The Keck OSIRIS Nearby AGN Survey (KONA): Spatially Resolved Inflows and Outflows in Seyfert Galaxies

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- *In collaboration with:* -

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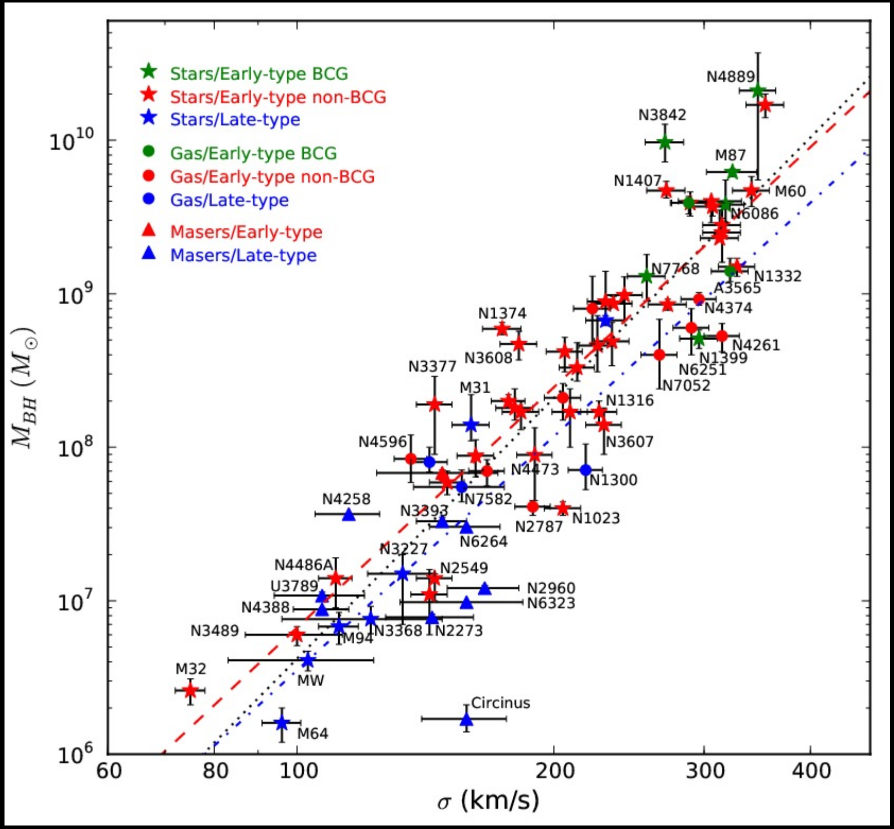
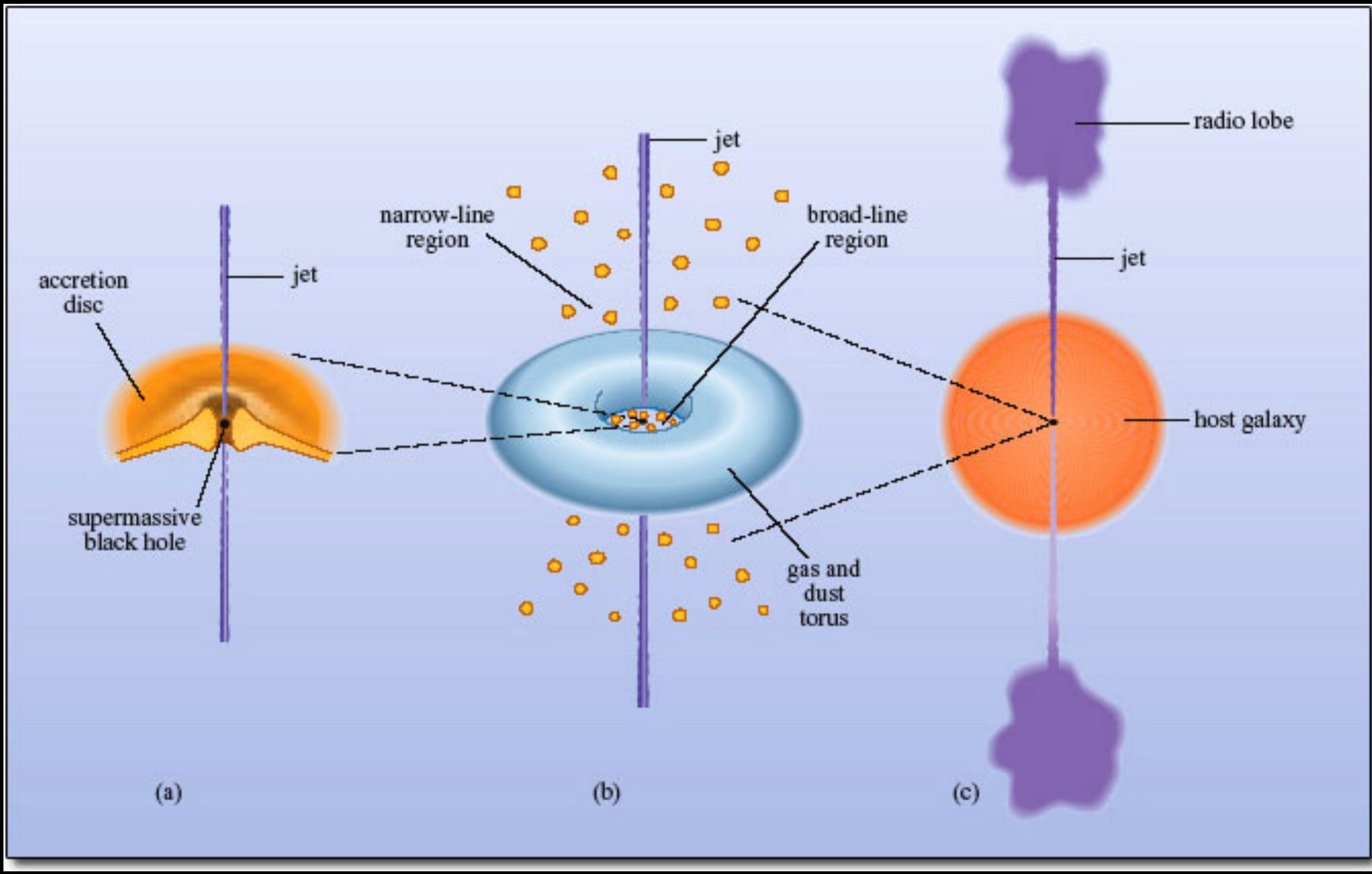
Motivation: Probe Co-evolution of SMBHs and Galaxies in the Local Universe via Integral-field Spectroscopy

- SMBHs grow via gas inflows to the nuclear region.
- Galaxy bulge grows through the formation of new stars in the nuclear region.
- Feedback regulates the growth of SMBH and bulge



