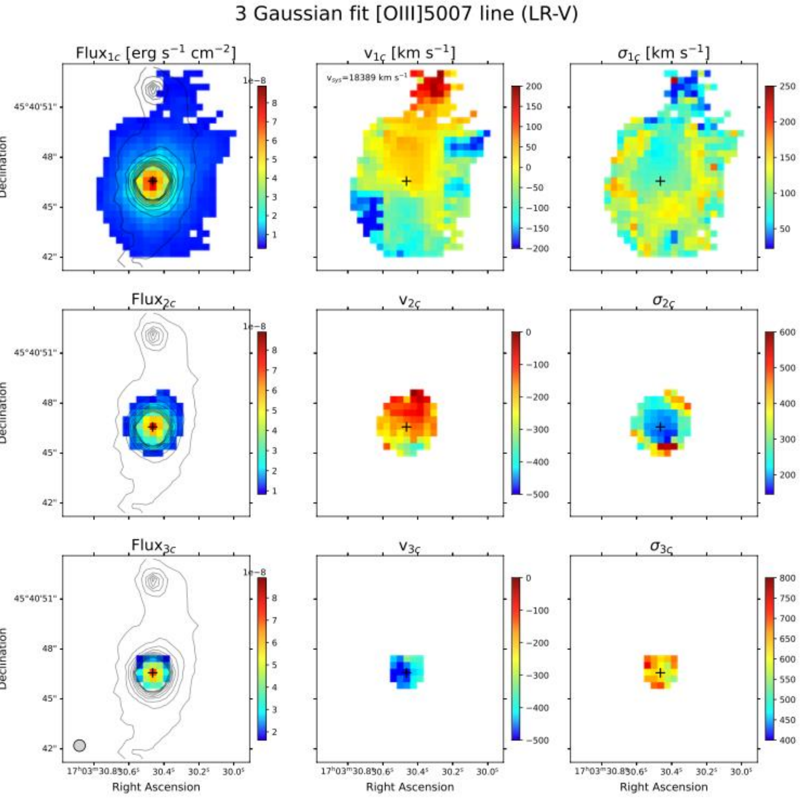
Contours:
Continuum emission (IRAS17+star)



1c: systemic

2c: (slow) outflow

3c: (fast) outflow



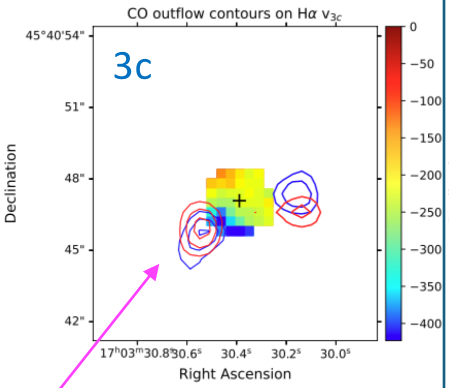
2D information: Constraining the size of the outflow(s)

→ Flux threshold at 10% the flux peak to derive the instrinsic size, $R_{eq} = (\text{Area}/\pi)^{1/2}$

($PSF_{10\%} = 1.82 \times PSF_{FWHM}$)

LR-R setup

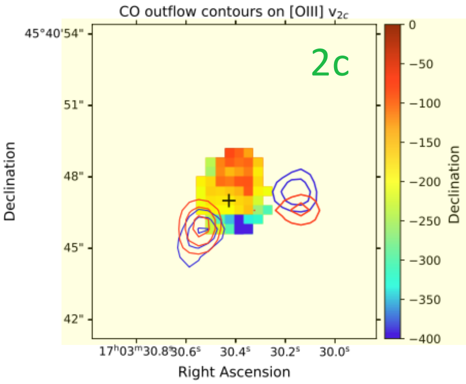
R(Hα) ~1 kpc



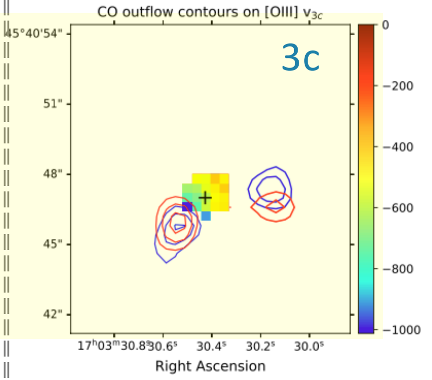
Molecular outflow R_{CO}=2.8±0.3 kpc (Longinotti+2023)

