The Impact of AGN Feedback in the Evolution of Seyfert Galaxies

Francisco Müller Sánchez

University of Colorado, Boulder

- *In collaboration with:* -

Matt Malkan (UCLA), Erin Hicks (UA), Ric Davies, Reinhard Genzel (MPE, Germany), Moshe Elitzur (UoK)

Science Objectives

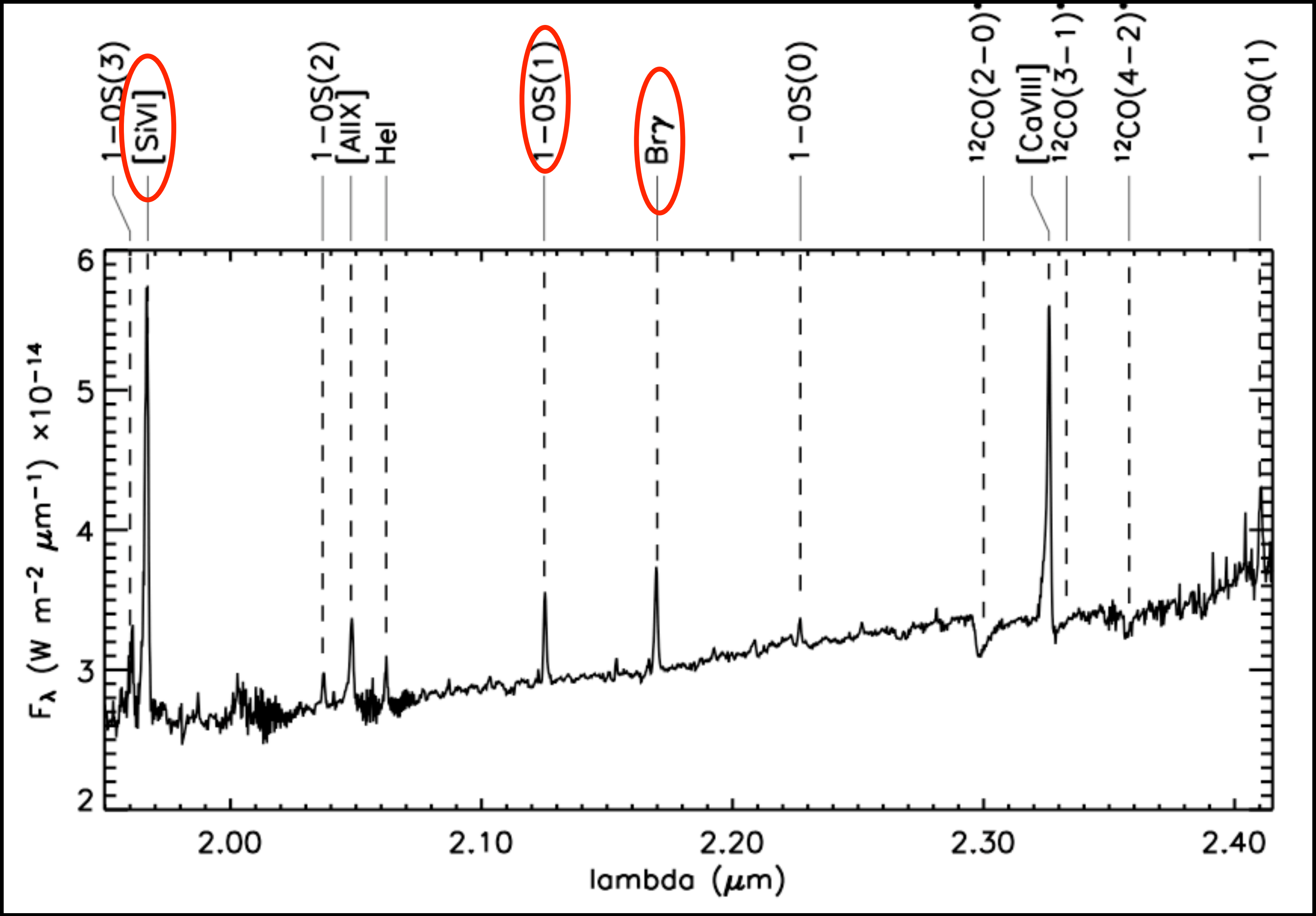
Using adaptive optics and integral-field spectroscopy on Keck and the VLT to reach scales down to 0.08” in the K- band, we can for the first time directly resolve the NLR/CLR and the molecular gas in the centers of nearby active galaxies and investigate:

- Which inflow mechanisms are important for bringing gas to the environs of the SMBH?

- Do AGN outflows actually deliver enough energy to their environments to alter the evolution of the host galaxy in a meaningful way?

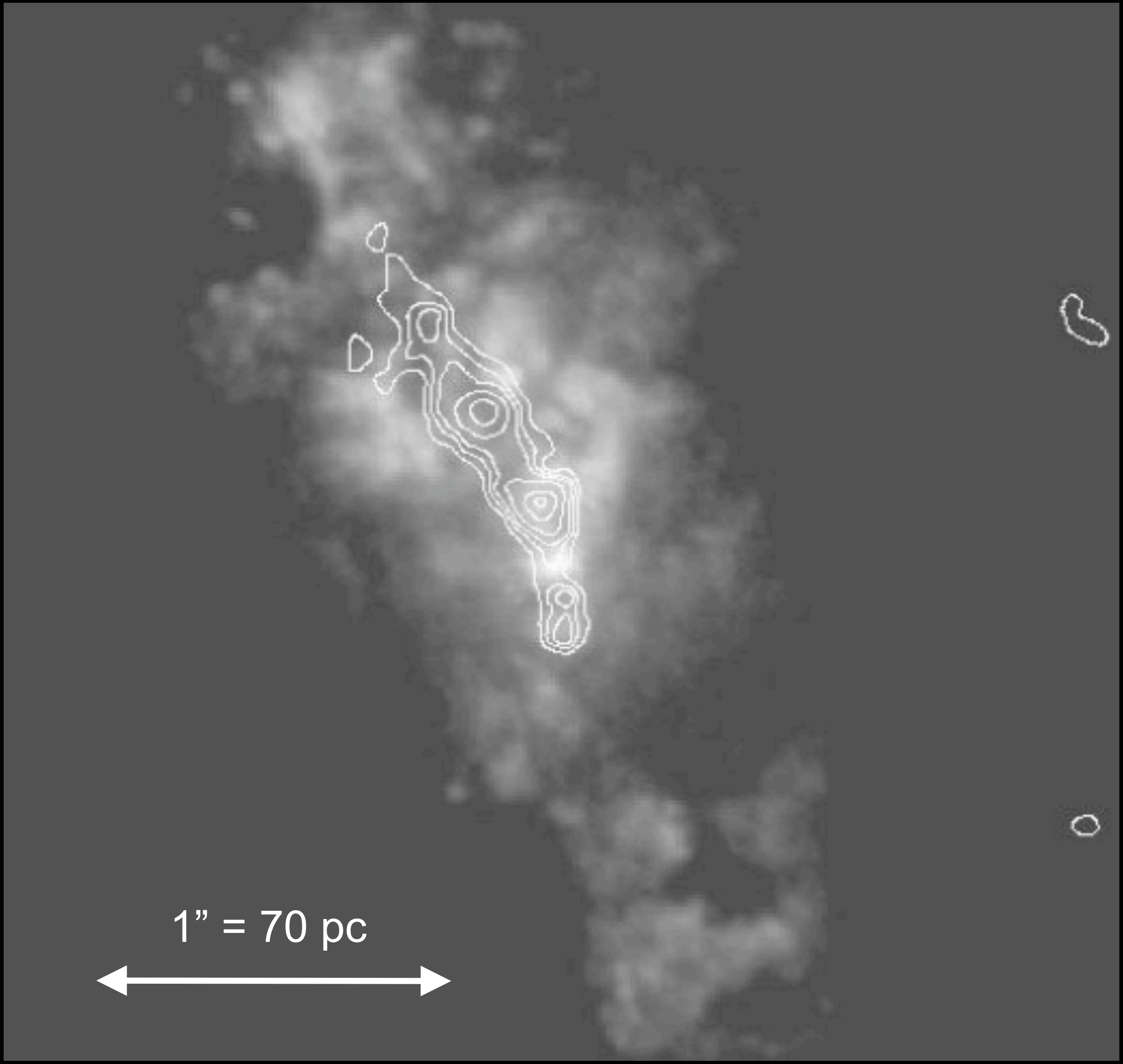
Object	Type[a]	z[a]	Instrument	Band	T_{int} (min)	Date	FWHM[b] ($''$)	Brγ[c] 2.16μm	H_2[c] 2.12μm	[Si VI][c] 1.96μm
Circinus	Sy2	0.00045	SINFONI	K	80	Jul 2004	0.22 (4.4)	D	D	D
Mrk 9	Sy1	0.00632	OSIRIS	K	40	Nov 2013				
Mrk 79	Sy1	0.02208	OSIRIS	K	40	Mar 2013				
Mrk 573	Sy2	0.01726	OSIRIS	K	60	Mar 2013				
Mrk 766	Sy1	0.01330	OSIRIS	K	40	Jul 2012				
Mrk 993	Sy2	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	Sy2	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	40	Nov 2013				
NGC 1320	Sy2	0.00993	OSIRIS	K	40	Nov 2013				
NGC 1386	Sy2	0.00765	SINFONI	K	60	Sep 2011				
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 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				
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 5506	Sy2	0.00618	OSIRIS	K	80	Mar 2011				
NGC 5728	Sy2	0.01003	OSIRIS	K	40	Mar 2013				
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	SINFONI	K	60	Sep 2006	0.11 (35)	D	D	D
NGC 7582	Sy1	0.00525	SINFONI	K	60	Sep 2011				
NGC 7682	Sy2	0.01712	OSIRIS	K	40	Nov 2013				