McConell & Ma 2013

Main Components of AGN

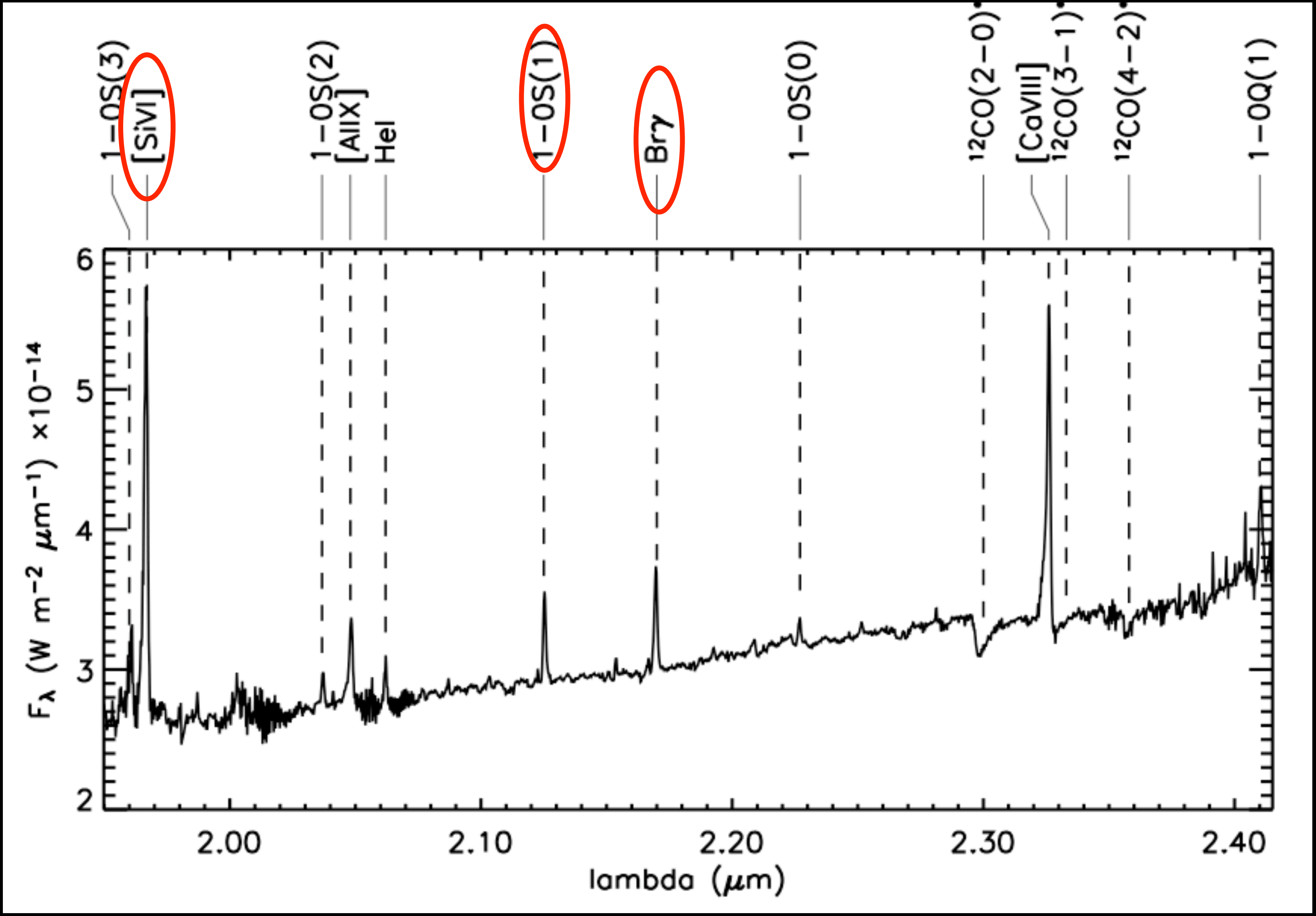


Keck Osiris Nearby AGN Survey

PI: F. Müller-Sánchez

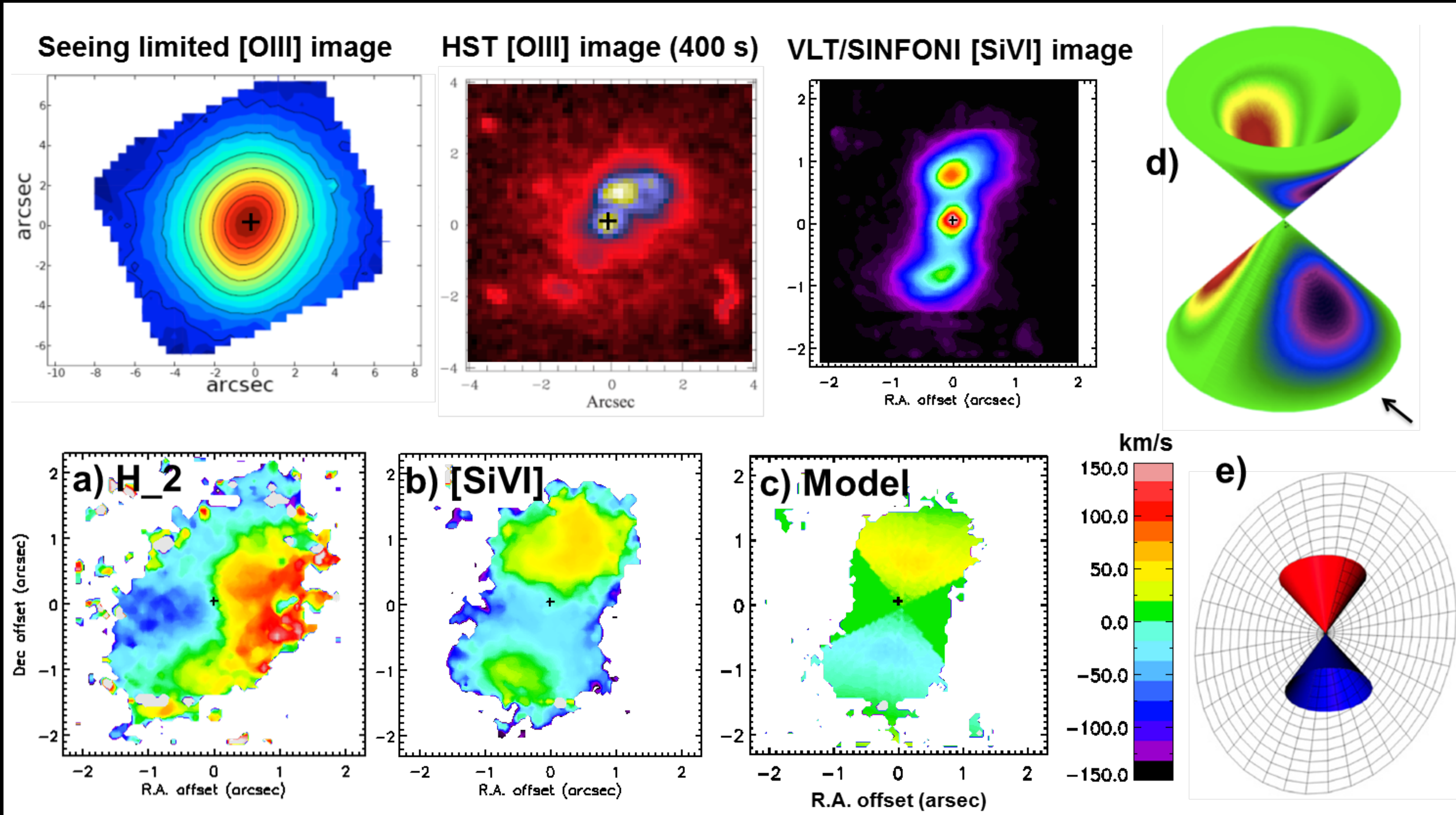
Object	Type[a]	z[a]	Instrument	Band	T_{int} (min)	Date	FWHM[b] ($''$)	Brγ[c] 2.16μm	H_2[c] 2.12μm	[Si VI][c] 1.96μm
Circinus	Sy2	0.00045	SINFONI	K	[illegible]	Jul 2004	0.22 (4.4)	D	D	D
Mrk 9	Sy1	0.00632	OSIRIS	K	40	Nov 2013				
Mrk 79	Sy1	0.02208	OSIRIS	K	40	Mar 2013				
Mrk 573	Sy2	0.01726	OSIRIS	K	60	Mar 2013				
Mrk 766	Sy1	0.01330	OSIRIS	K	40	Jul 2012				
Mrk 993	Sy1	0.01553	OSIRIS	K	60	Jul 2012				
Mrk 1066	Sy2	0.01202	OSIRIS	K	40	Nov 2013				
Mrk 1210	Sy2	0.01406	OSIRIS	K	60	Mar 2011				
Mrk 1239	Sy1	0.01927	OSIRIS	K	40	Mar 2013				
NGC 0262	Sy2	0.01503	OSIRIS	K	60	Jul 2012				
NGC 0513	Sy2	0.01948	OSIRIS	K	40	Nov 2013				
NGC 0591	Sy2	0.01516	OSIRIS	K	40	Nov 2013				
NGC 0931	Sy1	0.01643	OSIRIS	K	40	Nov 2013				
NGC 1068	Sy2	0.00334	SINFONI	$H+K$	120	Nov 2006	0.08 (5.6)	D	D	D
NGC 1194	Sy2	0.01339	OSIRIS	K	60	Nov 2013				
NGC 1320	Sy2	0.00993	OSIRIS	K	40	Nov 2013				
NGC 1386	Sy2	0.00765	SINFONI	K	60	Sep 2011		D	D	D
NGC 1667	Sy2	0.01527	OSIRIS	K	40	Nov 2013				
NGC 2110	Sy2	0.08192	SINFONI	K	60	Sep 2011				
NGC 2992	Sy1	0.01466	SINFONI	K	90	Mar 2005	0.3 (42)	D	D	D
NGC 3081	Sy2	0.00797	OSIRIS	K	90	Feb 2011	0.2 (30)	D	D	D
	Sy2	0.00797	SINFONI	K	90	Sep 2011	0.22 (34)	D	D	D
NGC 3227	Sy1	0.00386	SINFONI	K	80	Dec 2004	0.09 (7.2)	D	D	NA
NGC 3393	Sy2	0.01275	OSIRIS	K	40	Mar 2013		D	D	D
NGC 3783	Sy1	0.01523	SINFONI	$H+K$	80	Mar 2005	0.085 (17)	D	D	D
NGC 4051	Sy1	0.00234	OSIRIS	K	80	Jan 2008	0.12 (5.8)	D	D	NA
NGC 4151	Sy1	0.00345	OSIRIS	K	80	Mar 2006	0.11 (7.5)	D	D	D
NGC 4388	Sy2	0.00849	OSIRIS	K	40	Mar 2013				
NGC 4501	Sy2	0.00774	OSIRIS	K	40	Mar 2013				
NGC 4748	Sy1	0.00774	OSIRIS	K	60	Mar 2011		D	D	D
NGC 5506	Sy2	0.00618	OSIRIS	K	80	Mar 2011		D	D	D
NGC 5728	Sy2	0.01003	OSIRIS	K	40	Mar 2013		D	D	D
NGC 6814	Sy1	0.01276	OSIRIS	K	80	Sep 2006	0.17 (18)	D	D	D
NGC 7212	Sy1	0.01096	OSIRIS	K	40	Mar 2013				
NGC 7469	Sy1	0.01631	OSIRIS	K	60	Sep 2006	0.11 (35)	D	D	D
	Sy1	0.01631	SINFONI	K	60	Jul 2004	0.14 (44)	D	D	D
NGC 7582	Sy1	0.00525	SINFONI	K	60	Sep 2011		D	D	D
NGC 7682	Sy2	0.01712	OSIRIS	K	40	Nov 2013				
IRAS 04385-0828	Sy2	0.01510	OSIRIS	K	40	Nov 2013				
IRAS 01475-0740	Sy2	0.01766	OSIRIS	K	40	Nov 2013				
IRAS 05589+2828	Sy2	0.03280	OSIRIS	K	30	Nov 2013				
ESO 428-G14	Sy2	0.00566	SINFONI	K	60	Sep 2011				
MCG -05-23-016	Sy2	0.00848	SINFONI	K	60	Sep 2011				

