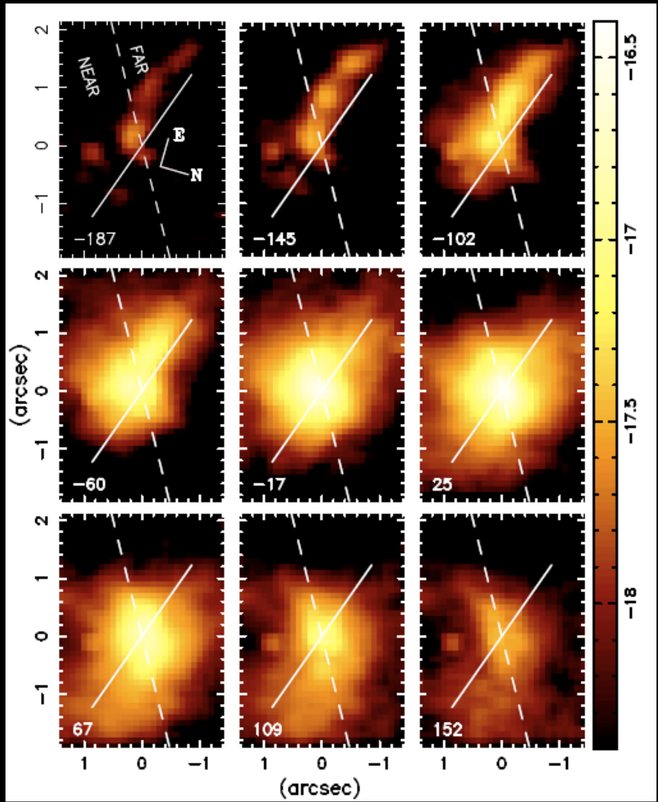

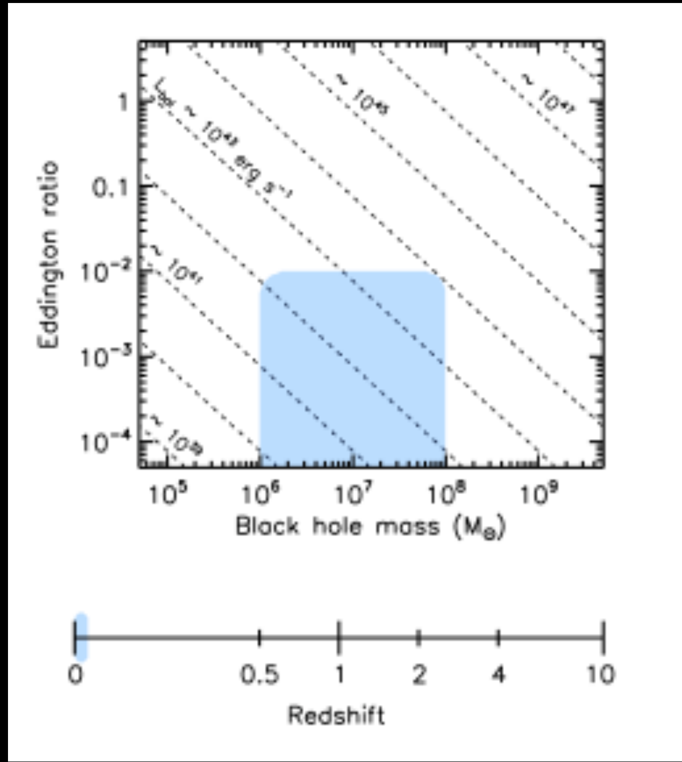

Mapping gas inflows in nearby AGN

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Outline

- Introduction: role of inflows
- Signature of inflows: nuclear spirals
- Kinematics: ionized and molecular gas
- New results and methods (PCA)
- Mass inflow rates
- Conclusions