Ionized (Hα & [OIII]5007) outflows are *confined* within the molecular outflow

R([OIII]) = 0.7 kpc

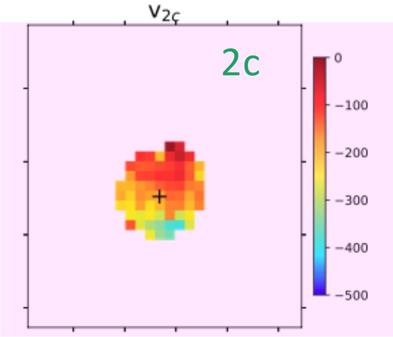


R([OIII]) <1.3 kpc
(unresolved)



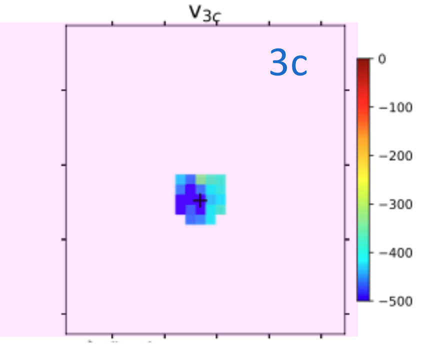
MR-G setup

R([OIII]) = 0.74 kpc



(slow outflow)

R([OIII]) =0.47 kpc
(resolved!)



(fast outflow)

LR-V setup

Constraining n_e from Baron & Netzer (2019) method

Combining information of 2c+3c:

$$\log U = -3.766 + 0.191 \log\left(\frac{[\mathrm{O\,III}]}{\mathrm{H}\beta}\right) + 0.778 \log^2\left(\frac{[\mathrm{O\,III}]}{\mathrm{H}\beta}\right) - 0.251 \log\left(\frac{[\mathrm{N\,II}]}{\mathrm{H}\alpha}\right) + 0.342 \log^2\left(\frac{[\mathrm{N\,II}]}{\mathrm{H}\alpha}\right)$$

$$\mathrm{n_e} \approx 3.2 \left(\frac{\mathrm{L_{bol}}}{10^{45}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{r}{1\ \mathrm{kpc}}\right)^{-2}\left(\frac{1}{U}\right)\ \mathrm{cm^{-3}}$$

→ $n_e \sim 2500\ cm^{-3}$

Deriving the parameters of the ionized outflow

Venturi et al. 2023

→ A_V = 2.7 mag from combining the flux of the 2c + 3c components

$$\mathrm{M_{out}} = 6.1 \times 10^8 \left(\frac{\mathrm{L_{H\alpha}}}{10^{44}\ \mathrm{erg\ \ s^{-1}}}\right)\left(\frac{500\ \mathrm{cm^{-3}}}{n_\mathrm{e}}\right)\mathrm{M_\odot}$$

Fiore et al. 2017
(Peralta de Arriba et al. 2023)

$$\begin{cases} \mathrm{M_{out}^{[OIII]}} = 8.0 \times 10^7 \left(\frac{\mathrm{L_{[OIII]}}}{10^{44}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{500\ \mathrm{cm^{-3}}}{<\mathrm{n_e}>}\right)\frac{\mathcal{CF}}{10^{[\mathrm{O/H}]-[\mathrm{O/H}]_\odot}}\mathrm{M_\odot} \\ \mathrm{M_{tot}^{out}} = 3 \times \mathrm{M_{out}^{[OIII]}} \end{cases}$$

Rupke et al. 2005

$$v_{out} = v_{21} + FWHM_2/2 \sim v_{21} + 1.18\sigma_2$$

Lutz et al. 2020

$$\dot{\mathrm{M}}_\mathrm{out} = \frac{\mathrm{M_{out}\ \ v_{out}}}{\mathrm{R_{out}}}$$