Integrated Spectrum of Circinus



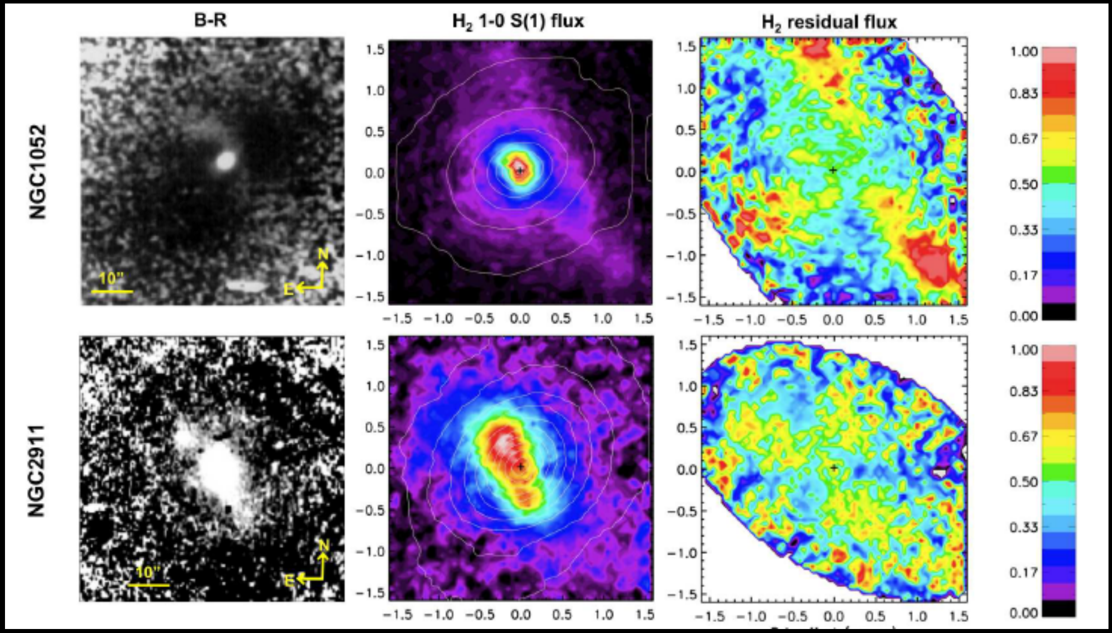
Müller-Sanchez et al. 2006

The Bipolar Outflow and the Nuclear Molecular Bar in NGC 3081

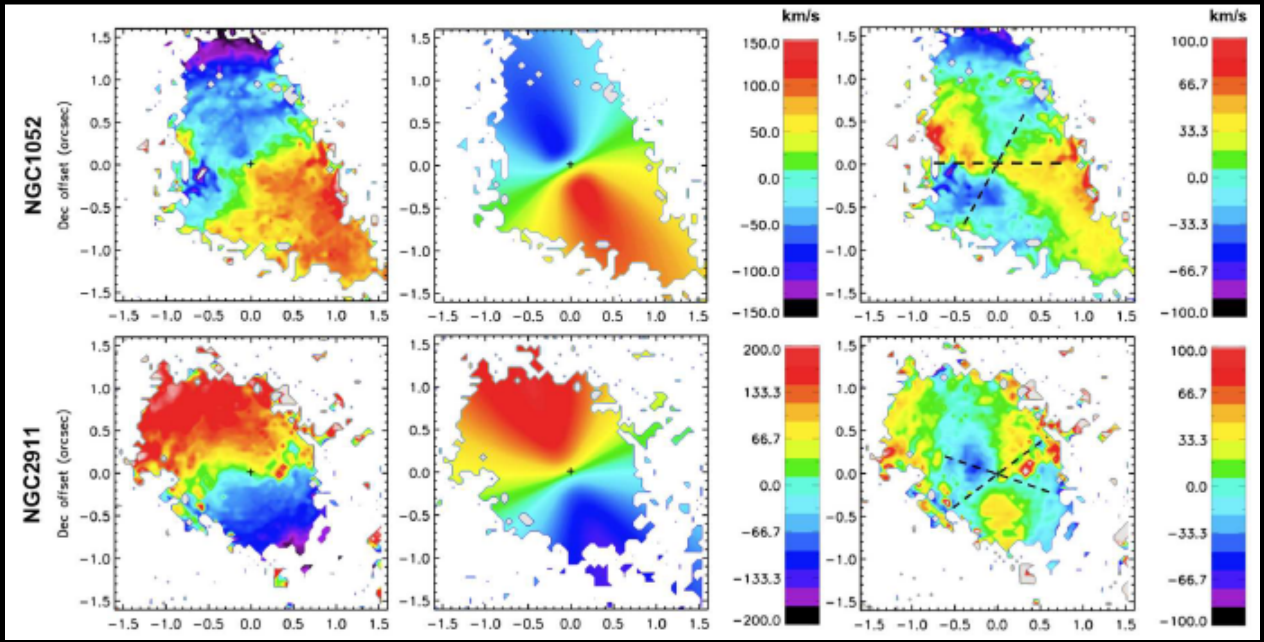


Müller-Sanchez et al. 2016a, ApJ, to be submitted

Nuclear Spirals in E/S0 galaxies



- Inner spiral with three photometric arms
- The gas kinematics reveal a strong non-circular velocity residual in the form of a 2-arm spiral. From linear theory, the projected LOS velocity pattern of an m-arm spiral is an (m − 1)-arm kinematic spiral.



- The inflow rate to the central few parsecs is of order 0.1-1 M_sun yr−1.

Müller-Sanchez et al. 2013a

Mass Outflow Rates and Kinetic Energy

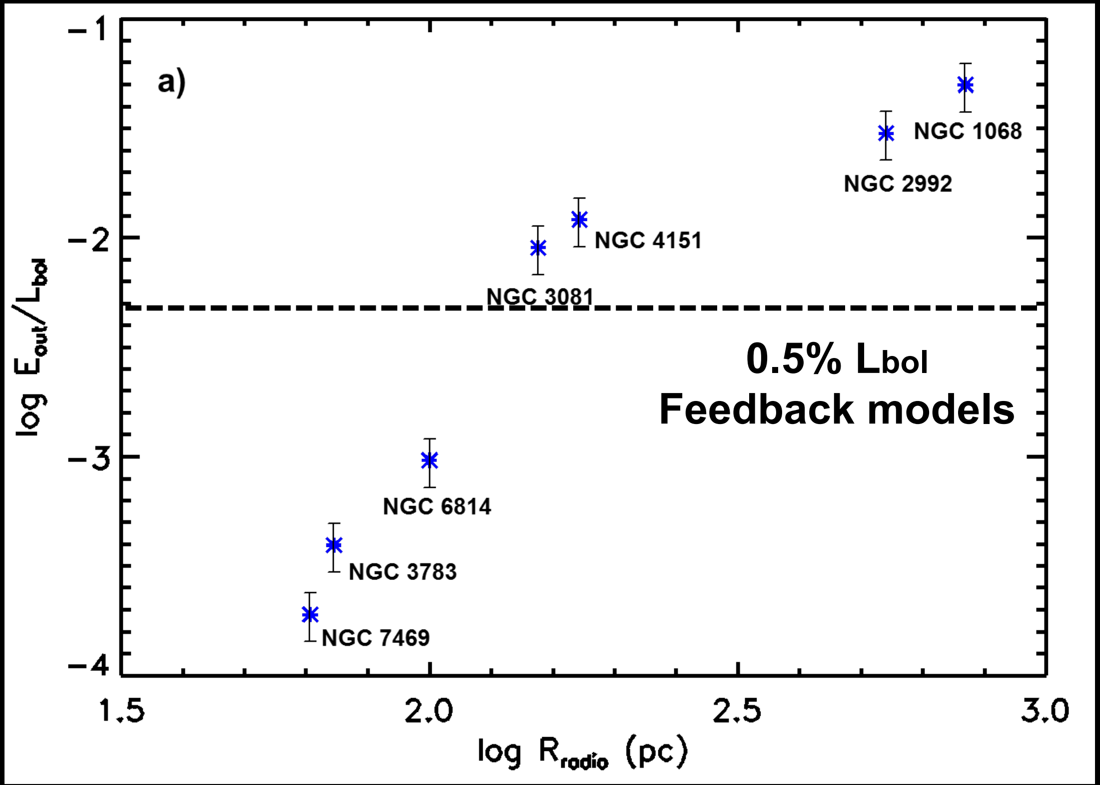
Galaxy	A^{a} (10^4 pc^2)	$\dot{M}_{out}$ ($M_\odot$ yr^{-1})	$\dot{M}_{acc}$ ($M_\odot$ yr^{-1})	$\dot{E}_{out}$ (10^{42} erg s^{-1})	L_{bol} (10^{42} erg s^{-1})	$\dot{E}_{out}/L_{bol}$	Ref.[b]
NGC 1068	2	9	0.015	5	88	0.05	1
NGC 2992	200	120	0.015	2.5	85	0.029	2
NGC 3783	4	2.5	0.03	0.07	180	0.0004	1
NGC 4151	8	9	0.01	0.65	55	0.012	2
NGC 6814	25	7.5	0.014	0.08	80	0.001	2
NGC 7469	11	4	0.04	0.06	250	0.0002	1