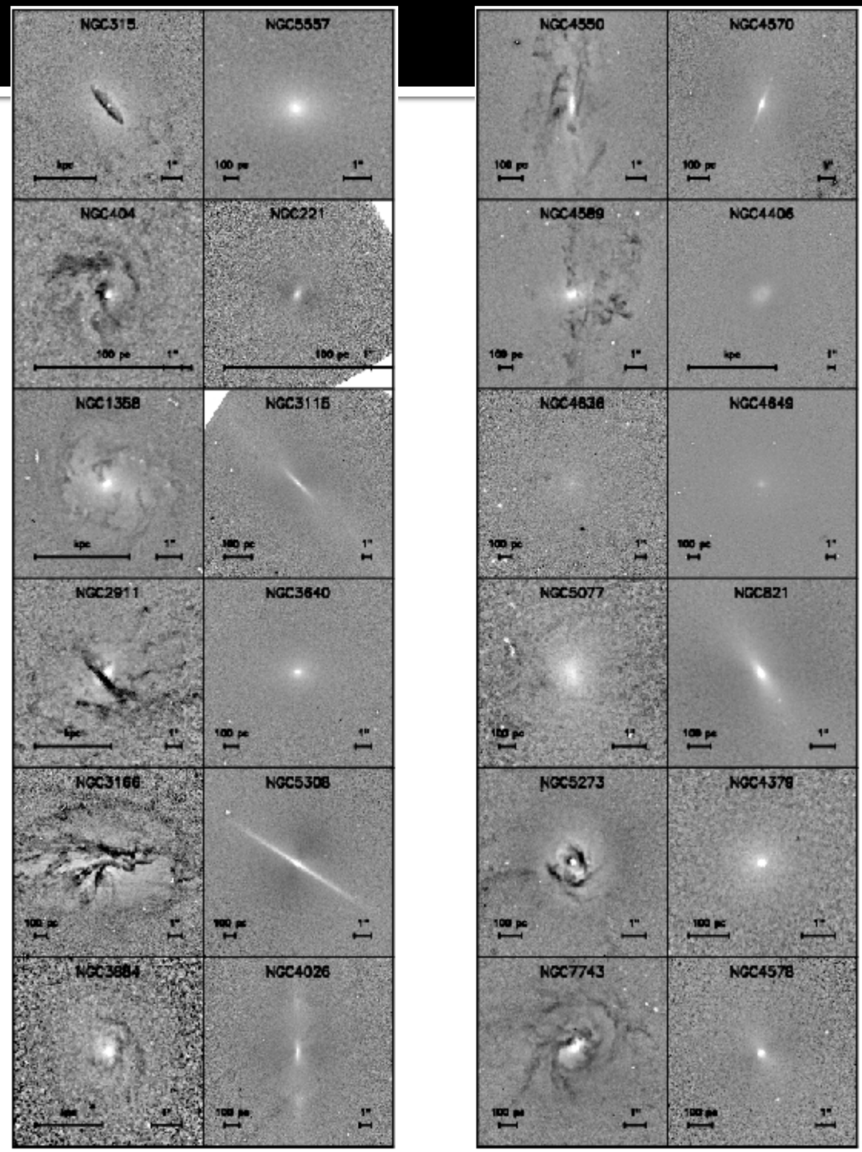
Introduction

- Inflows in galaxies: necessary to trigger nuclear starbursts and promote galaxy secular evolution (Combes 2010); in AGN, to feed the SMBHs;
- Models for inflows: bars (Shlosman et al. 1990), gravitational torques (Garcia Burillo et al. 2005, 2007);
- In the inner kpc, role of nuclear bars (Englmaier & Shlosman 2004) and spirals (Englmaier & Shlosman 2004; Maciejewski 2004);
- Kinematic signatures of inflows in AGNs: difficult to find, as outflows dominate emission (over most wavelengths);
- Goal of present work search for these signatures in nearby AGN (Storchi-Bergmann, Riffel, Schnorr Muller);
- Other authors looking for inlfows: Davies, Hicks and collabs. ; two posters: 1.1 – Bartakova; 1.10– Westoby.

Morphology (Simões-Lopes et al. 2007)

- Structure maps: HST F606W early-type AGN vs. non-AGN
- Dusty nuclear spirals in ~100% AGN;
- But in ~ 25% of non-AGN;

→ Channels to feed the SMBH ?