Integrated Spectrum of Circinus



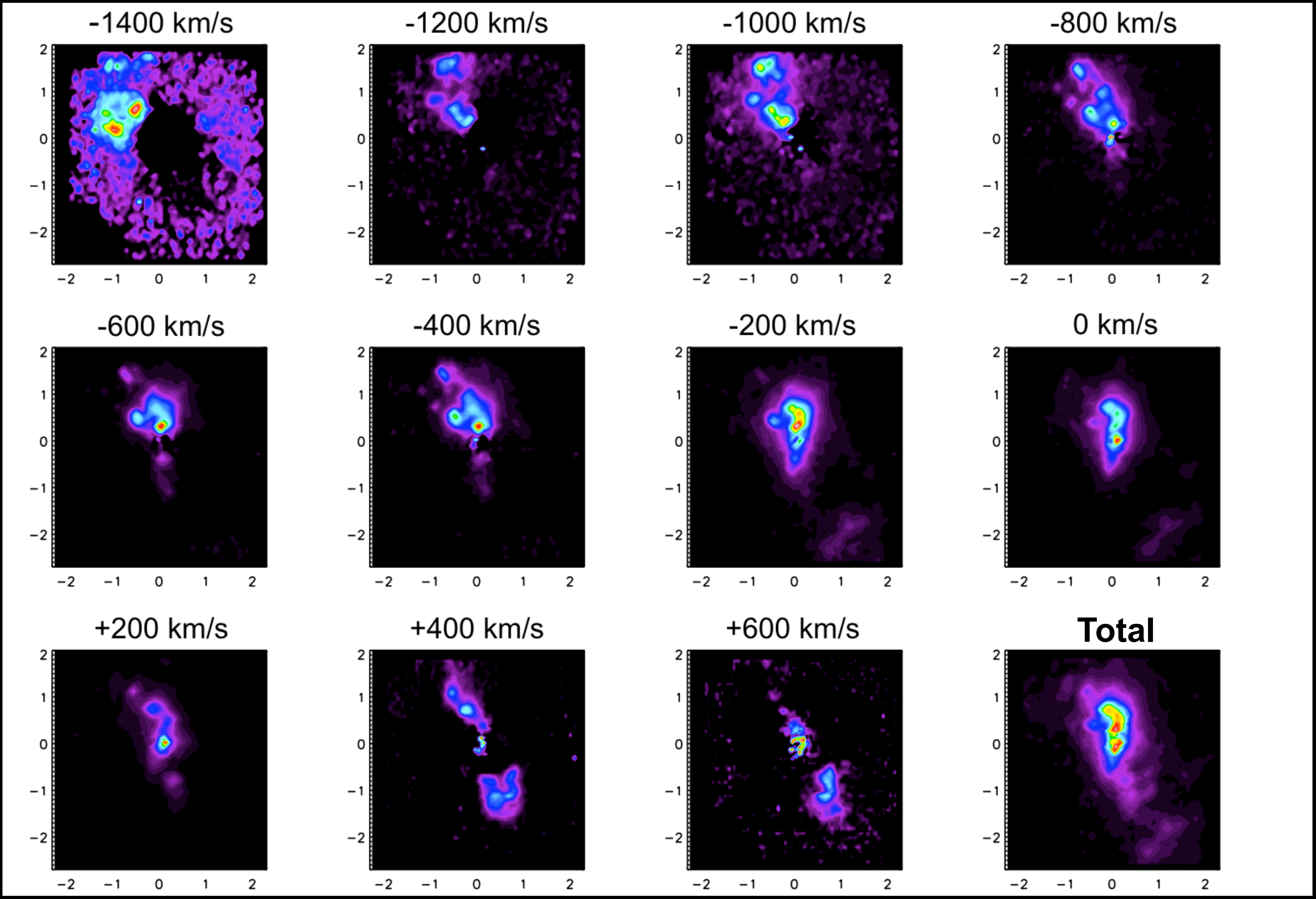
Müller-Sanchez et al. 2006

The NLR and CLR in NGC 1068



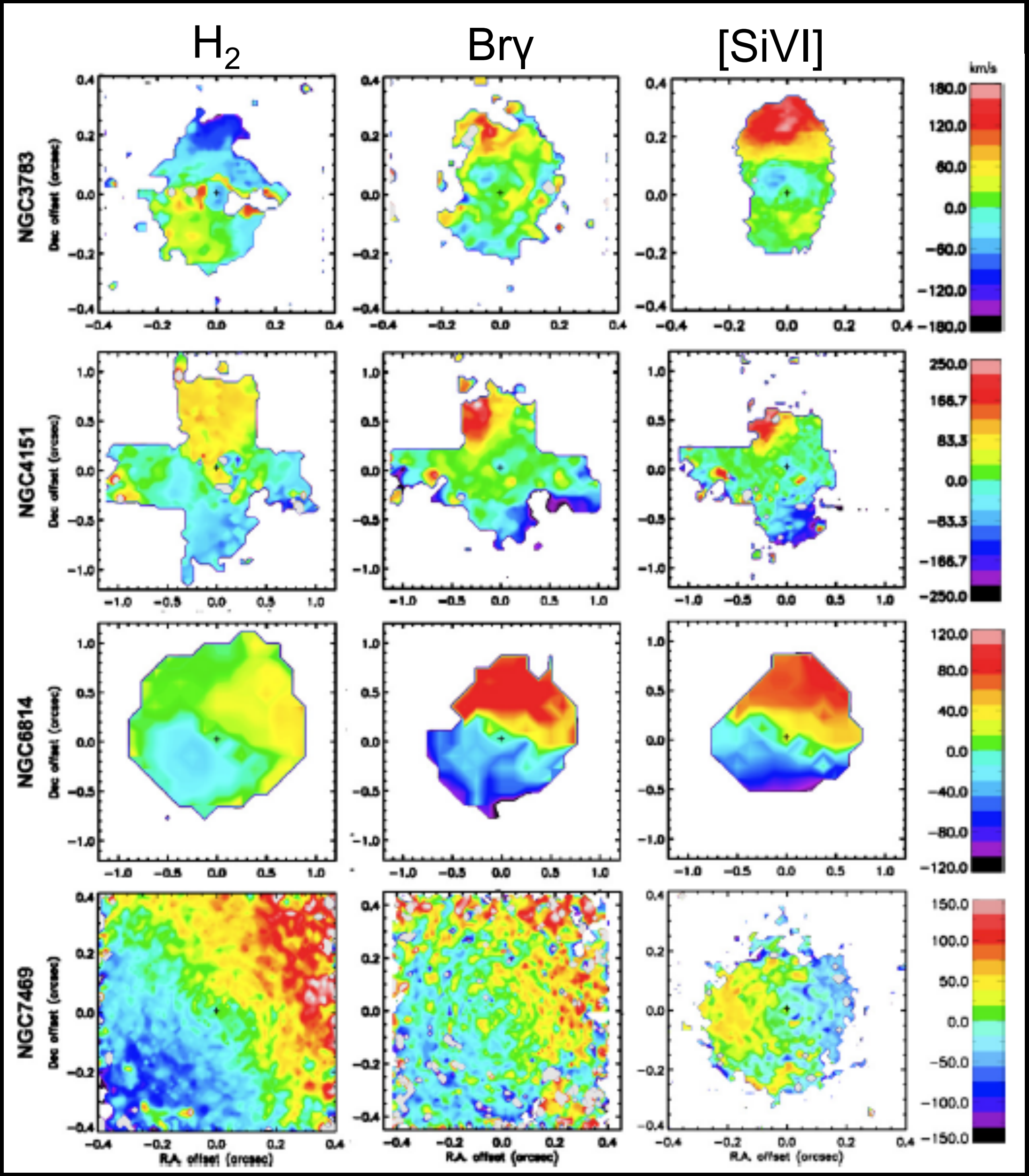
Allignment between radio jet and ionized gas, Gallimore et al. 1996