$M_{out} = 2n_e m_p A V(r) f \quad [M_{sun}\ yr^{-1}]$

$M_{accr} = L_{bol}/\eta c^2 \quad [M_{sun}\ yr^{-1}]$

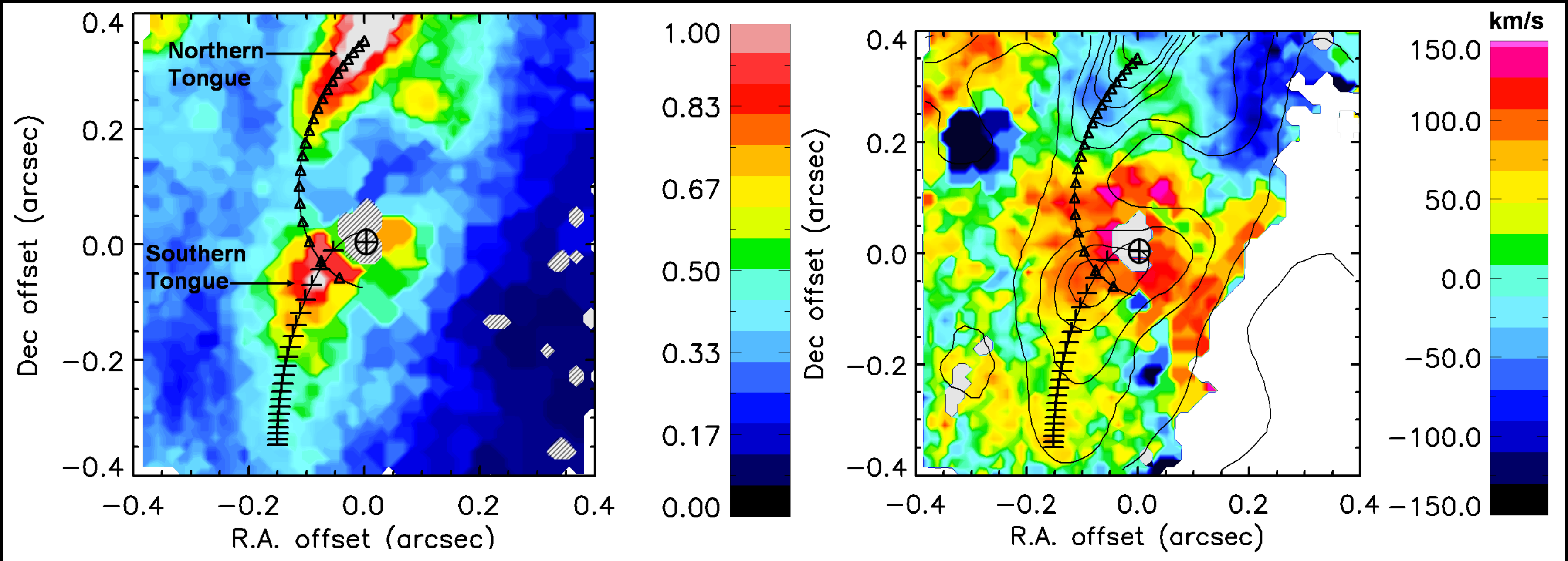
$E_{out} = M_{out}(V(r)^2 + \sigma^2)/2 \quad [erg\ s^{-1}]$

where A is the area of one cone, V(r) in km/s and η=0.1



Müller-Sanchez et al. 2011, 2013

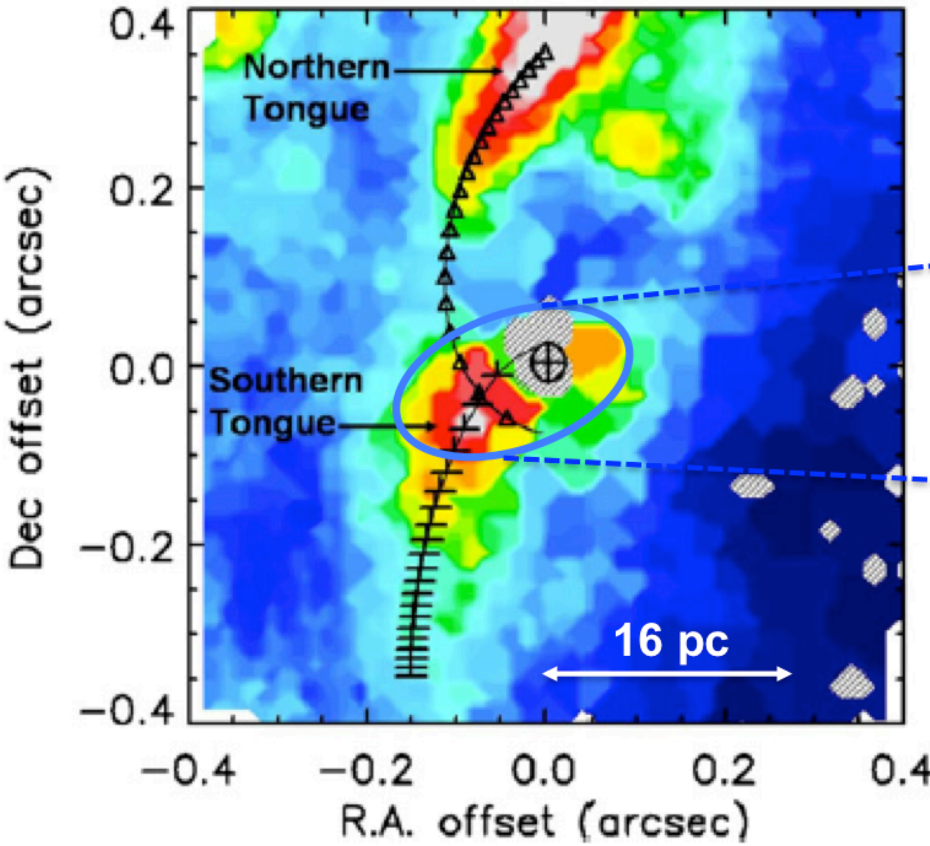
Gas Inflow in NGC 1068



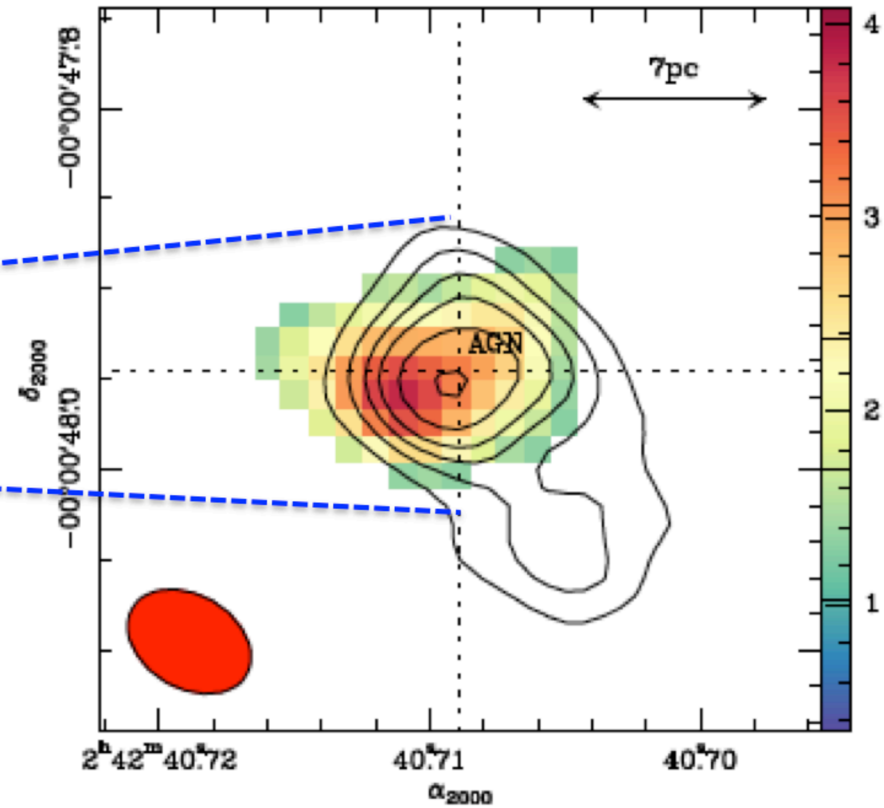
- Filaments of gas extend from the ring at a radius of about 30 pc to the AGN
- The inflow rate to the central few parsecs is of order 15 M_sun yr−1. This is 2–3 orders of magnitude greater than that needed to power the AGN itself
- These models indicate that the infall timescale for a gas mass of 2x10^7 M_sun is about 1.3 Myr.
- This rapid inflow appears to be due to chance combination of circumstances, and is probably unsustainable