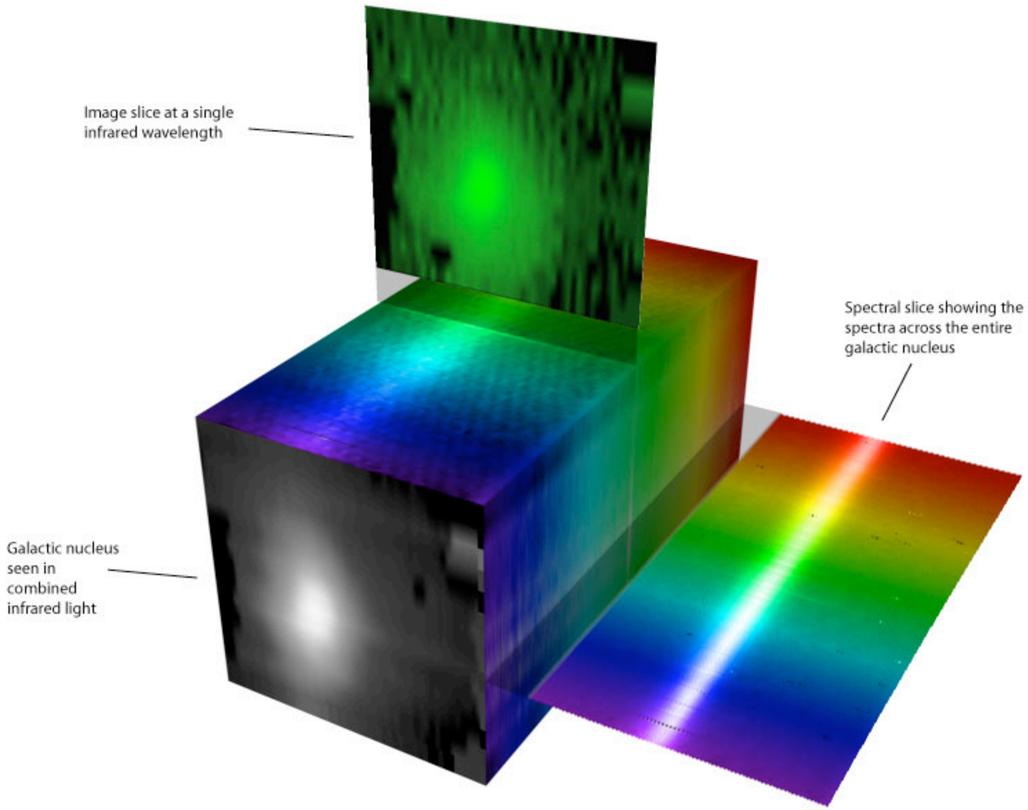
AGN Non-AGN AGN Non-AGN

Observations: Integral Field Spectrographs

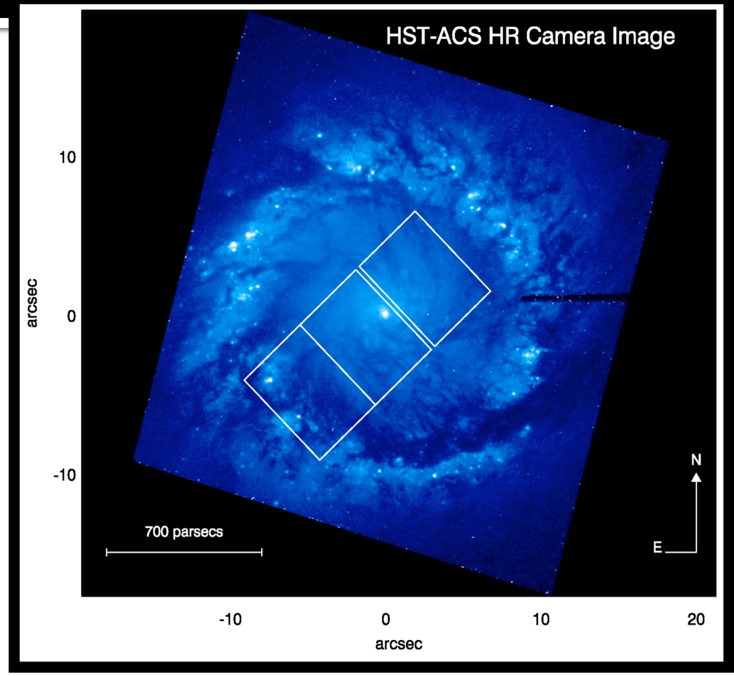
Gemini

- Optical: GMOS
- FOV: 3.5"x5" or 5"x7"
- Sampling 0.2" , Res. 0.6"
- R~3000, λ6000 - λ9500A

- Near-IR: NIFS+ALTAIR
- FOV: 3" x3"
- Sampling: 0.04"×0.1"
- Res. 0.1"
- R~6000, J, H & K-band



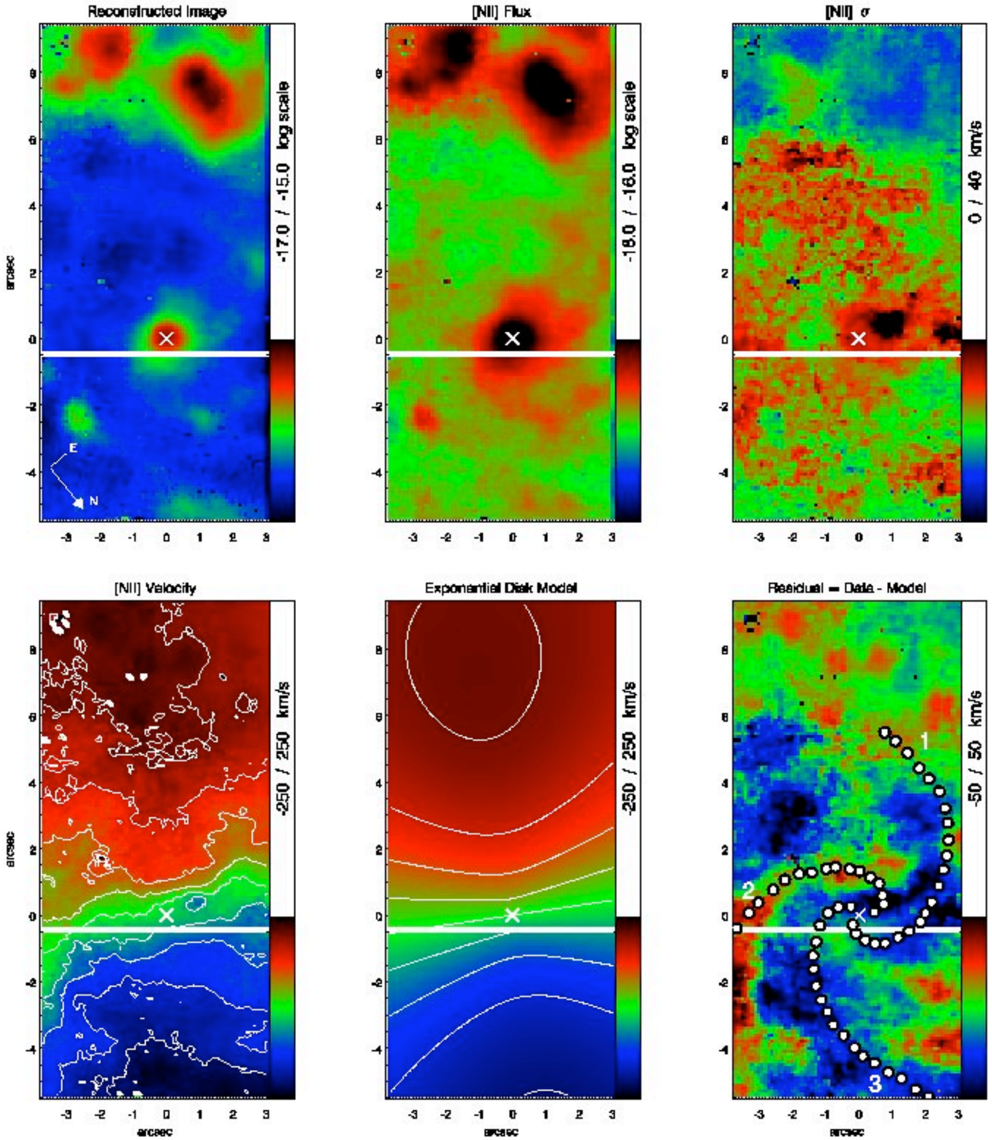
Kinematics: NGC1097 (Fathi et al. 2006)