Outflows in the NLR/CLR of NGC 1068



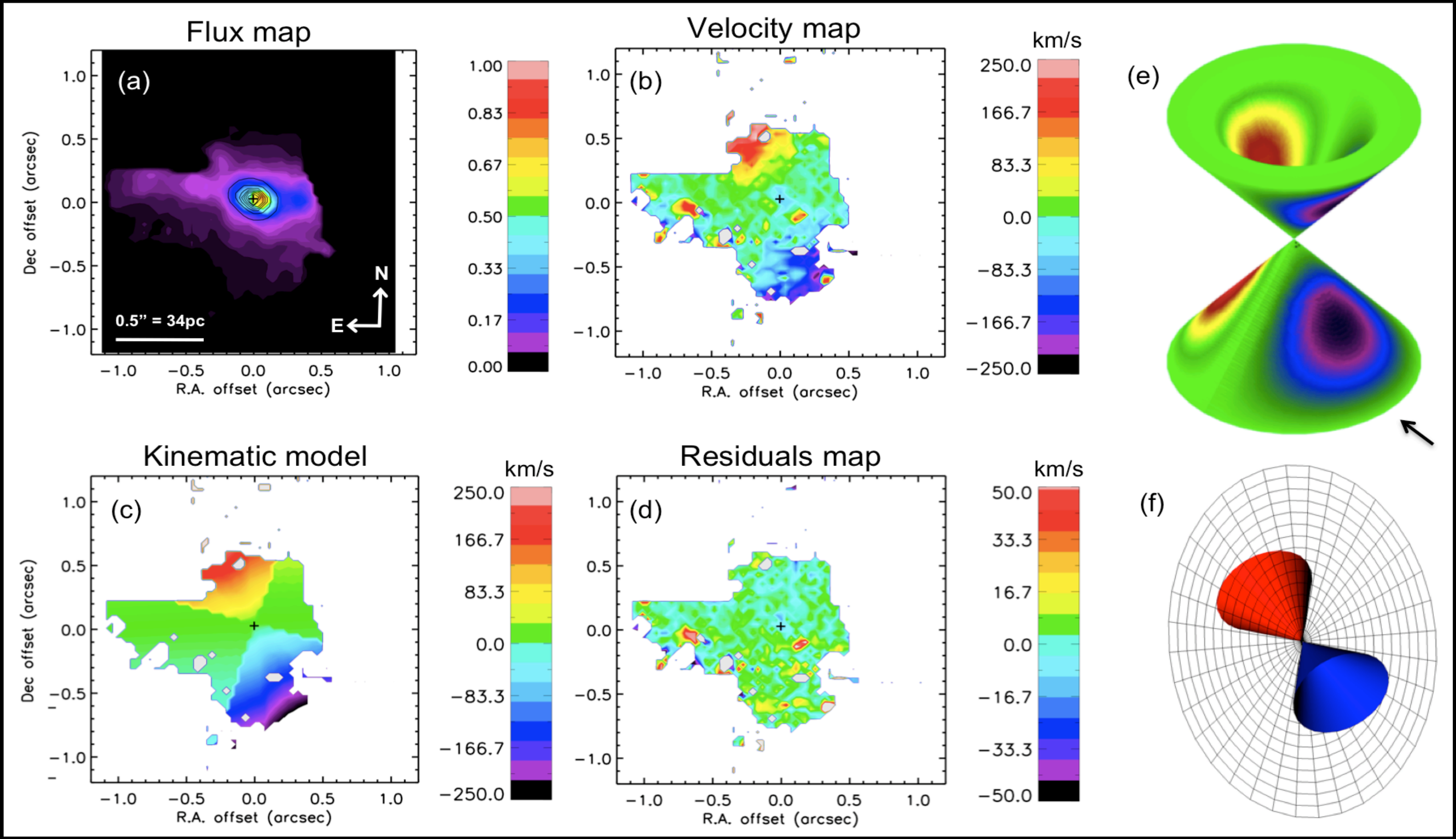
Müller-Sanchez et al. 2011

Evidence for Outflows of Ionized Gas



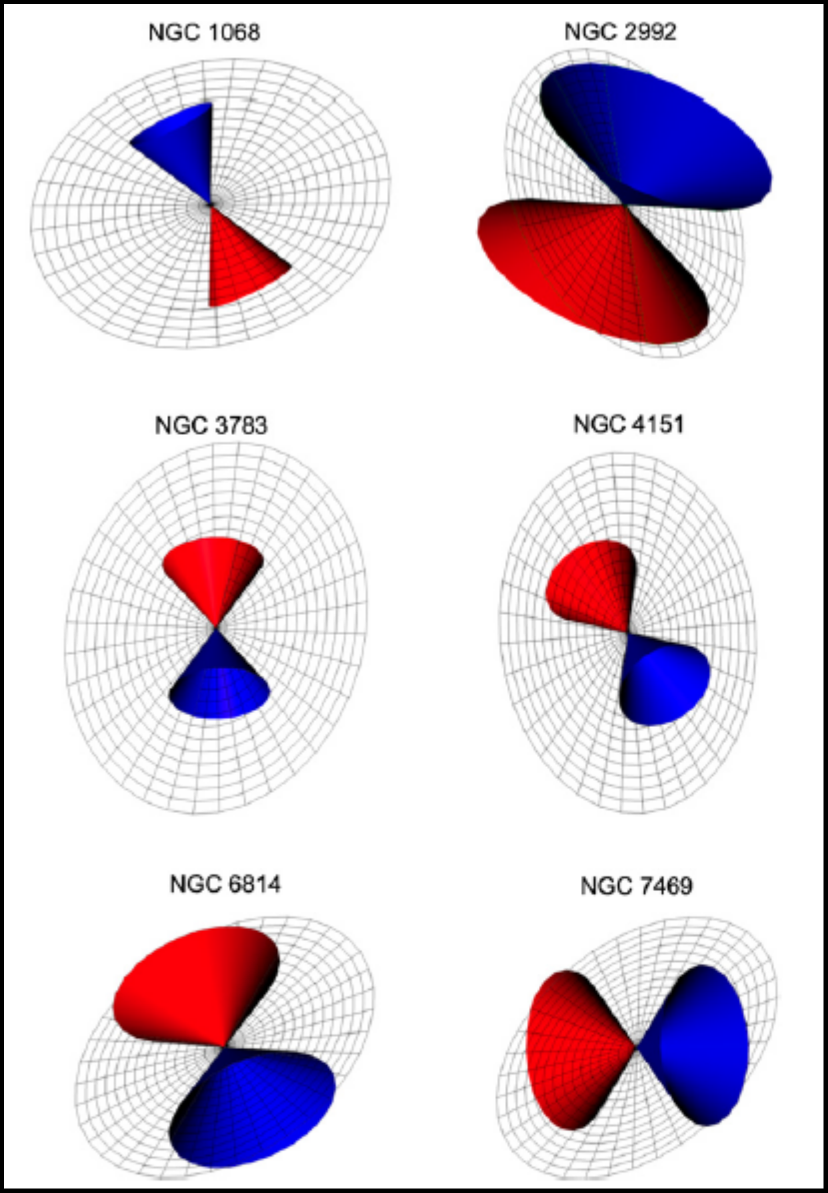
Müller-Sanchez et al. 2011

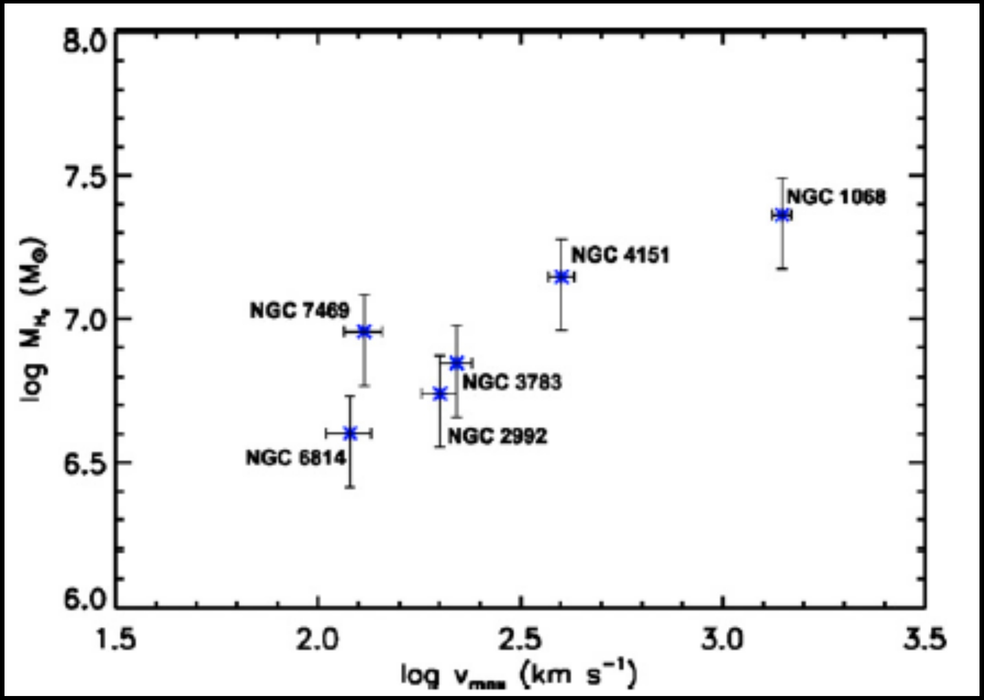
Kinematic Modeling



Müller-Sanchez et al. 2011

Implications for the Unified Model of AGN





- The presence of inner disks of highly ionized gas implies a clumpy torus
- While Seyfert 2s are viewed nearly edge-on, intermediate-type Seyferts are viewed at intermediate angles, consistent with unified schemes.
- The accumulation of gas around the AGN increases the collimation and velocity

Mass Outflow Rates and Kinetic Energy

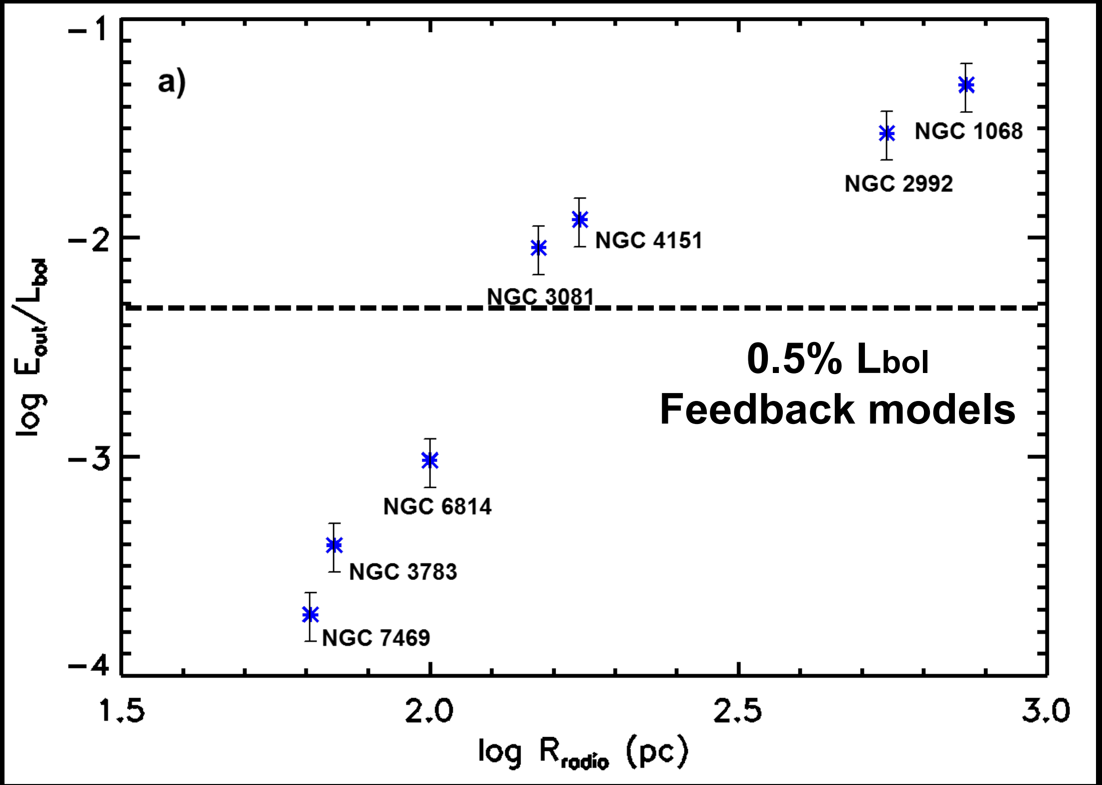
Galaxy	A[a] (10^4 pc^2)	$\dot{M}_{out}$ ($M_\odot$ yr^{-1})	$\dot{M}_{acc}$ ($M_\odot$ yr^{-1})	$\dot{E}_{out}$ (10^{42} erg s^{-1})	L_{bol} (10^{42} erg s^{-1})	$\dot{E}_{out}/L_{bol}$	Ref.[b]
NGC 1068	2	9	0.015	5	88	0.05	1
NGC 2992	200	120	0.015	2.5	85	0.029	2
NGC 3783	4	2.5	0.03	0.07	180	0.0004	1
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

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

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

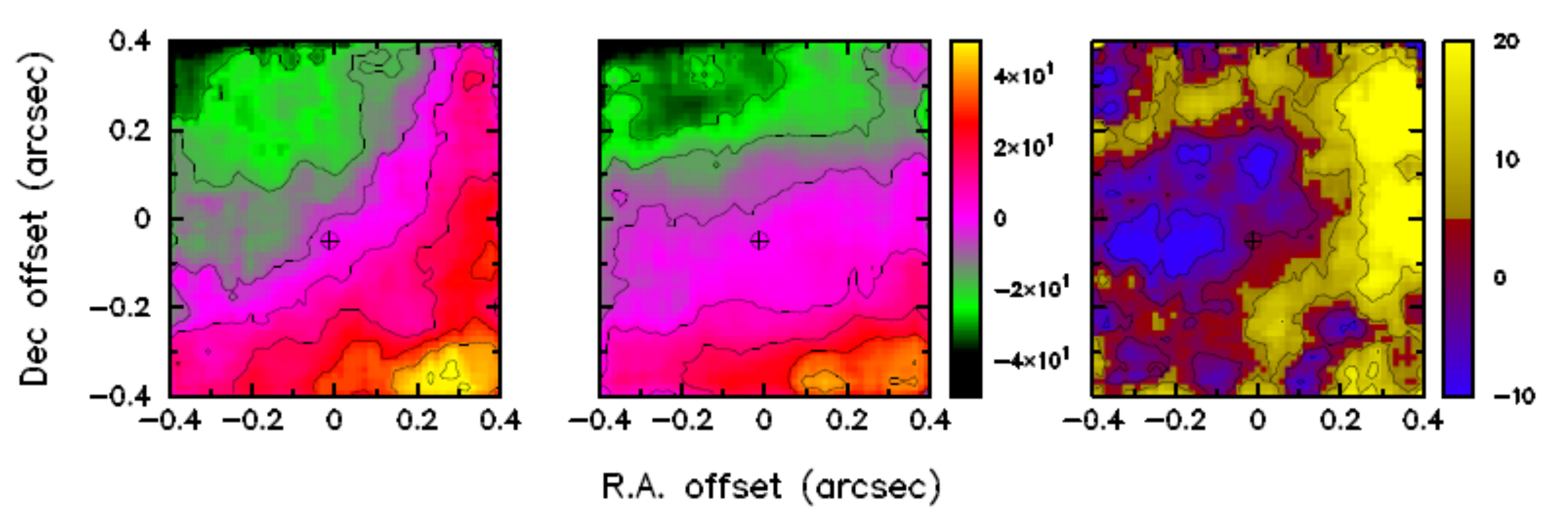
$E_{out} = M_{out}(V(r)^2 + \sigma^2)/2 \quad [erg\ s^{-1}]$

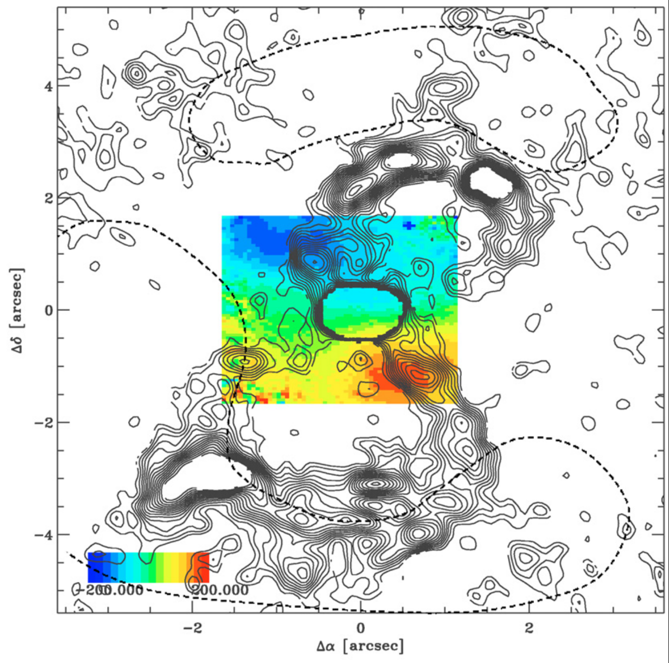
where A is the area of one cone, V(r) in km/s and η=0.1