Müller-Sanchez et al. 2009

The Torus in NGC 1068



Müller-Sanchez et al. 2009



Garcia-Burillo et al. 2016

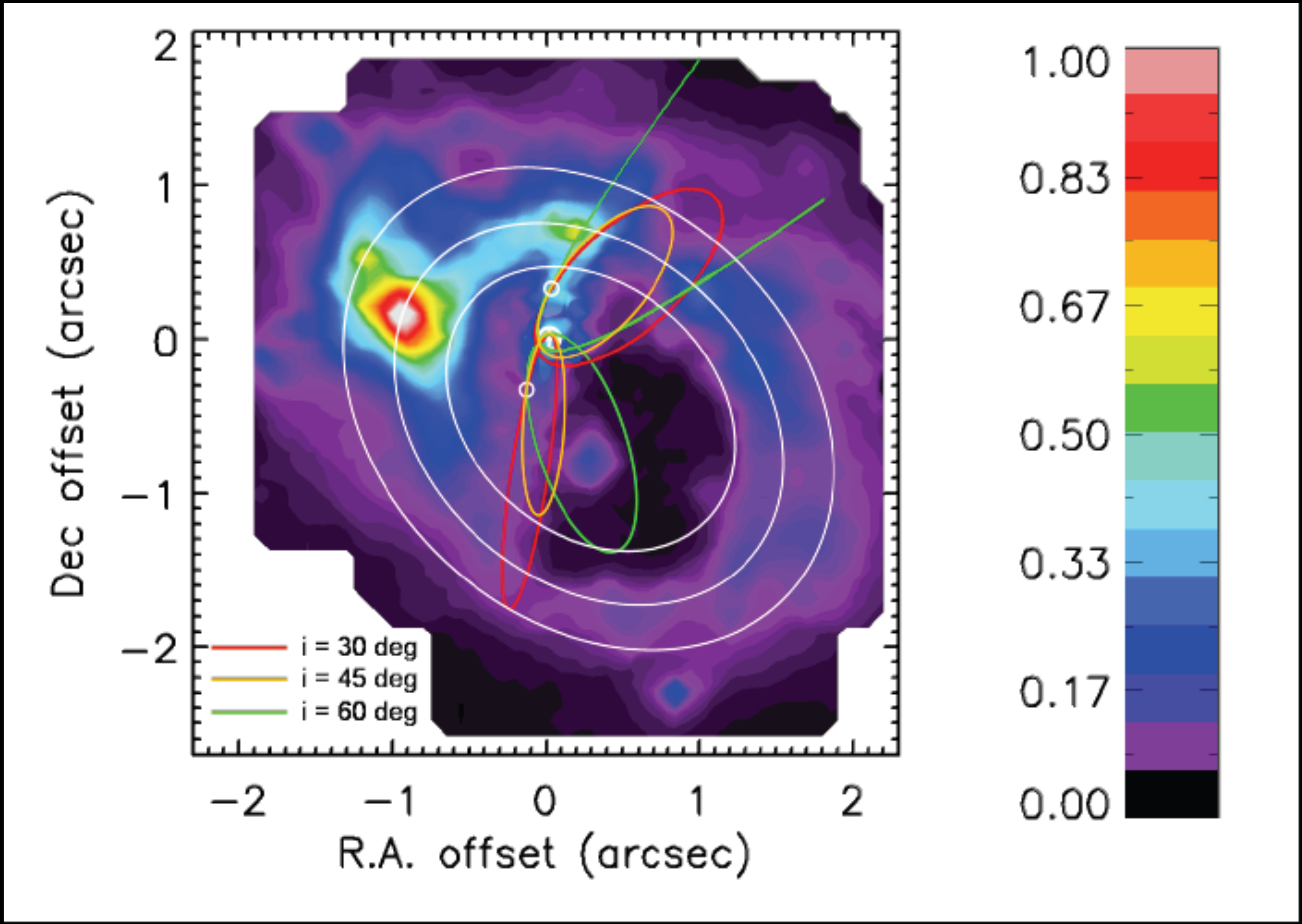
- Molecular gas/dust in front of the nucleus
- Size scale similar to mid-IR observations and models
- Gas is optically thick

Same structure recently detected with ALMA
(size, orientation, position of the peak of emission and kinematics)

Torus models

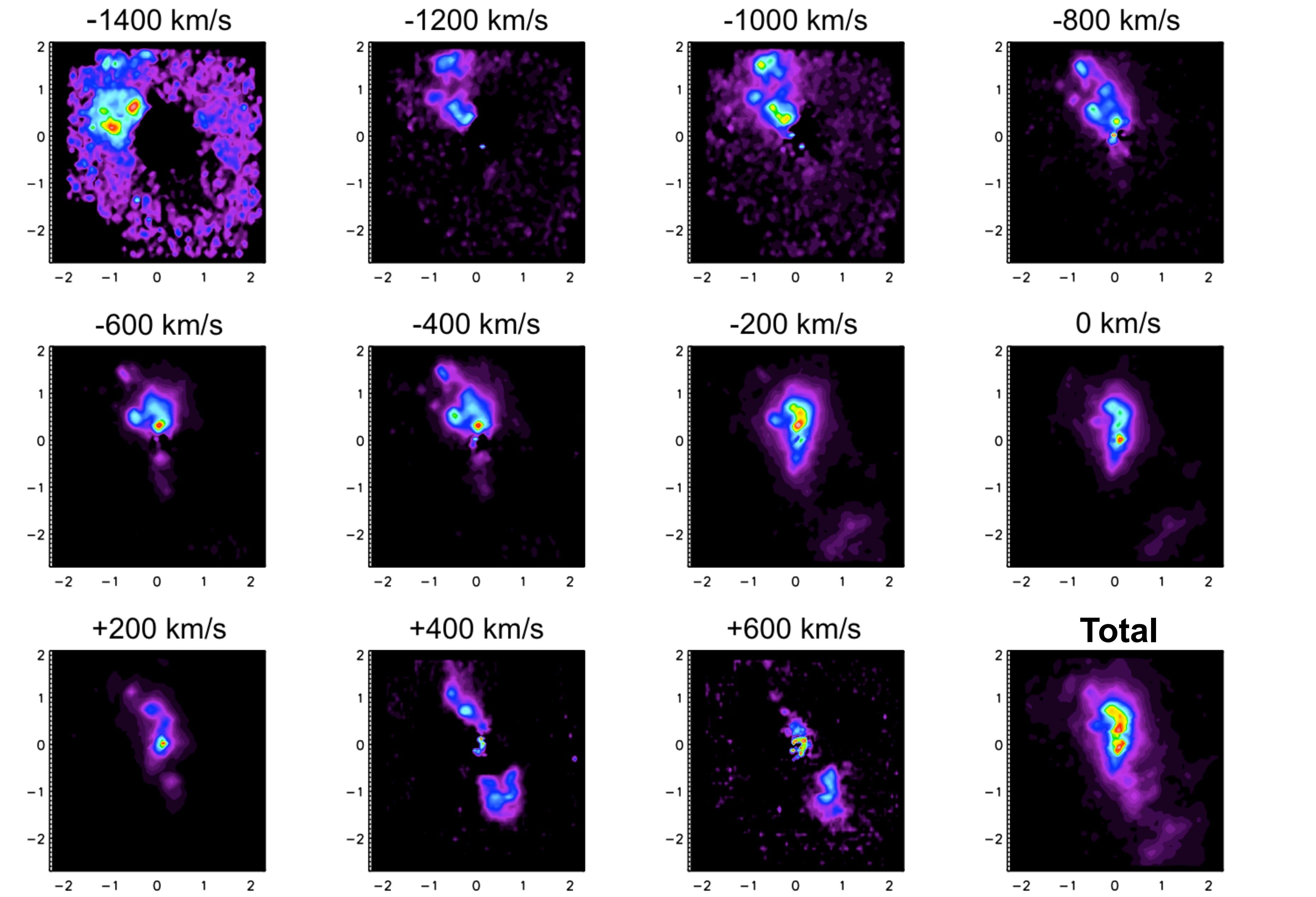
- Fritz et al. (06): 17pc
- Schartmann et al. (05): 5pc radius (70pc outer)
- Hoenig et al. (06): 17pc