- GMOS IFU: 3 fields 5″x7″=15″x7″(1.2x0.6 kpc)
- Measured gas kinematics (Hα +[NII])
- Fit and subtract a circular rotating disk model
- Look for residuals in association with nuclear spirals

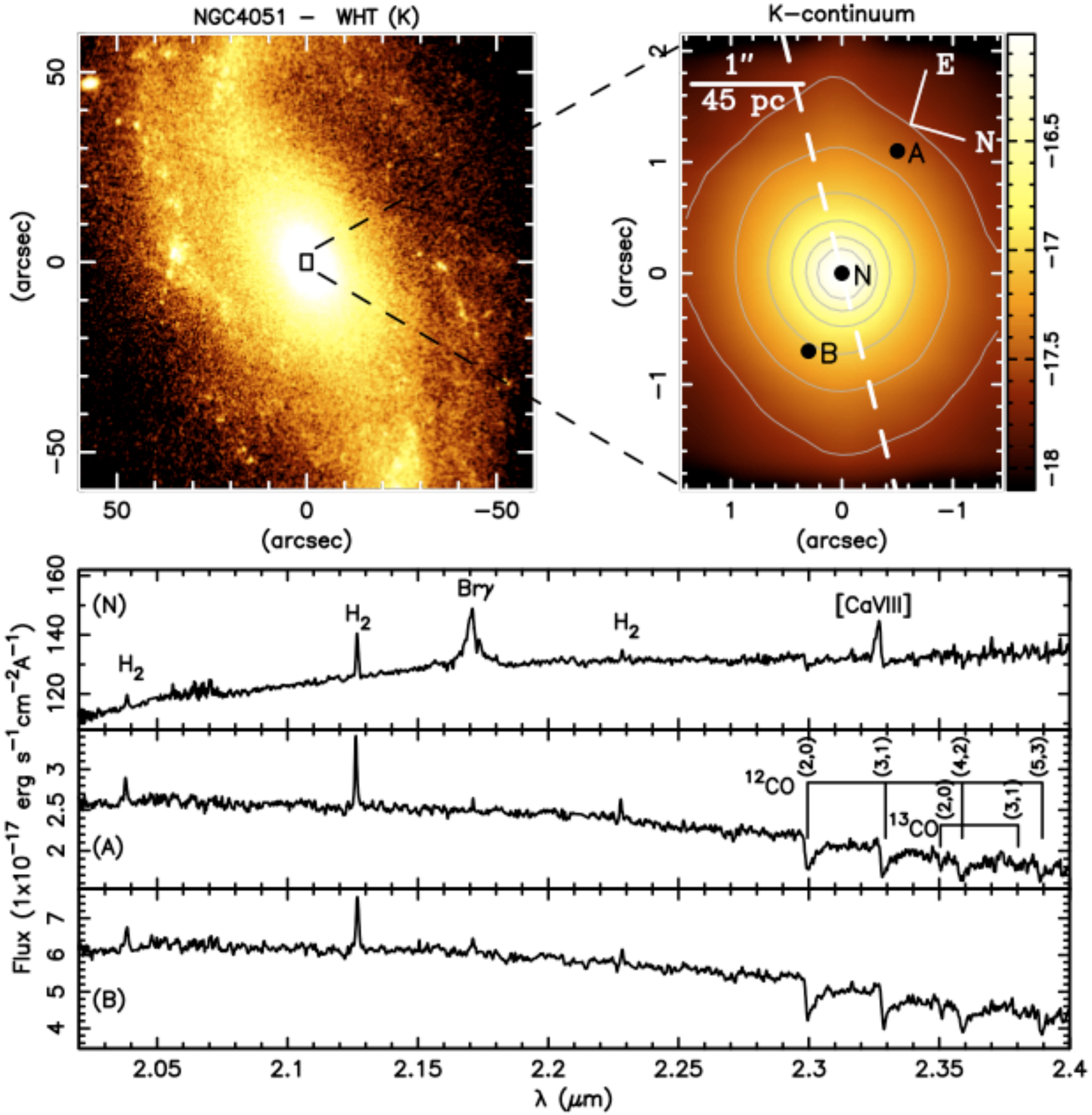
Kinematics: NGC1097 (Fathi et al. 2006)