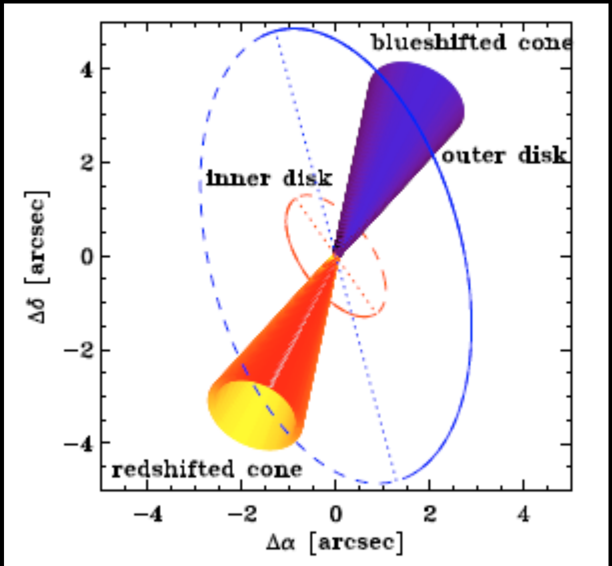
Müller-Sanchez et al. 2011, 2013

Outflows of Molecular Gas



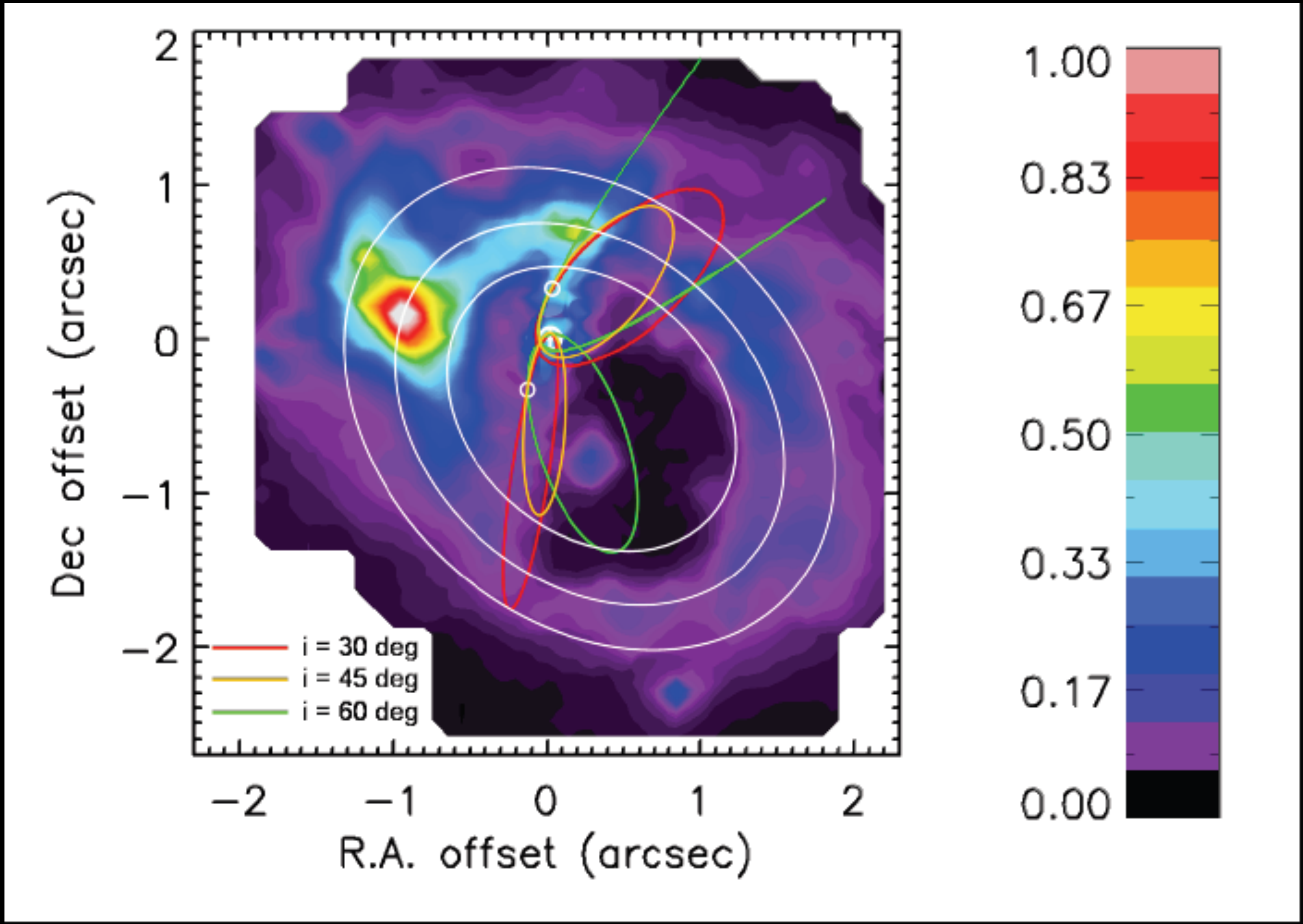


Circinus, Mueller-Sanchez et al. 2006



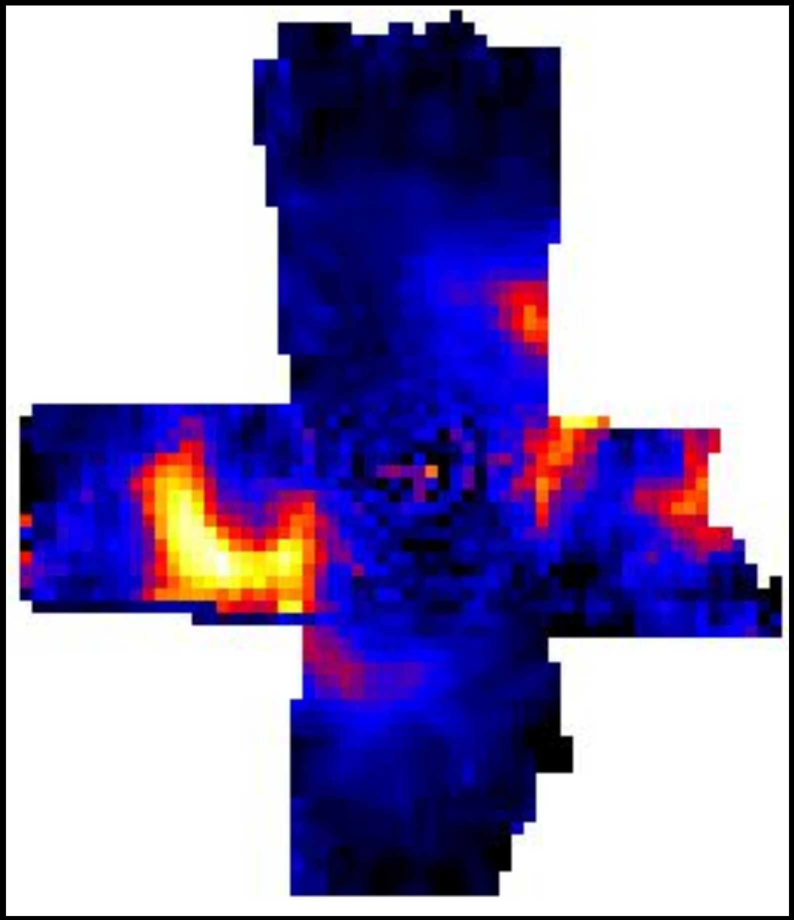
NGC 2992, Friedrich et al. 2010

The Creation of a Cavity of Molecular Gas

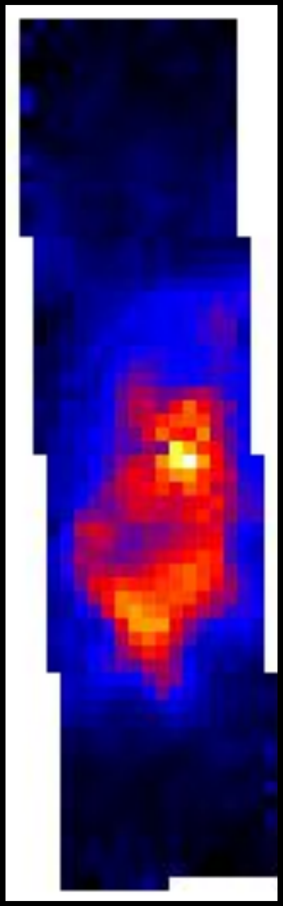


Müller-Sanchez et al. 2009

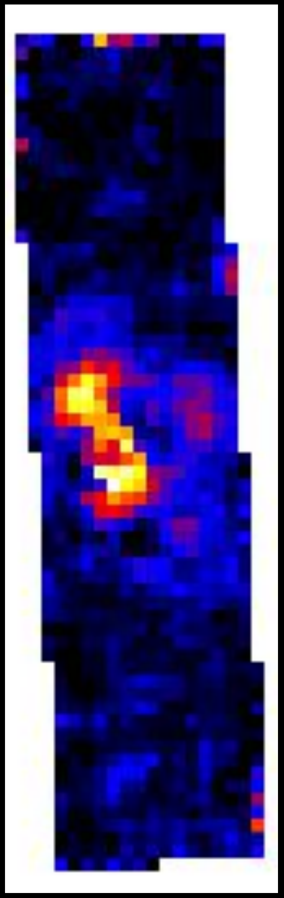
Expanding Clouds of Molecular Gas



NGC 4151



Mrk 1066



NGC 591

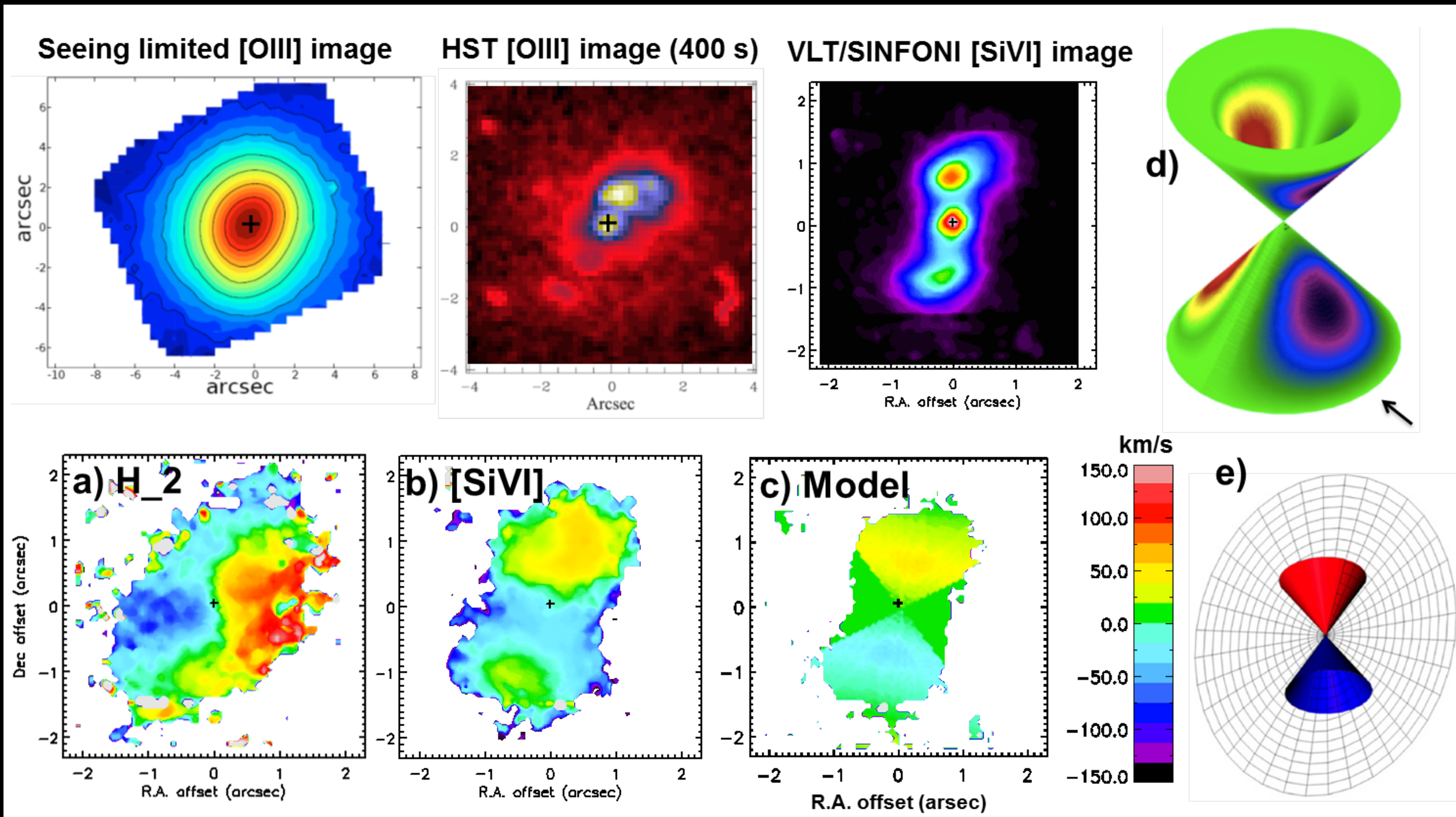
AGN feedback has little impact on star-forming galaxy disk.

- The AGN empties the gas only from the nuclear region, leaving the galaxy disk intact.

- The nuclear region is replenished rapidly due to instability-driven gas inflows, ultimately triggering additional AGN and outflows.