The Creation of a Cavity of Molecular Gas



Müller-Sanchez et al. 2009

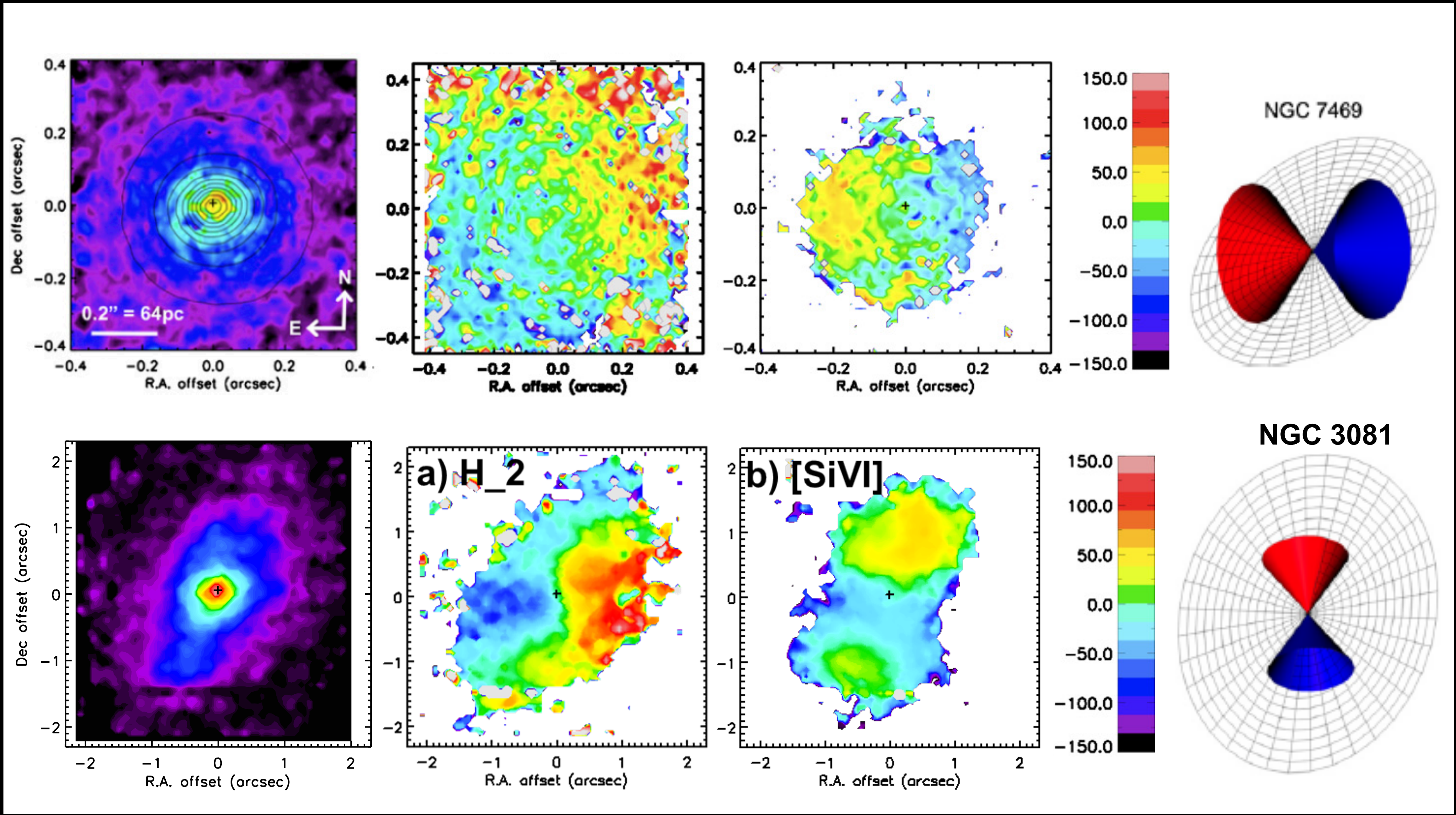
Outflows in the NLR/CLR of NGC 1068



Müller-Sanchez et al. 2011

Interaction of the Outflows with the Local ISM

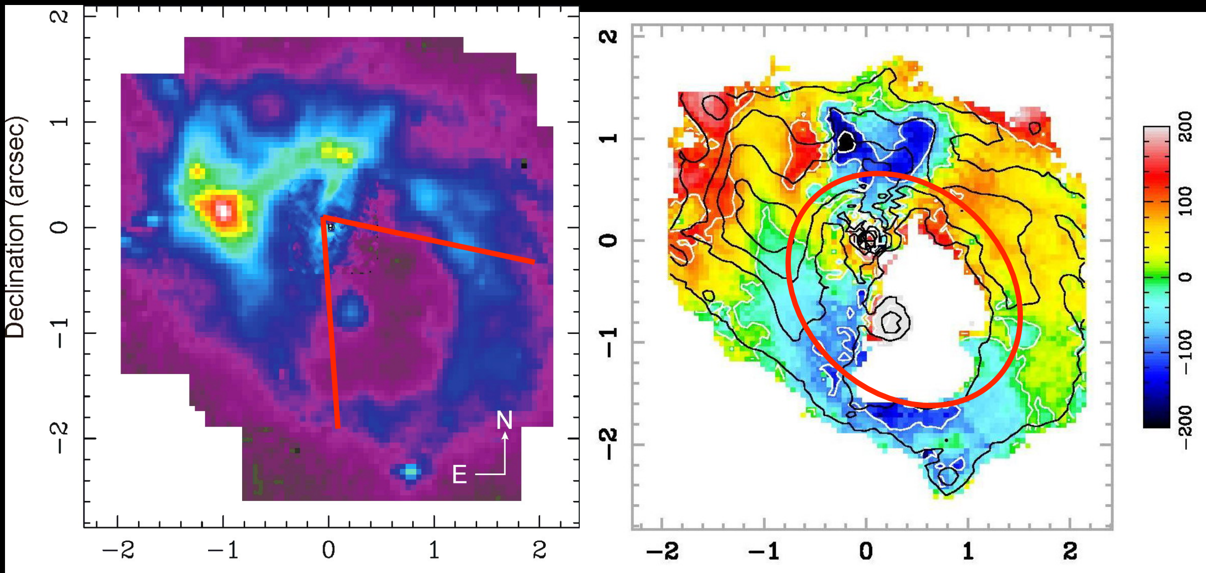
I. No significant Interaction

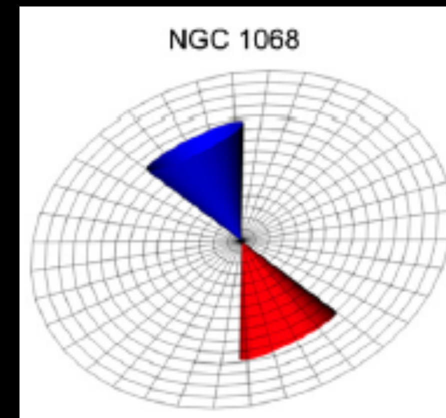


Mueller-Sanchez et al. 2011, 2014

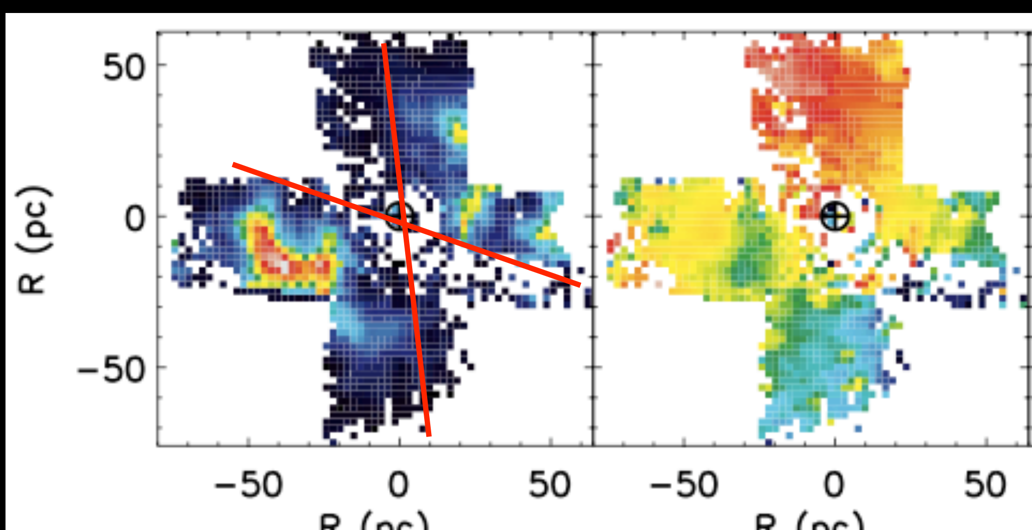
Interaction of the Outflows with the Local ISM