- Residuals of up to 50 km/s along nuclear spirals
- Mass inflow rate of ionized gas: ~10^{-3} M_{sun} yr^{-1}
- Flow in neutral and molecular gas much larger (Davies et al. 2009)
- Another case: NGC6951 (Storchi-Bergmann et al. 2007)
- Difficulties: in most cases kinematics is too disturbed to fit circular model



Kinematics: NGC4051 (Riffel et al. 2008)

- NIFS, K-band 3”x4”(135x180pc)
- Stellar and H_2 gas kinematics
- Channel maps in H_2



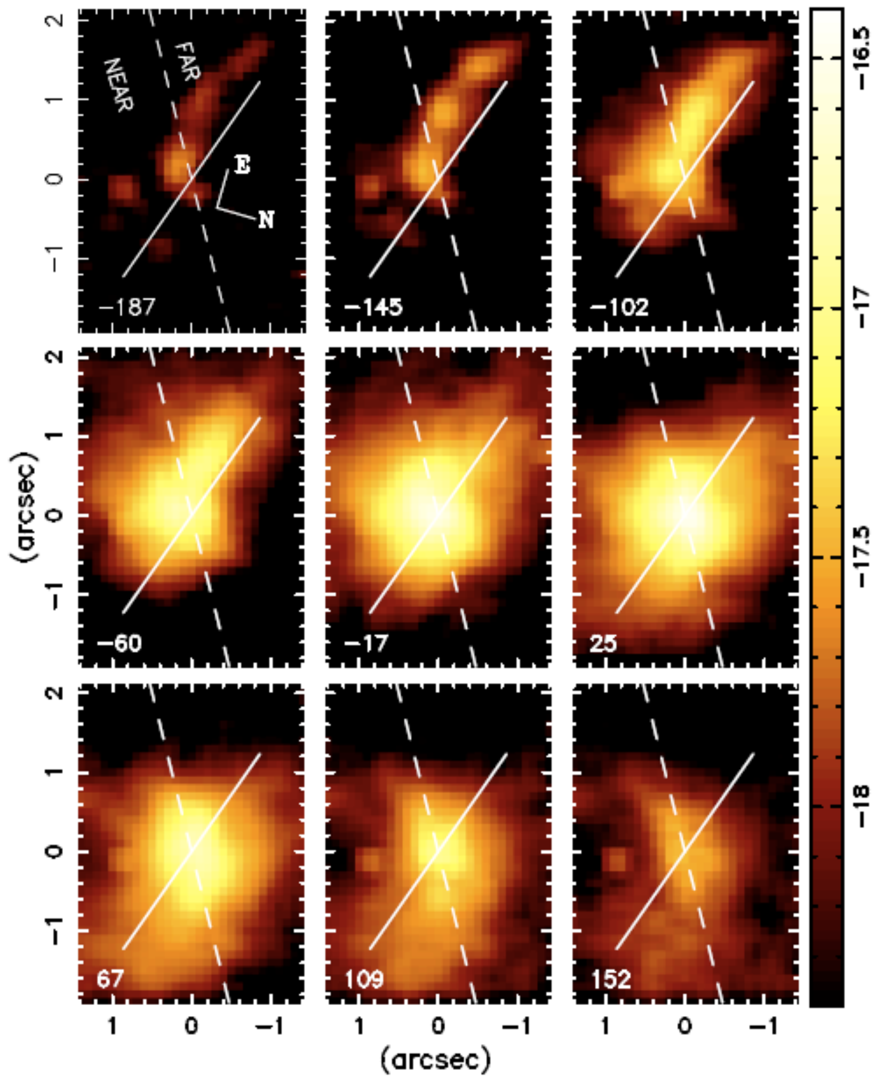
Kinematics: NGC4051 (Riffel et al. 2008)

H_2 channel maps

- Blueshifts in far side, redshifts in near side. If gas is in the plane ➔ inflow.