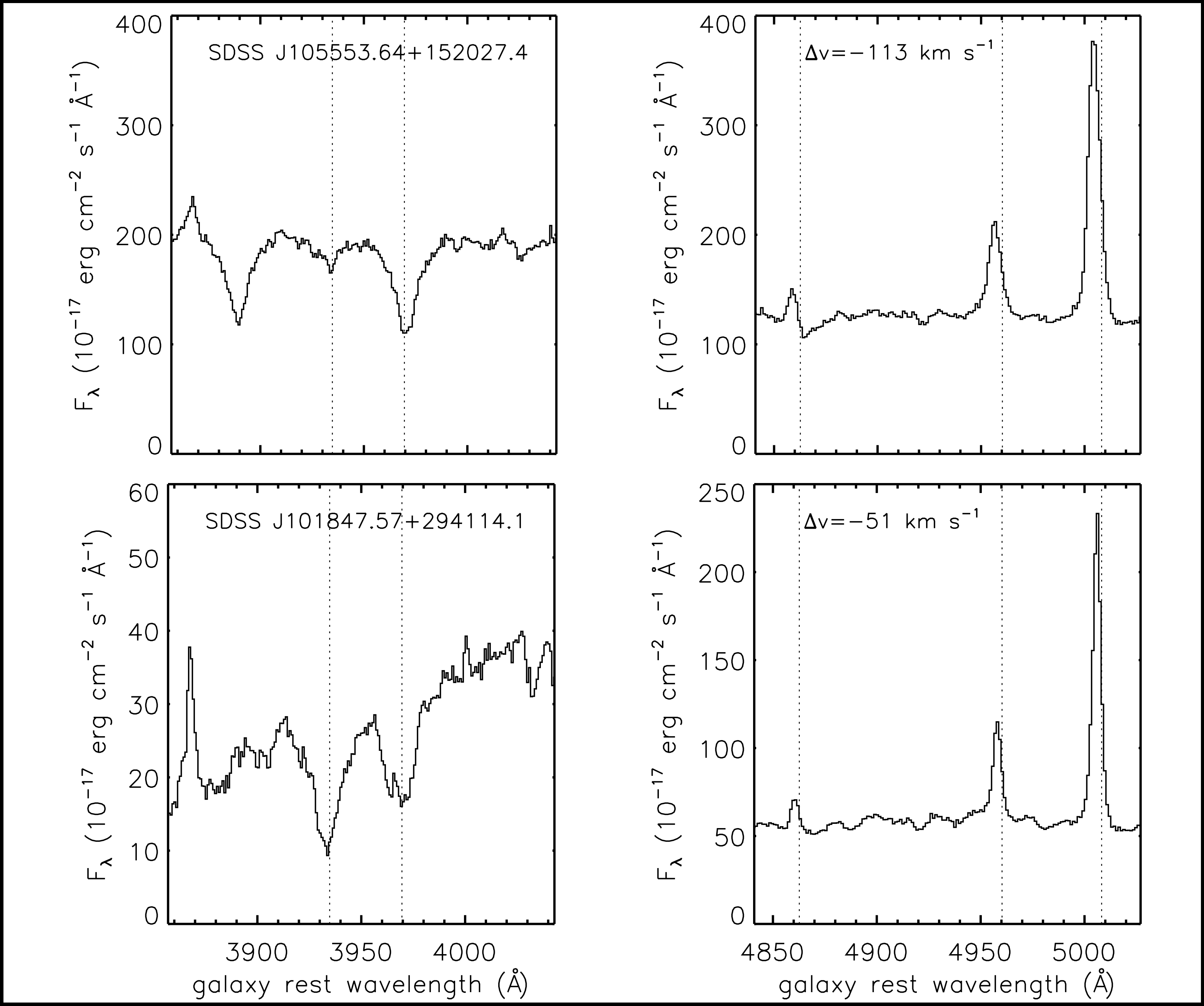
- AGN-driven outflows are roughly balanced by gas inflows. Since the SFR of the galaxy is dominated by the disk, not the nucleus, the total instantaneous SFR is practically unaffected by AGN feedback.

The Bipolar Outflow and the Nuclear Molecular Bar in NGC 3081

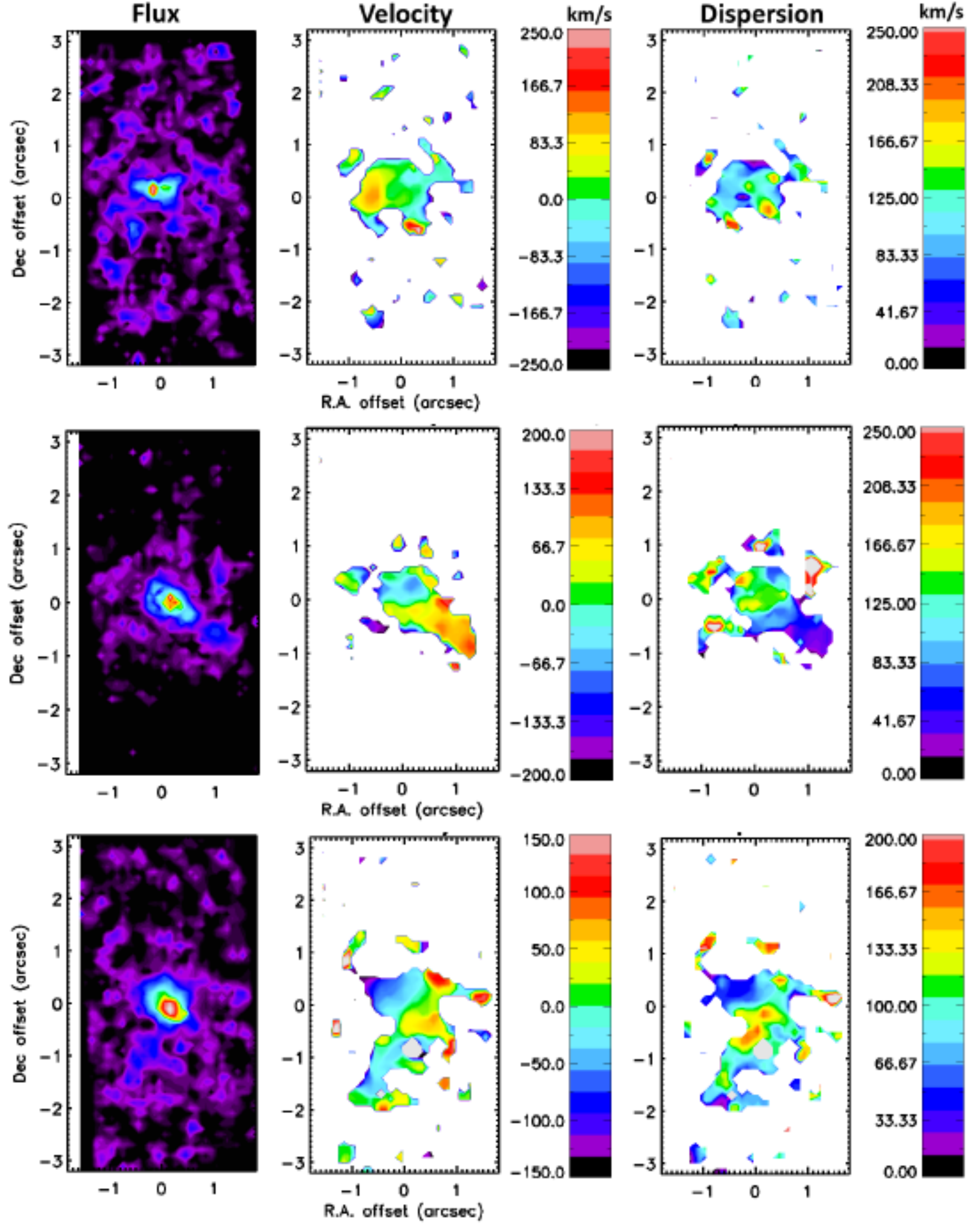


Müller-Sanchez et al. 2014, ApJ, submitted

Offset-AGN



SDSS J105553.64+152027.4
Δv=−113 km s⁻¹
SDSS J101847.57+294114.1
Δv=−51 km s⁻¹
F_λ (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
galaxy rest wavelength (Å)
3900
3950
4000
4850
4900
4950
5000



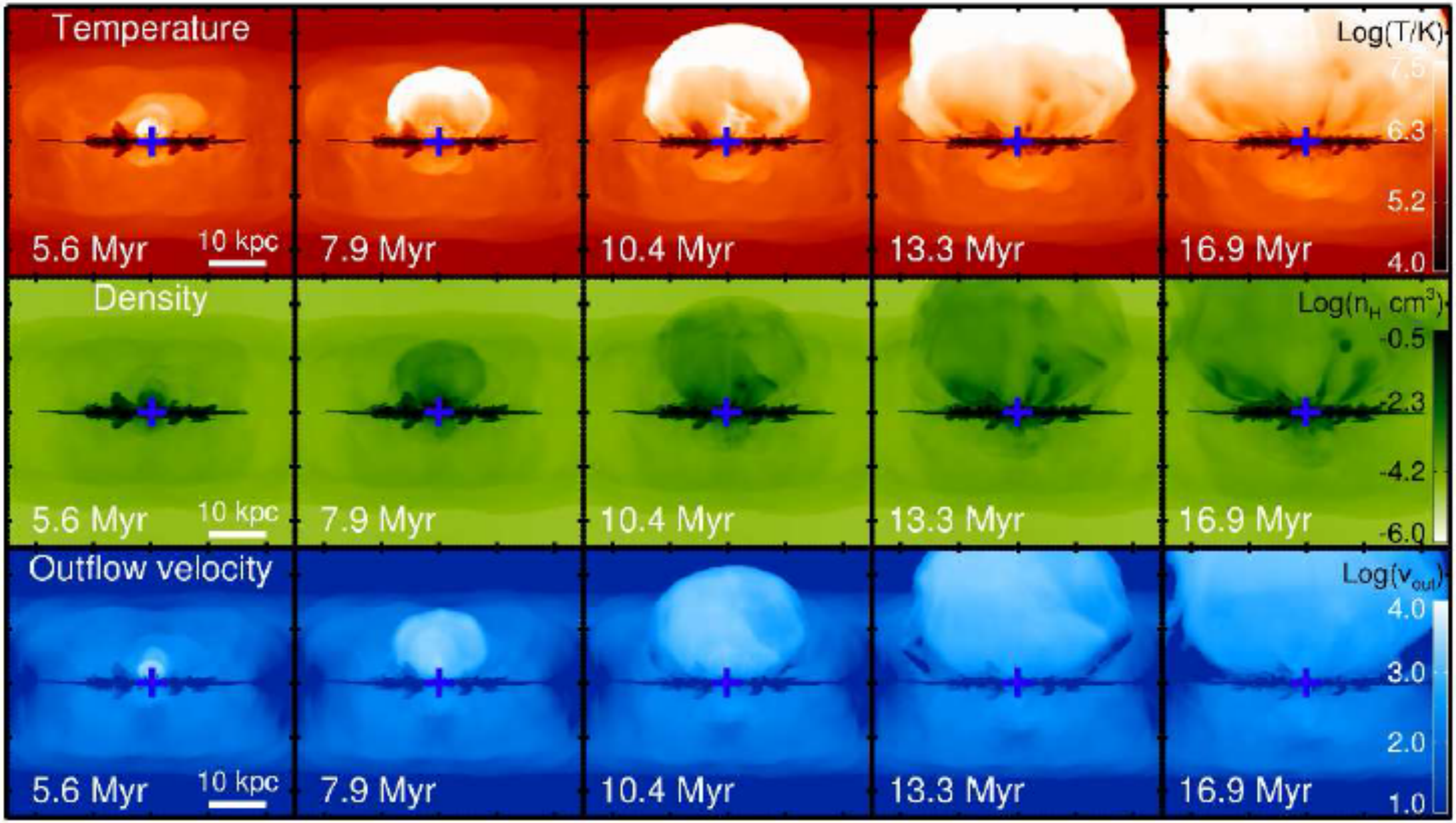
Flux
Velocity
Dispersion
km/s
km/s
Dec offset (arcsec)
R.A. offset (arcsec)
250.0
166.7
83.3
0.0
−83.3
−166.7
−250.0
250.00
208.33
166.67
125.00
83.33
41.67
0.00
200.0
133.3
66.7
0.0
−66.7
−133.3
−200.0
150.0
100.0
50.0
0.0
−50.0
−100.0
−150.0
200.00
166.67
133.33
100.00
66.67
33.33
0.00