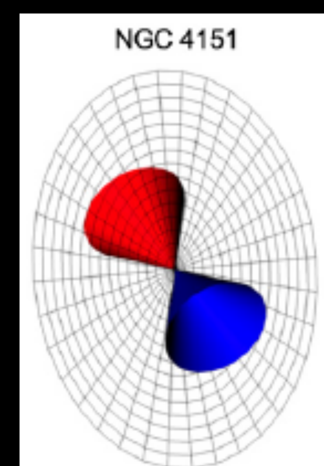
II. Cavities of Molecular Gas





Mueller-Sanchez et al. 2009

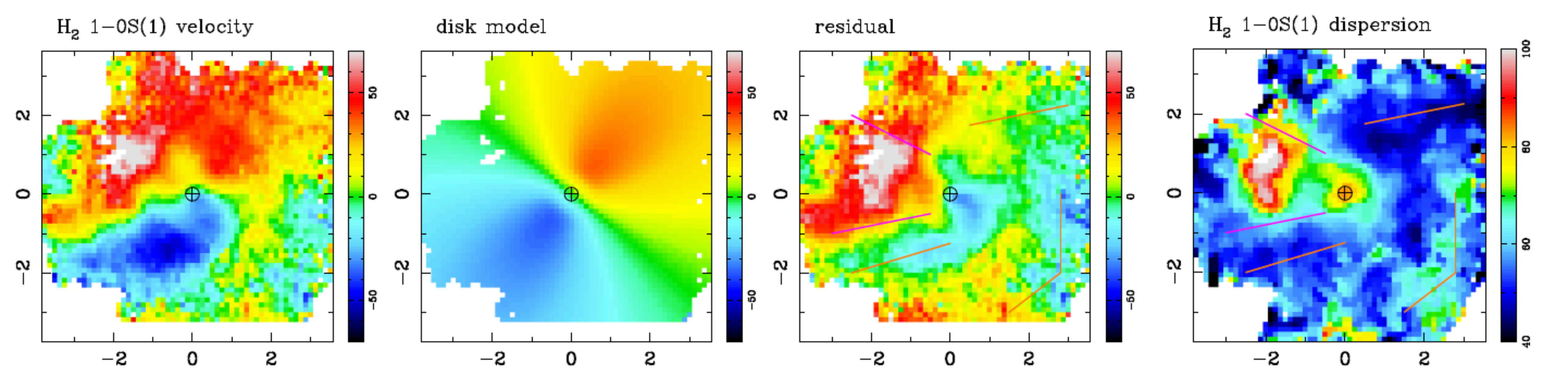




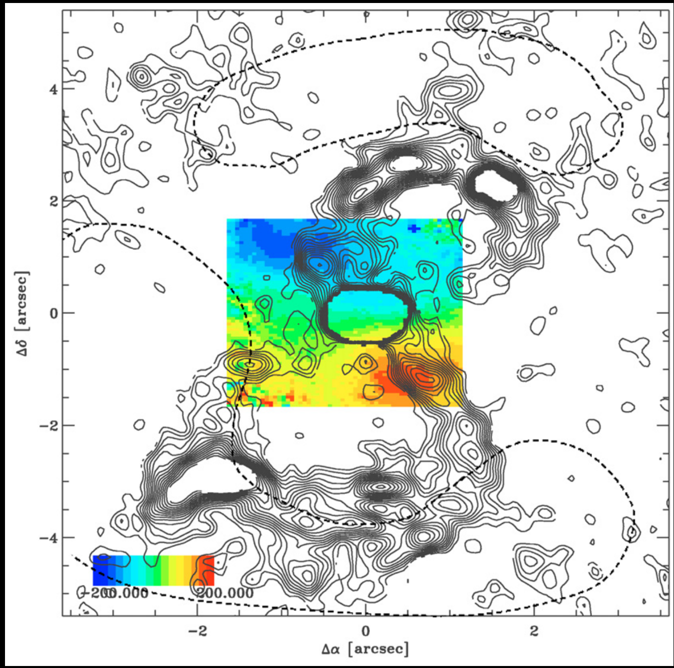
Hicks et al. 2009

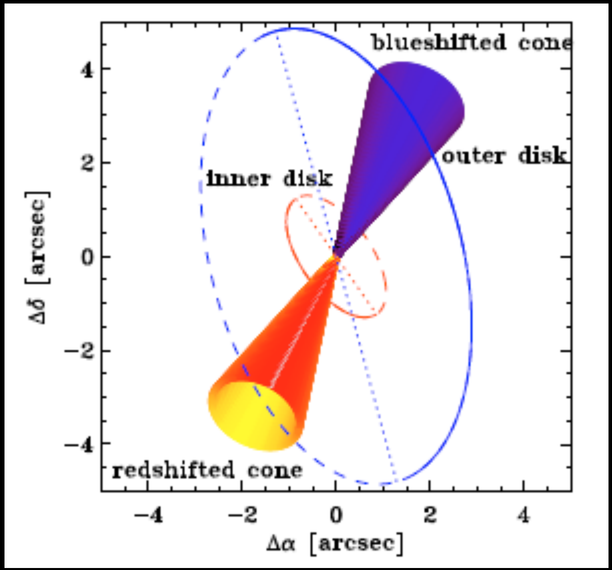
Interaction of the Outflows with the Local ISM