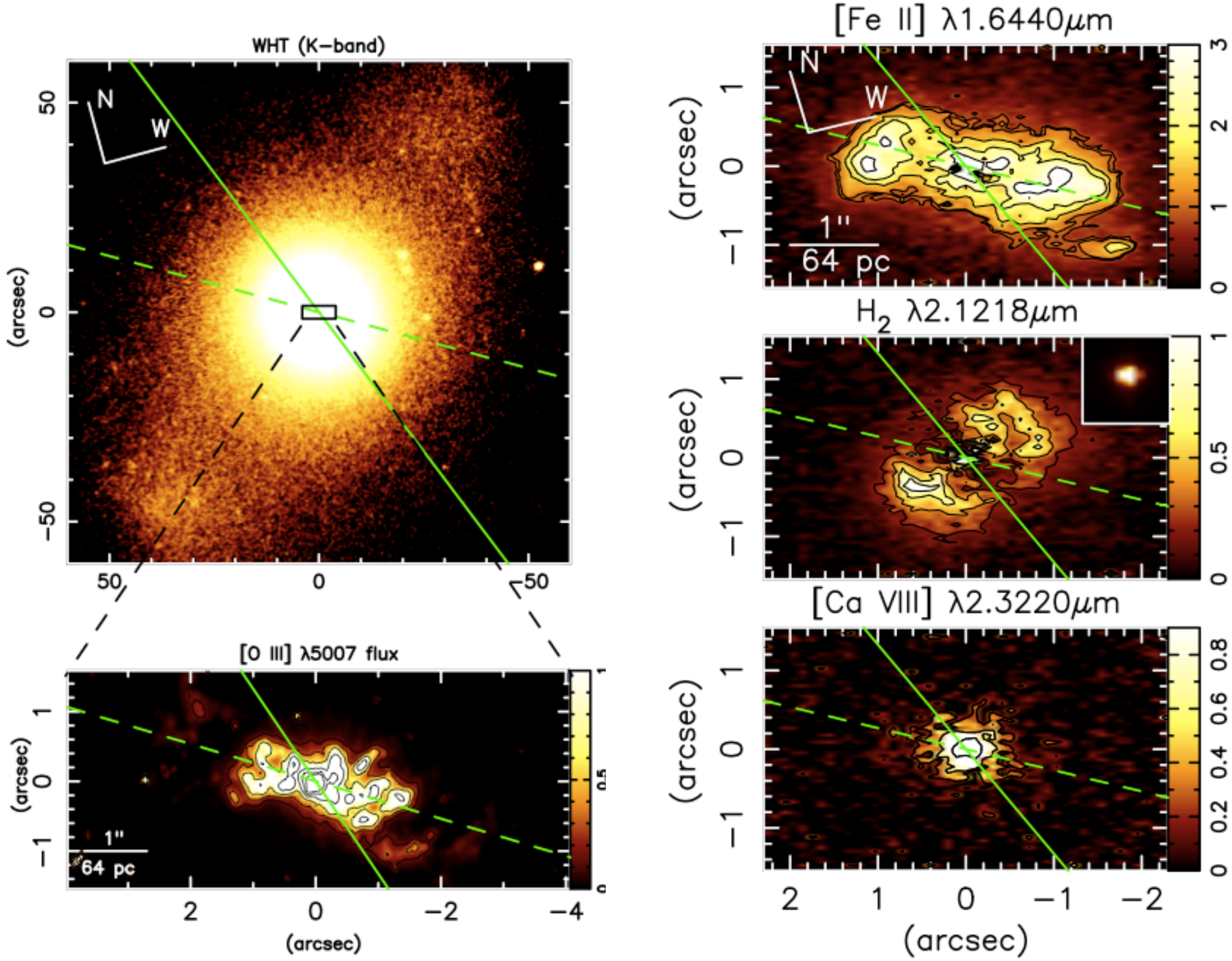
- Mass inflow rate ~1/100 mass accretion rate ➔ only "hot skin" of molecular gas flow

- Cold molecular gas: $\geq 10^5$ larger (Dale et al. 2005) ➔ Mass inflow rate ≥ 1 M_{sun} yr^{-1}