The Nearby AGN Sample

Object	*Classification*	*D (Mpc)*	*Resolution*	
Circinus	Sy2	4	0.22”	4pc
NGC 1068	Sy2	14	0.08”	6pc
NGC 2992	Sy1	33	0.30”	48pc
NGC 3227	Sy1	17	0.085”	7pc
NGC 3783	Sy1	42	0.18”	37pc
NGC 4051	Sy1	10	0.12”	5.8pc
NGC 4151	Sy1	14	0.11”	7.5pc
NGC 4945*	Starburst, Sy2	5	0.09”	2.5pc
NGC 6814	Sy1	22	0.17”	18.2pc
NGC 7469	Sy1	66	0.085”	27pc
NGC 1052**	LINER 1	18	0.17”	15pc
NGC 1097**	LINER 1	18	0.245”	21pc
NGC 2911**	LINER 2	40	0.23”	44pc
NGC 3169**	LINER 2	20	0.17”	16pc
NGC 3081	Sy2	30	0.13”	16pc

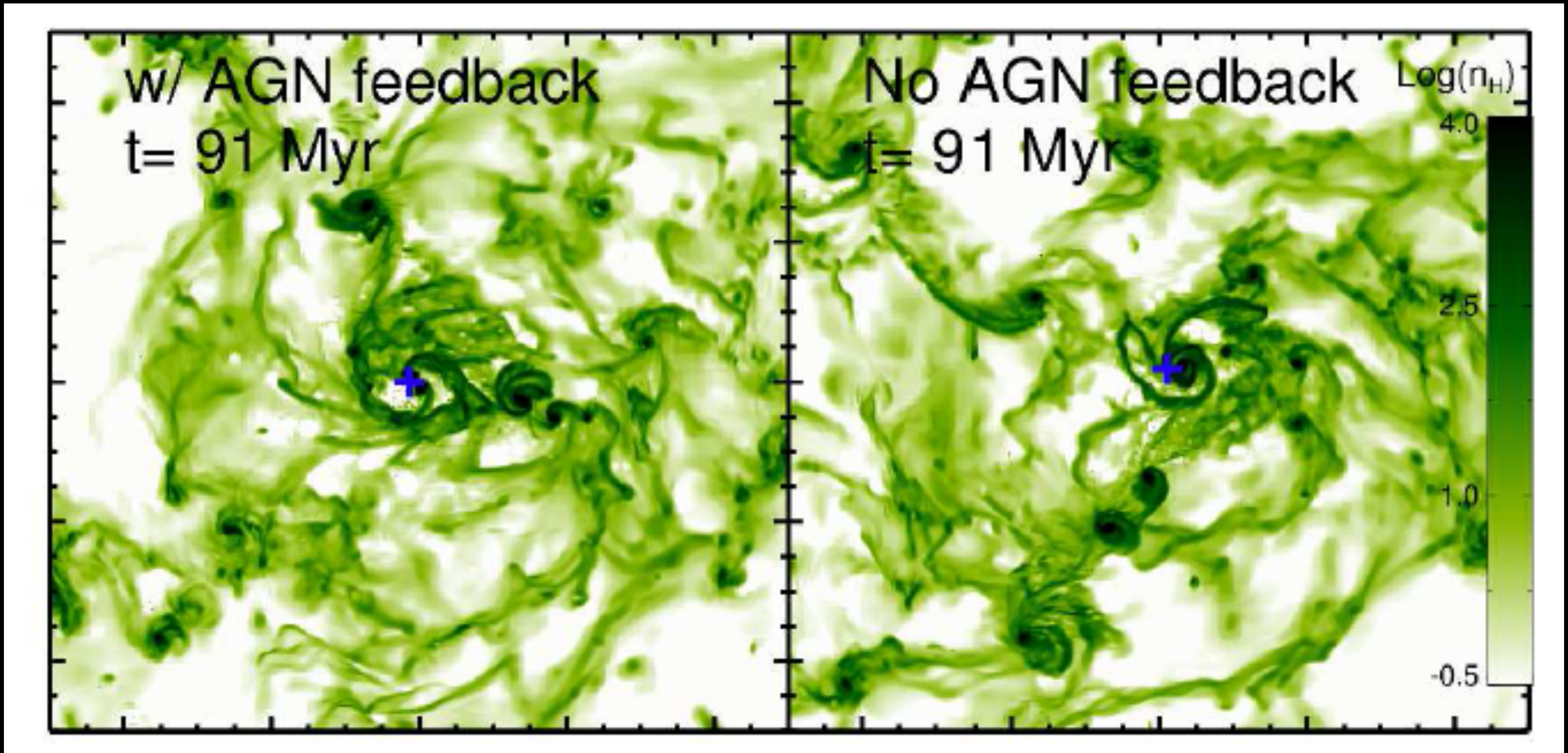
*No coronal lines
**No coronal lines, no Brγ emission

Hydrodynamical simulations



Gabor et al. 2014

AGN feedback has little impact on starforming galaxy disk.



- The AGN empties the gas only from the nuclear region, leaving the galaxy disk intact.
- The nuclear region is replenished rapidly due to instability-driven gas inflows, ultimately triggering additional AGN and outflows. AGN-driven outflows are roughly balanced on long time scales by gas inflows. Since the SFR of the galaxy is dominated by the disk, not the nucleus, the total instantaneous SFR is practically unaffected by AGN feedback.

Gas outflows in Nearby AGN

- Are there outflows of molecular/ionized gas?

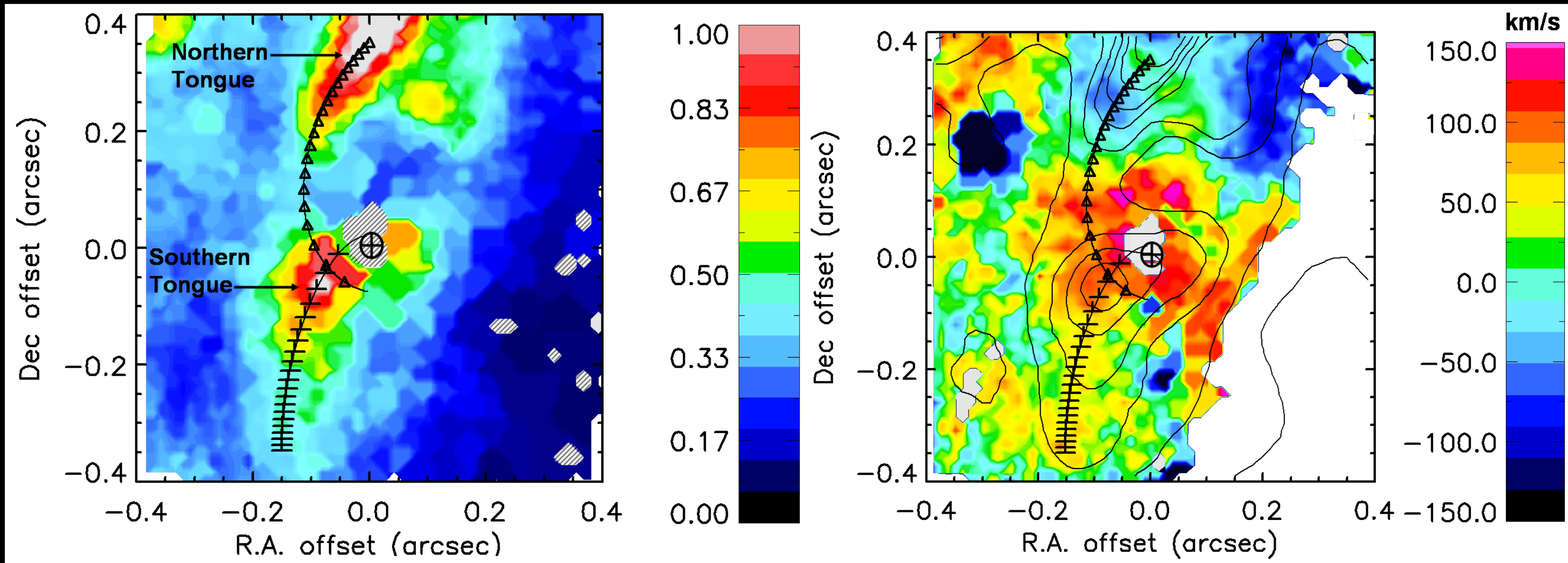
- Kinematics of the NLR: is the material in the ionization cones outflowing? Origin of the outflow: AGN processes, starburst-driven wind, radio jet?

- Morphology and kinematics of the coronal lines: are they part of the NLR (ionization cone)? do they show signs of rotation? are there any correlations with other AGN-based phenomena?

- Orientation effects invoked by the torus model of AGN

- Do AGN outflows actually deliver enough energy to their environments to alter the evolution of the galaxy in a meaningful way? e.g. are they capable of stripping away the ISM, controlling star formation and BH growth?