III. Molecular Gas is Entrained in the Outflows



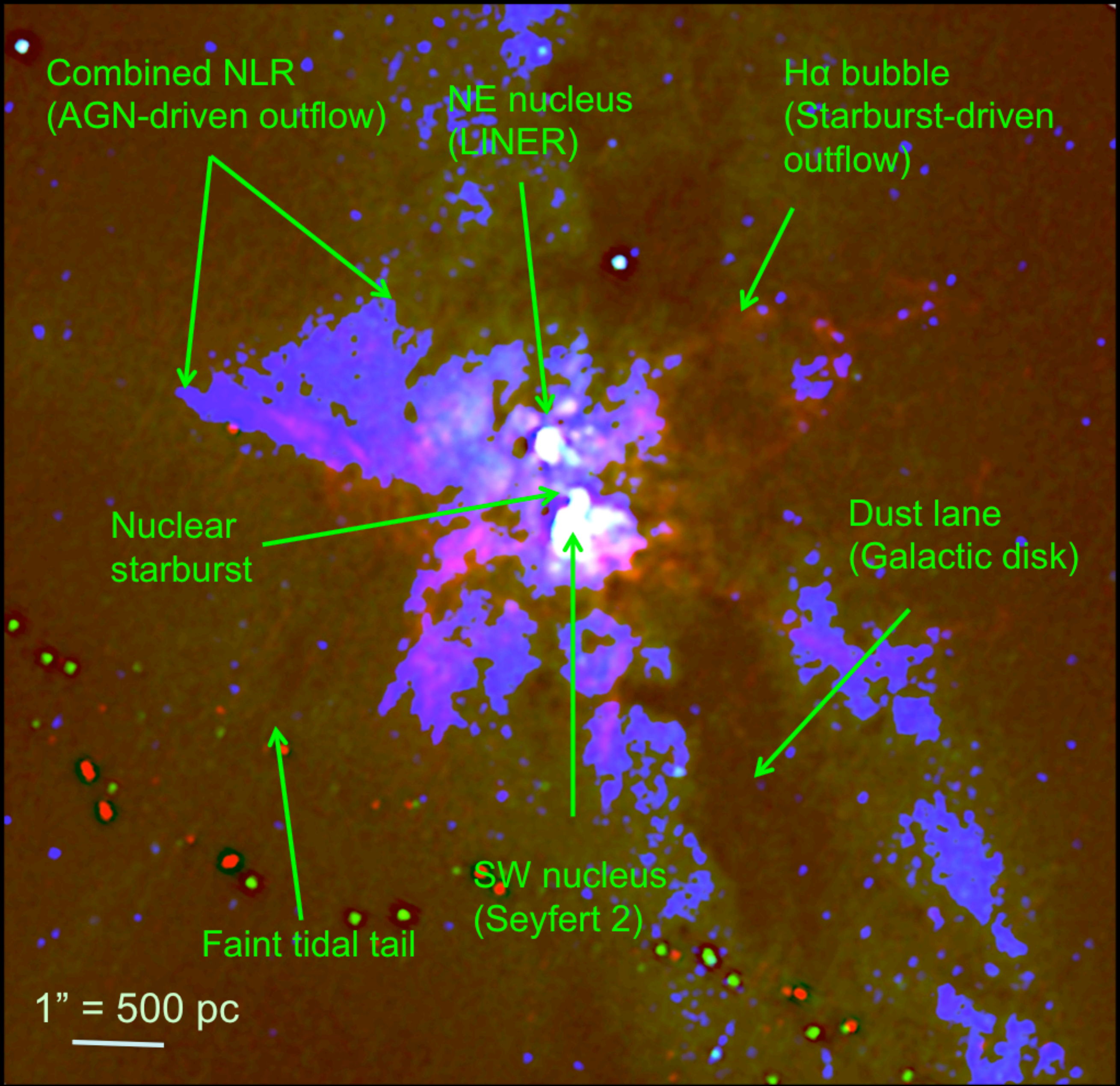
NGC 5643, Davies et al. 2014



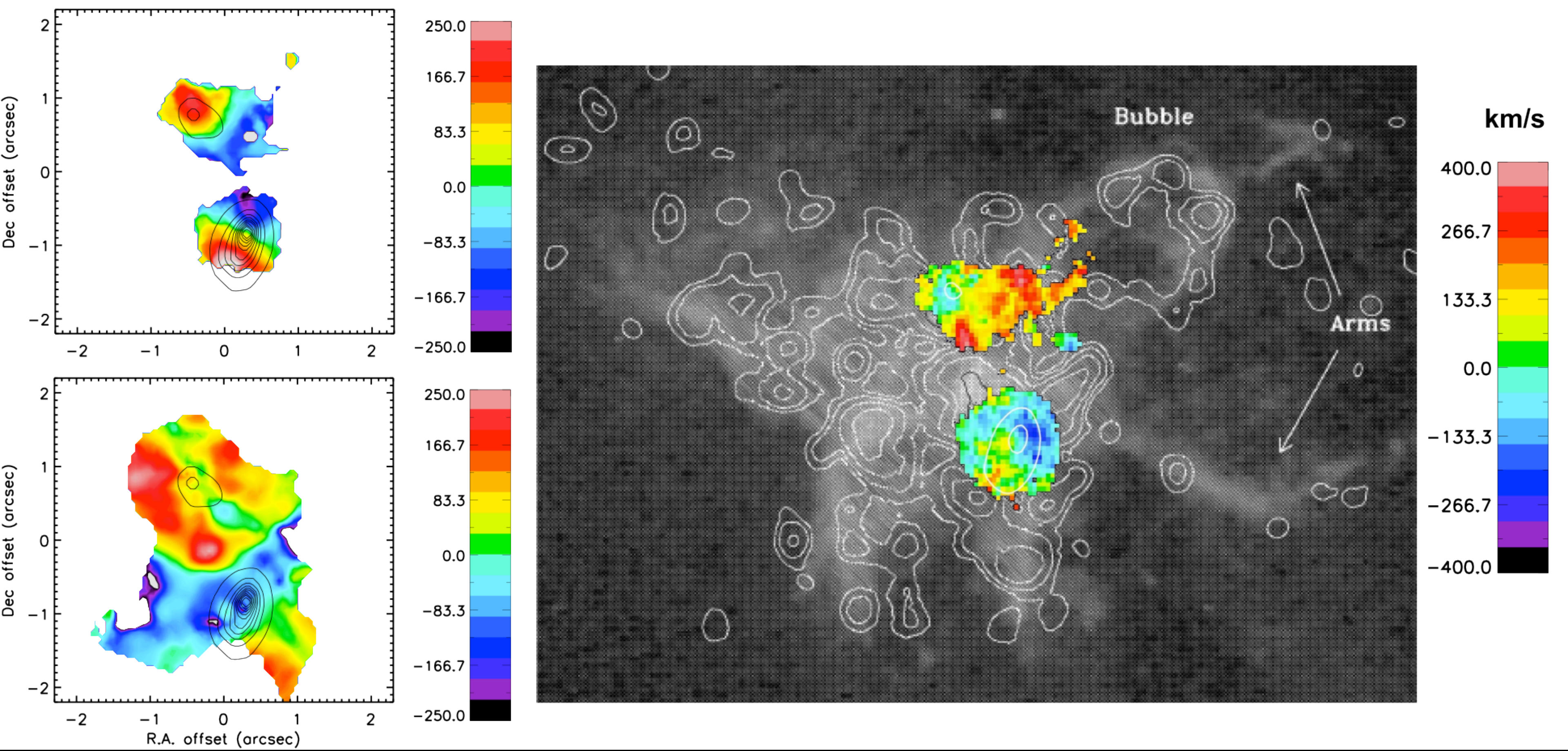


NGC 2992, Friedrich et al. 2010

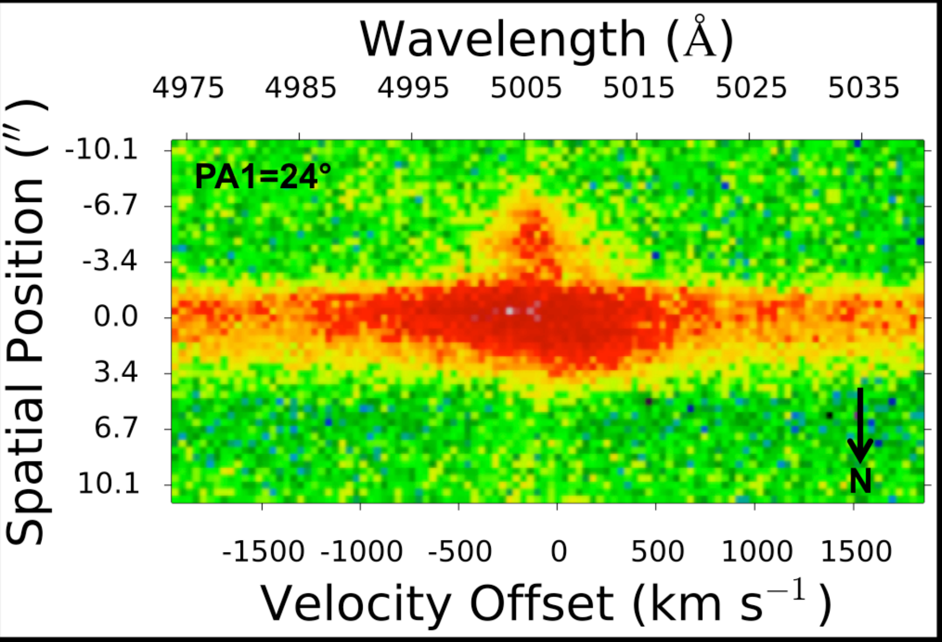
Multiwavelength Observations of Dual AGN (MODA): NGC6240

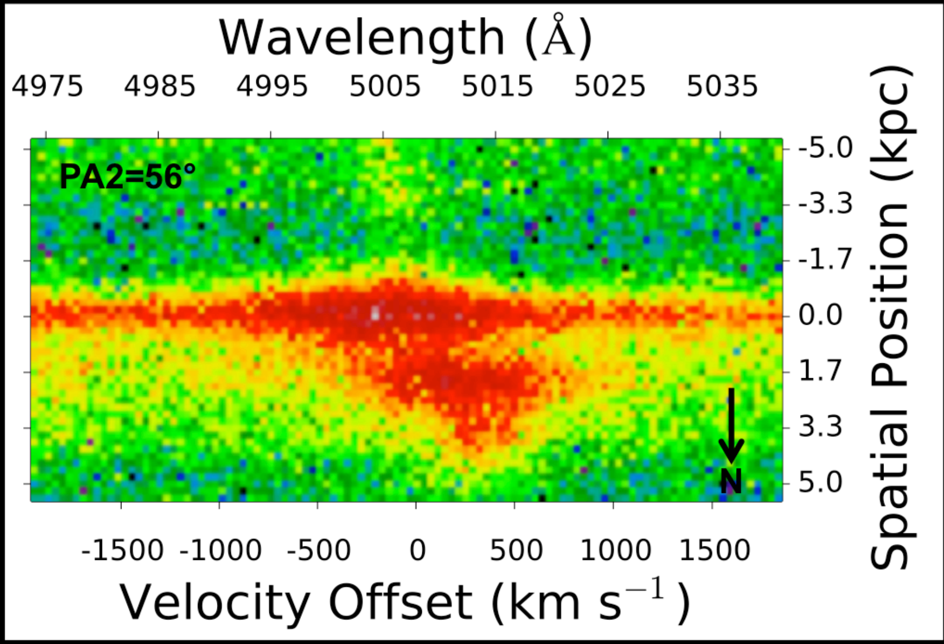


Dissecting the butterfly



MODA results: prototypical merger NGC6240





Müller-Sánchez et al. 2016b, ApJL, in prep.

Conclusions

- Inflows are observed only in molecular gas, outflows in molecular and ionized gas.

- The kinematics of the coronal lines are dominated by radial outflow, therefore special emphasis is given to these lines. Biconical models of radial outflow plus rotation provide a good match to the data.

- The outflow rate is 2–3 orders of magnitude greater than the accretion rate, implying that the outflow is mass loaded by the surrounding ISM.

- In half of the observed AGN, the kinetic power of the outflow is of the order of the power required by two-stage feedback models to be thermally coupled to the ISM and to match the MBH–σ∗ relation. These objects also present strong collimated radio emission, indicative of a link between jet power and outflow power.

- The feeding of the AGNs occurs through nuclear bars and nuclar spirals, suggesting that these structures might be common in the nuclear region of active galaxies.