$$\mathrm{E_{kin}} = \frac{1}{2}\sigma^2_\mathrm{out}\mathrm{M_{out}}$$

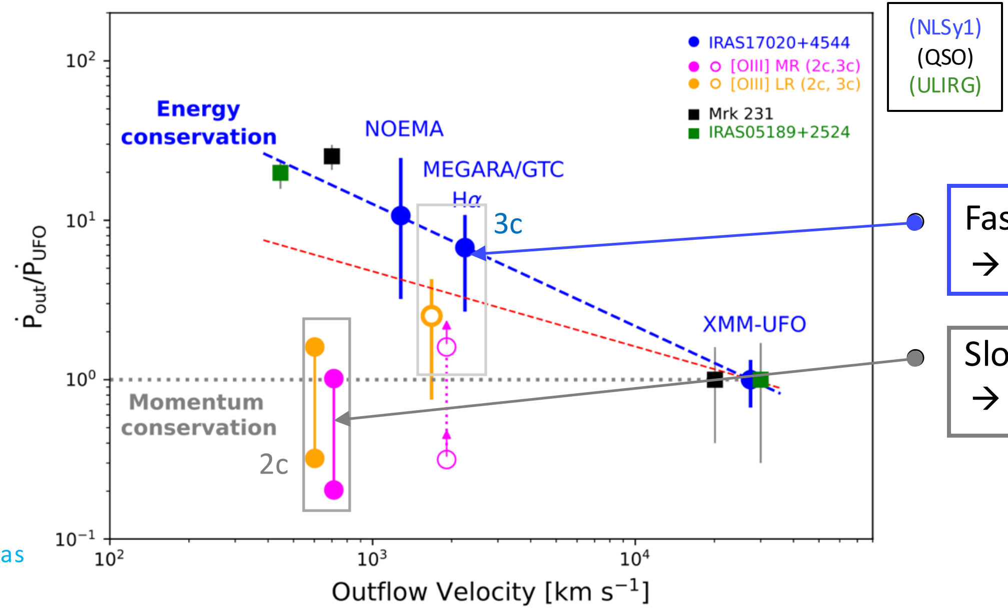
Rose et al. 2018

$$\dot{\mathrm{E}}_\mathrm{kin} = \frac{\dot{\mathrm{M}}_\mathrm{out}}{2}(\mathrm{v^2_{out}} + 3\sigma^2_\mathrm{out})$$

$$\dot{\mathrm{P}} = \dot{\mathrm{M}}_\mathrm{out}\ \mathrm{v_{out}}$$

Confirming the "energy-conserving" regime in the optical phase

CO ← (Hα , [OIII]) ← UFO

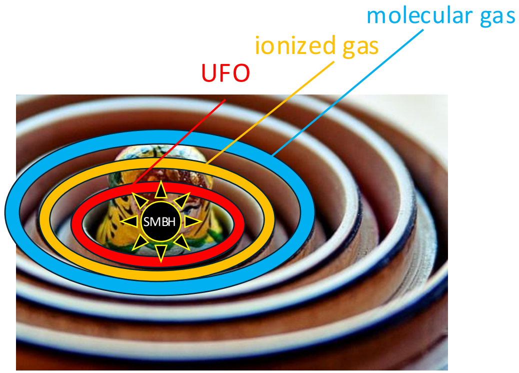


$\gg 1$: an AGN-driven wind (via an adiabatic expansion) shocks the surrounding medium and transfers energy efficiently to the ISM, resulting in a momentum boost

$\lesssim 1$: likely driven by radiation pressure

Fast Hα and [OIII] = 3c
→ **energy-conserving**

Slower [OIII] = 2c
→ **momentum-conserving**



Radial ("Matrioska") stratification in density, ionization, and velocity:

- ✓ 2c = Slower [OIII], v_{out}~450 km/s → disk gas partially accelerated and compressed (i.e., entrained) by the AGN outflow (3c)
- ✓ 3c = Fast outflow, similar v_{out} ~1500 km/s (Hα and [OIII])
- ✓ Ionized (Hα & [OIII]5007) outflows are *confined* within the molecular outflow
  → *in situ* molecular formation? (see Richings et al. 2018 a,b)

Conclusions and Future work

- ✓ Highly accreting NLSy1 galaxies provide excellent laboratories to study, trace, and potentially unravel the impact of a powerful nuclear X-ray (UFO) wind as it interacts with the surrounding ISM

- ✓ The ionized AGN-driven outflow, traced by Hα and [OIII] lines, follows the "energy-conserving" regime previously inferred for the molecular powerful outflow by NOEMA

- ✓ Using MEGARA/GTC we provide new (2D) spatial information on the distribution of the ionized outflow (i.e., confined within the molecular outflow) → finding a radial ("Matrioska") stratification in density, ionization, and velocity between the different phases ("*in situ*" molecular formation?)

- ✓ More NLSy1 galaxies (e.g., Ark 564…) hosting UFOs will be studied to confirm these results