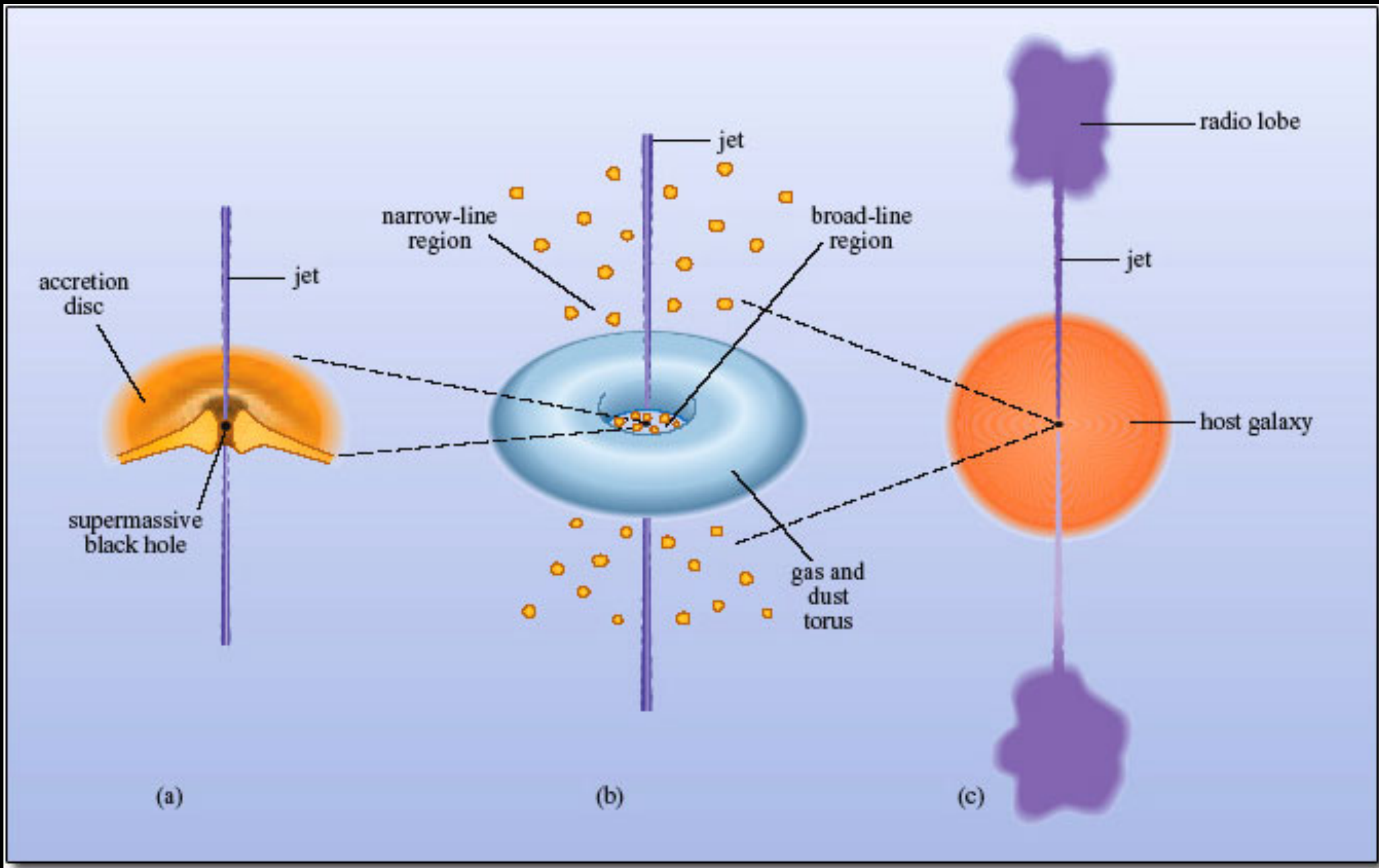
Gas Inflow in NGC 1068



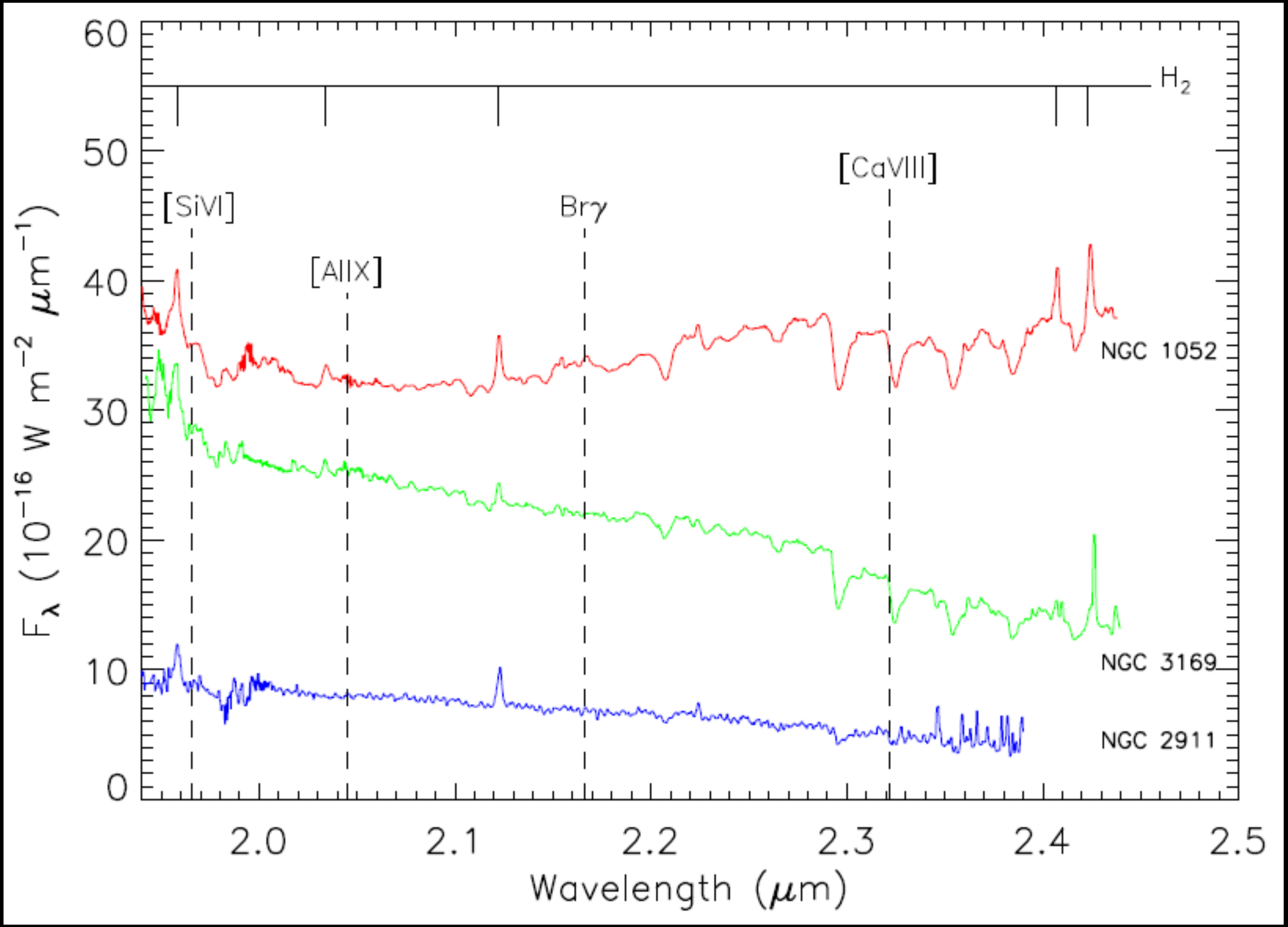
- Filaments of gas extend from the ring at a radius of about 30 pc to the AGN
- The inflow rate to the central few parsecs is of order 15 M_sun yr−1. This is 2–3 orders of magnitude greater than that needed to power the AGN itself
- These models indicate that the infall timescale for a gas mass of 2x10^7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

AGN Paradigm

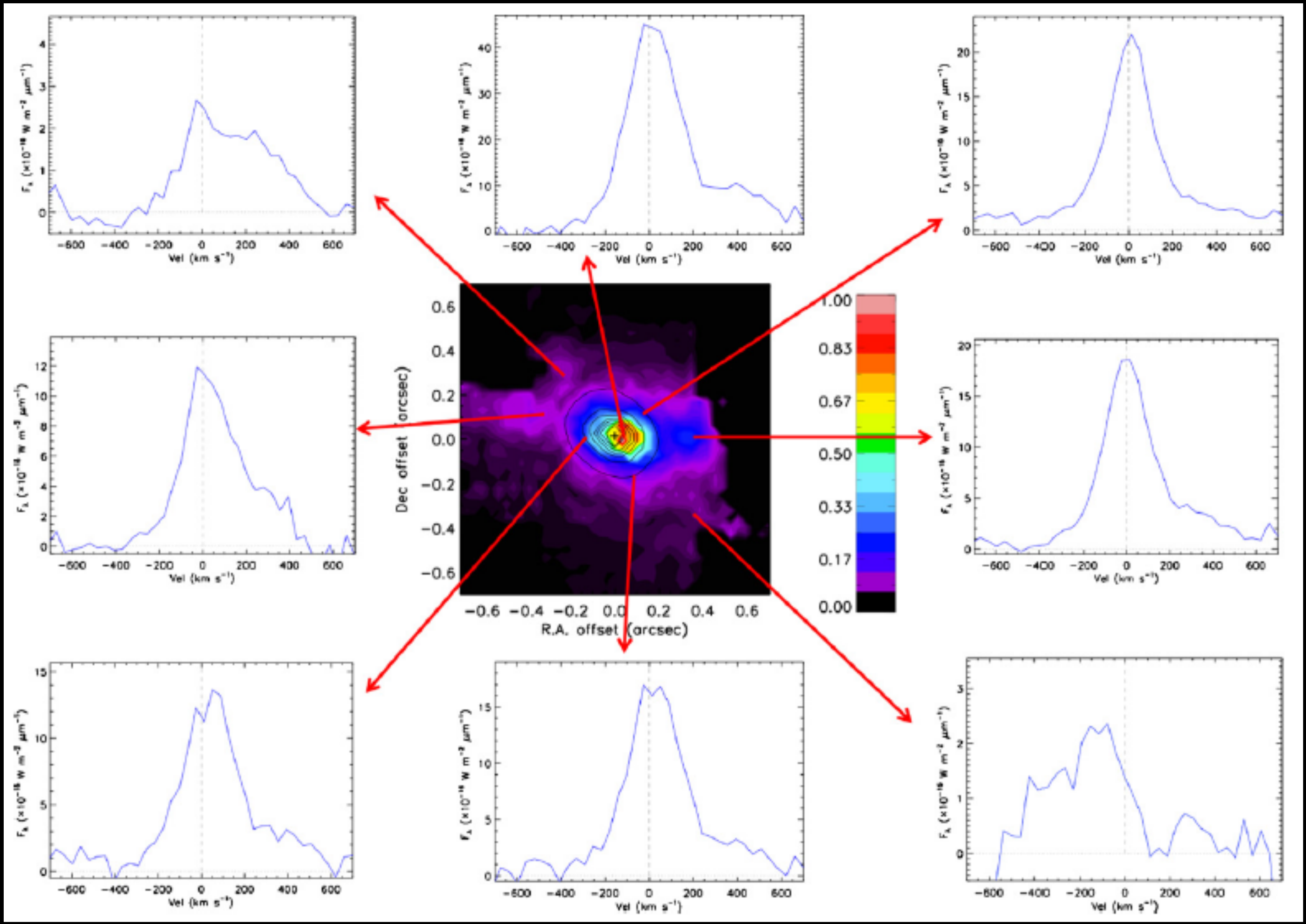


Integrated spectra of LLAGN

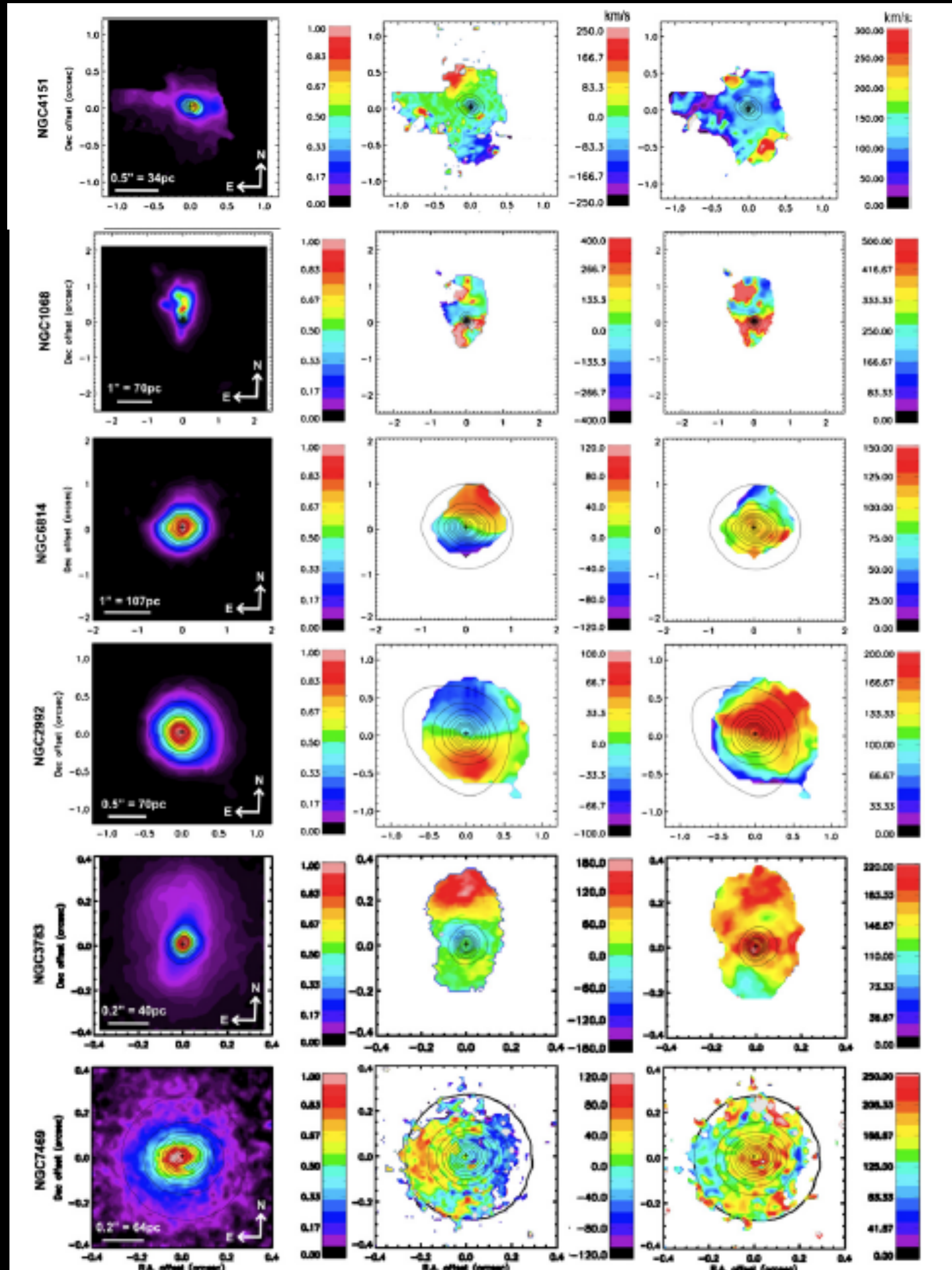


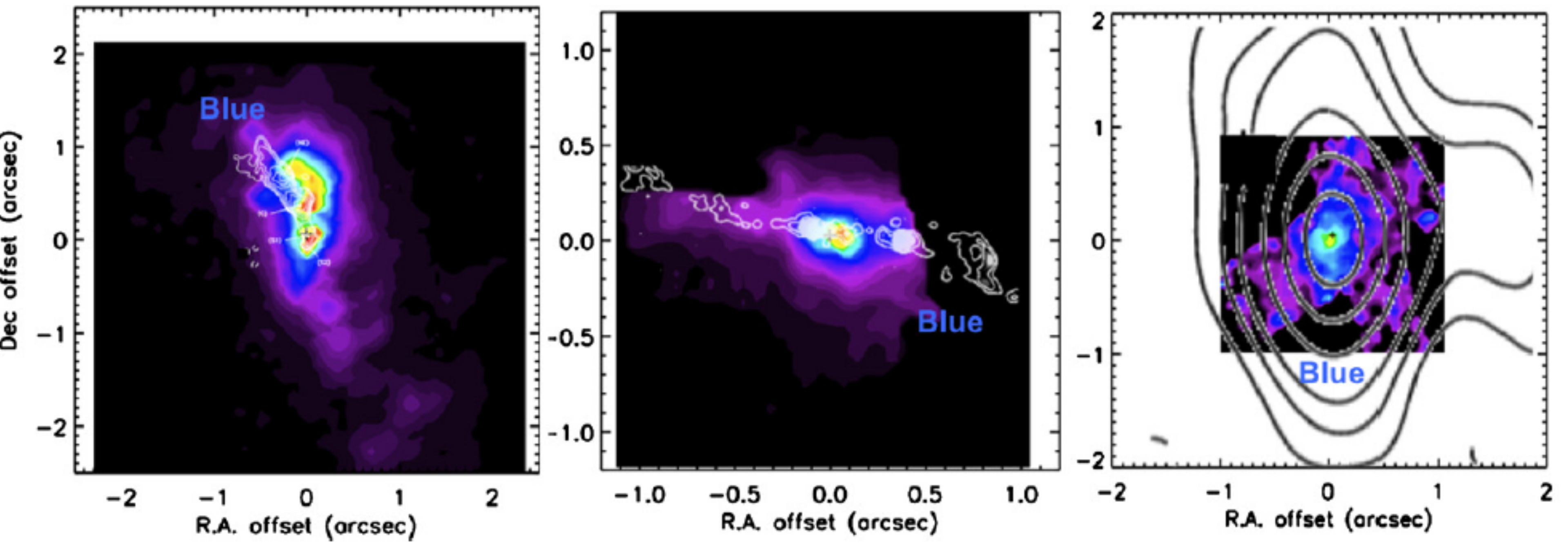
Müller-Sanchez et al. 2012

Outflows in NGC 4151



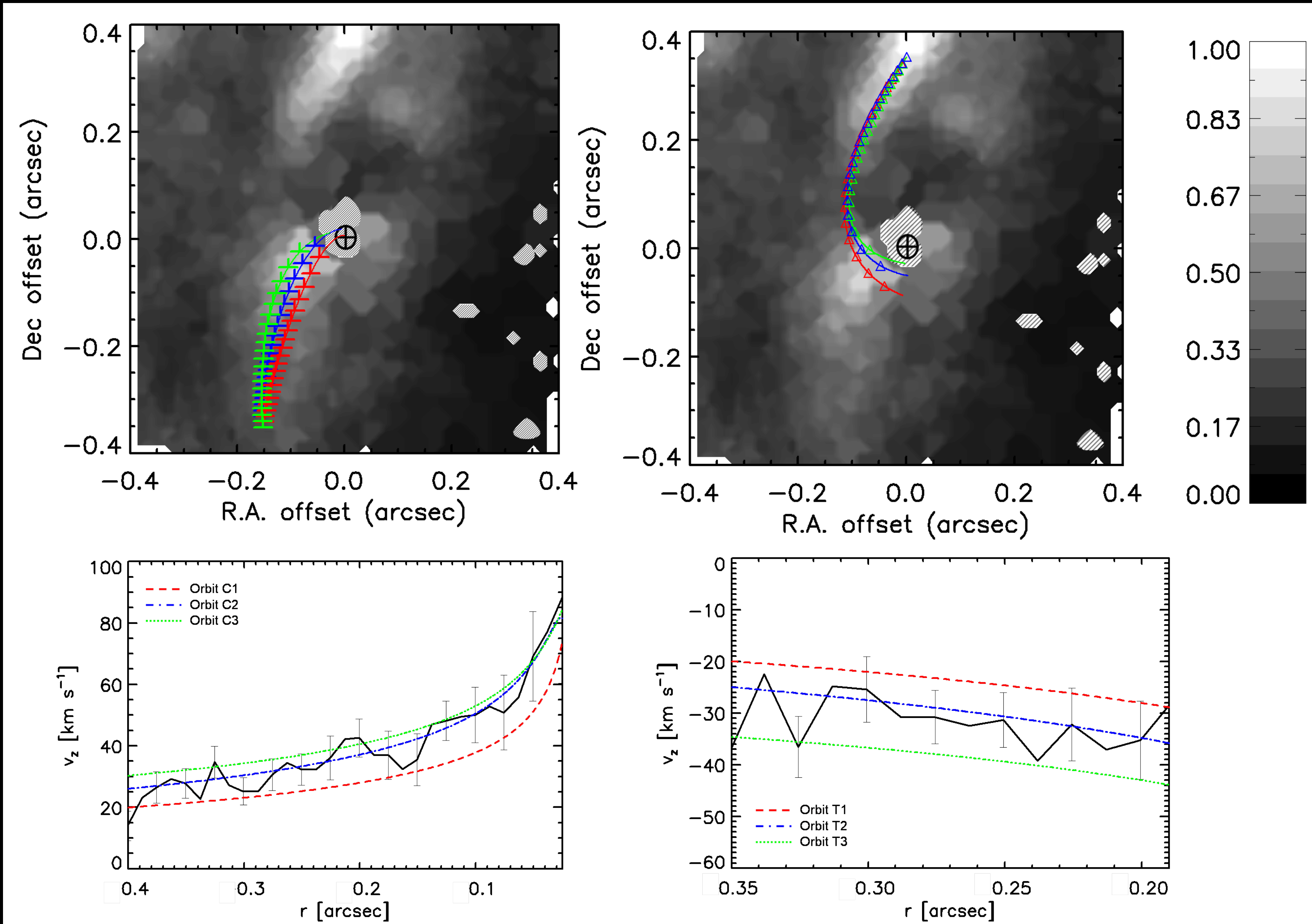
Müller-Sanchez et al. 2011


NGC4151
0.5" = 34pc
NGC1068
1" = 70pc
NGC6814
1" = 107pc
NGC2992
0.5" = 70pc
NGC3783
0.2" = 40pc
NGC7469
0.2" = 64pc
Dec offset (arcsec)
R.A. offset (arcsec)
km/s
N
E

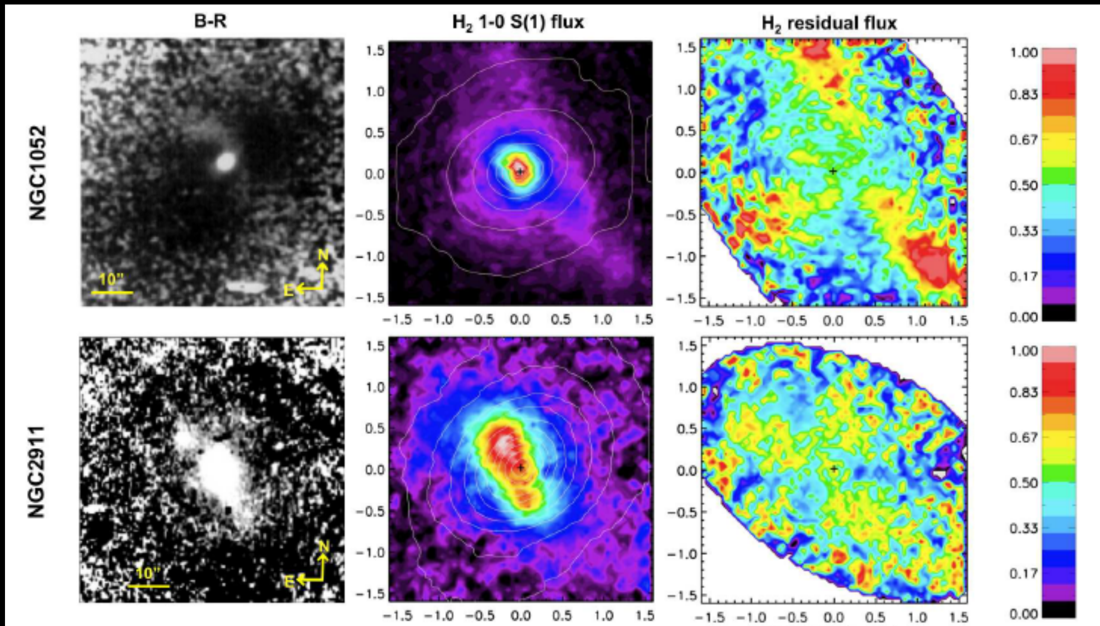


Blue
Dec offset (arcsec)
R.A. offset (arcsec)
Blue
R.A. offset (arcsec)
Blue
R.A. offset (arcsec)

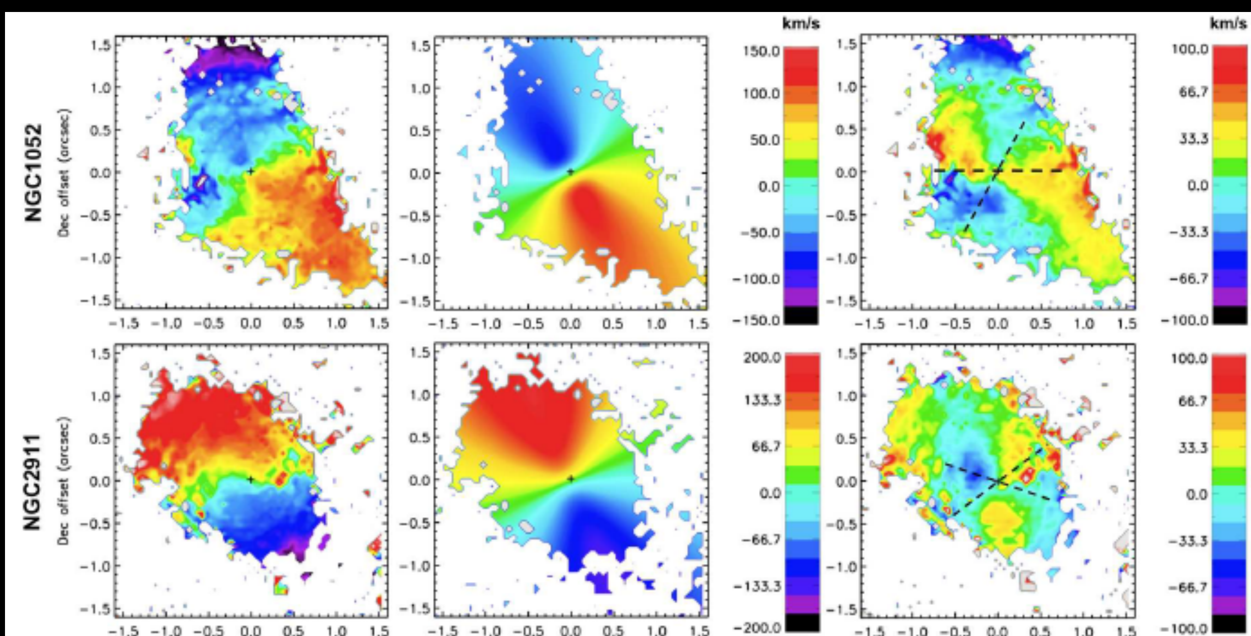
Gas on high elliptical/parabolic orbits



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

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 interstellar medium (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 M_{BH}–σ_* relation. These objects also present strong collimated radio emission, indicative of a link between jet power and outflow power.

- There exist orientation effects favoring the torus model of AGN.