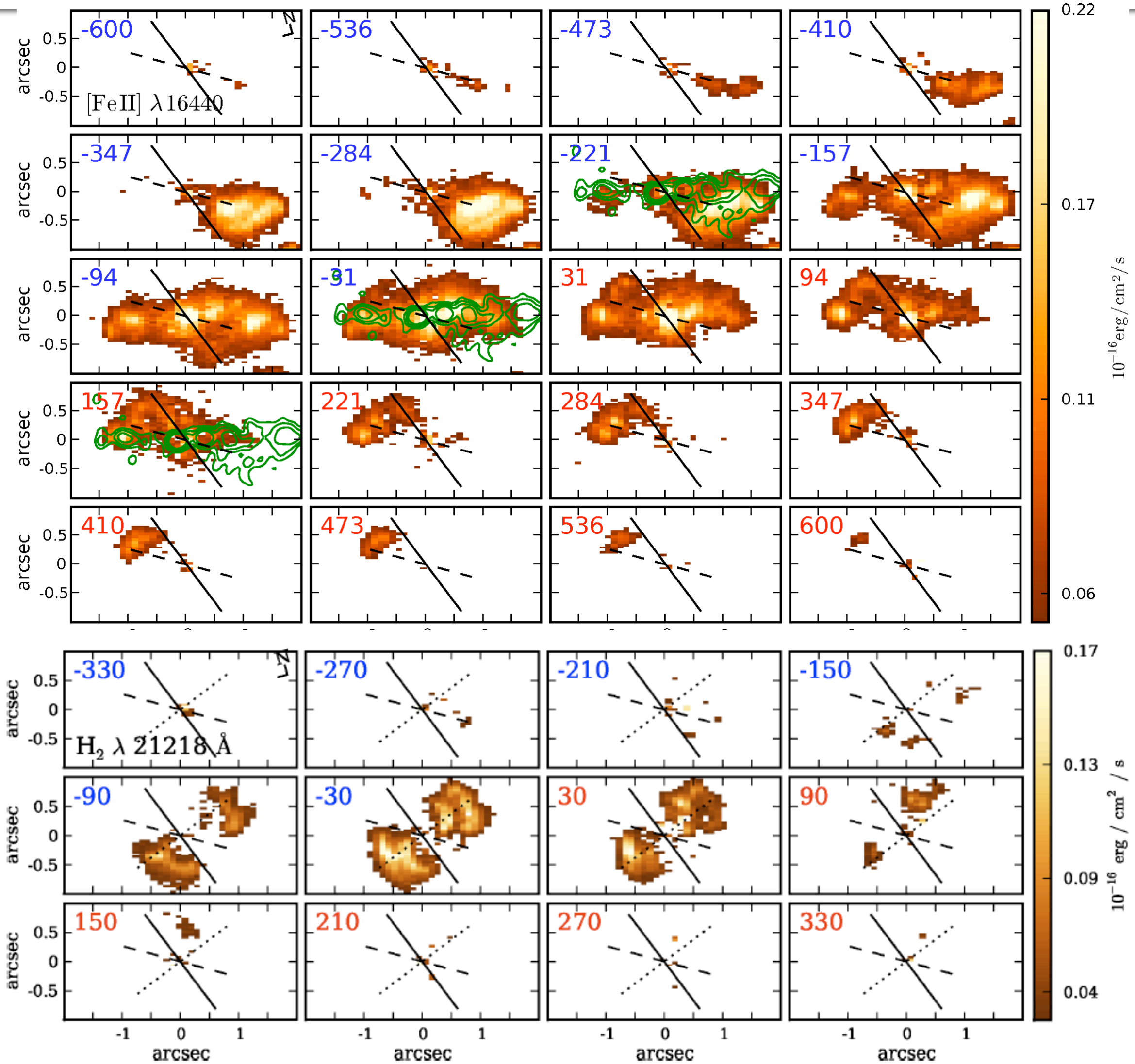


NGC4151 (Storchi-Bergmann et al. 2009, 2010)

- NIFS: Z, J, H,K
- 3"x8" (200x500pc)
- Distinct flux distributions
- H_2: "toroidal" flux distribution at the apex of ionization cone



Kinematics: NGC4151 (Storchi-Bergmann et al. 2010)



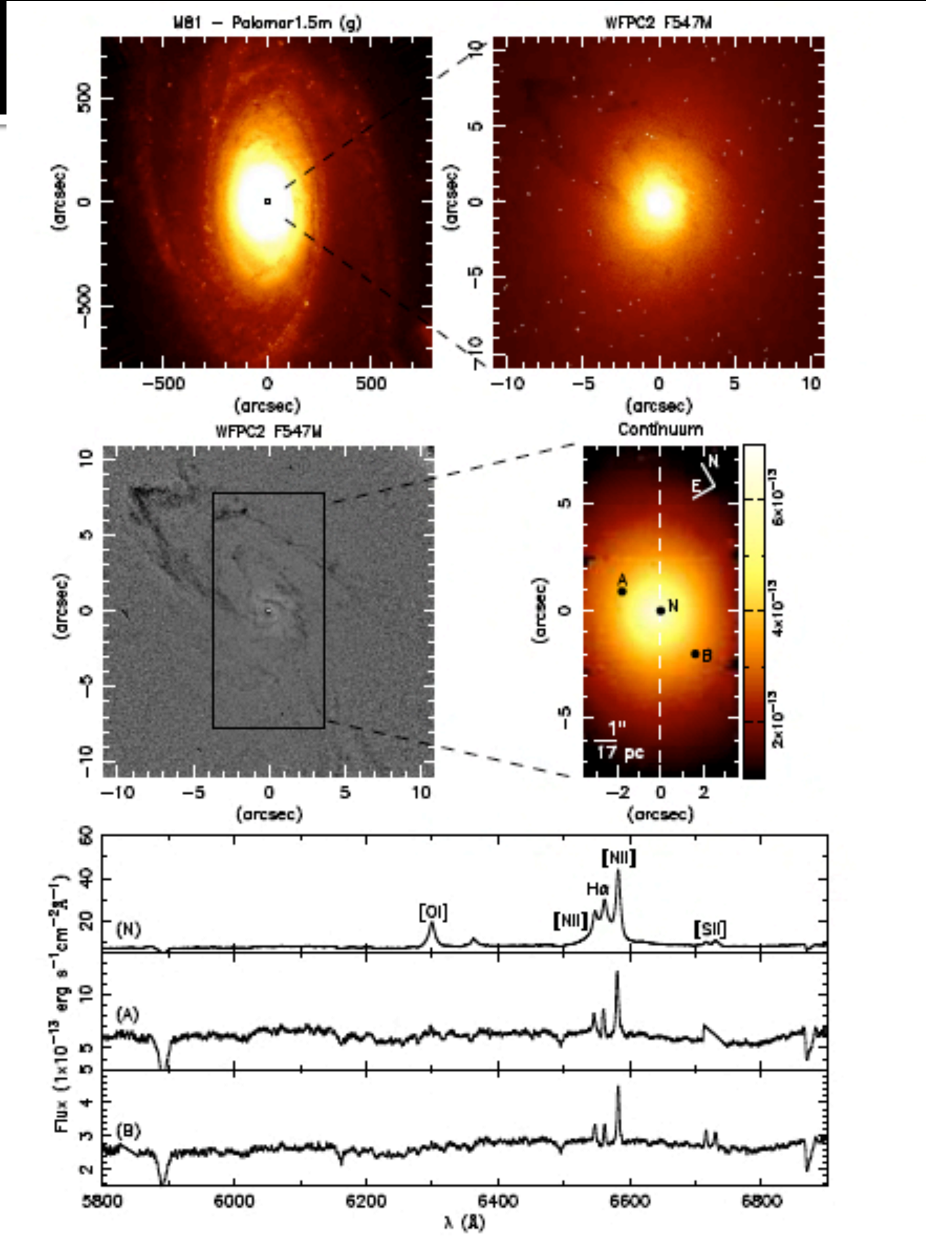
Channel maps: distinct kinematics between ionized and molecular gas:

- [Fe II]: high velocities along radio jet: outflows at 2 M_{sun} yr^{-1}

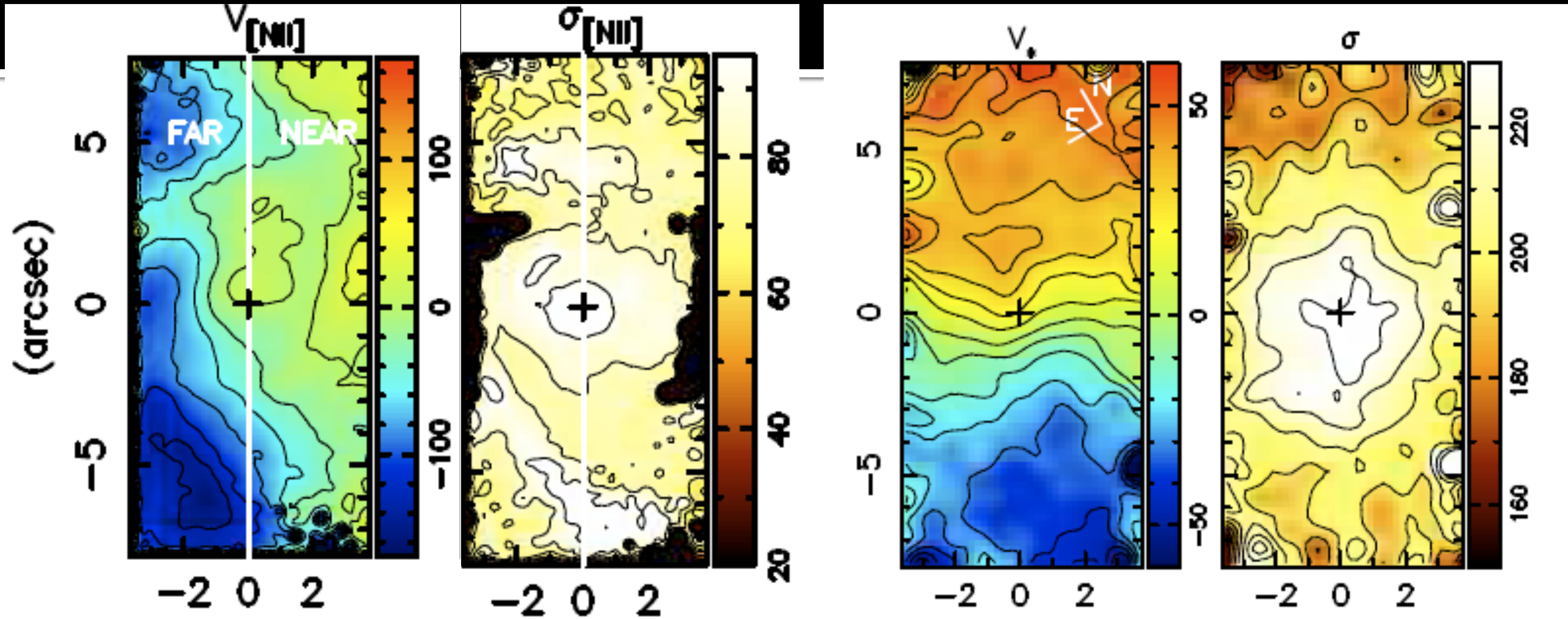
- H_2: low velocities: rotation in the plane, total mass only 240 M_{sun}; again, cold gas 10^5 times larger.

Kinematics: M81 (Schnorr-Muller et al. 2010)

- GMOS IFU: 3 fields 5″x7″=15″x7″(255x120 pc²)
- Measured stellar and gas kinematics (Hα +[NII])
- Subtract stellar from gaseous kinematics
- Look for residuals in association with nuclear spirals



Kinematics: M81 (Schnorr Muller et al. 2010)

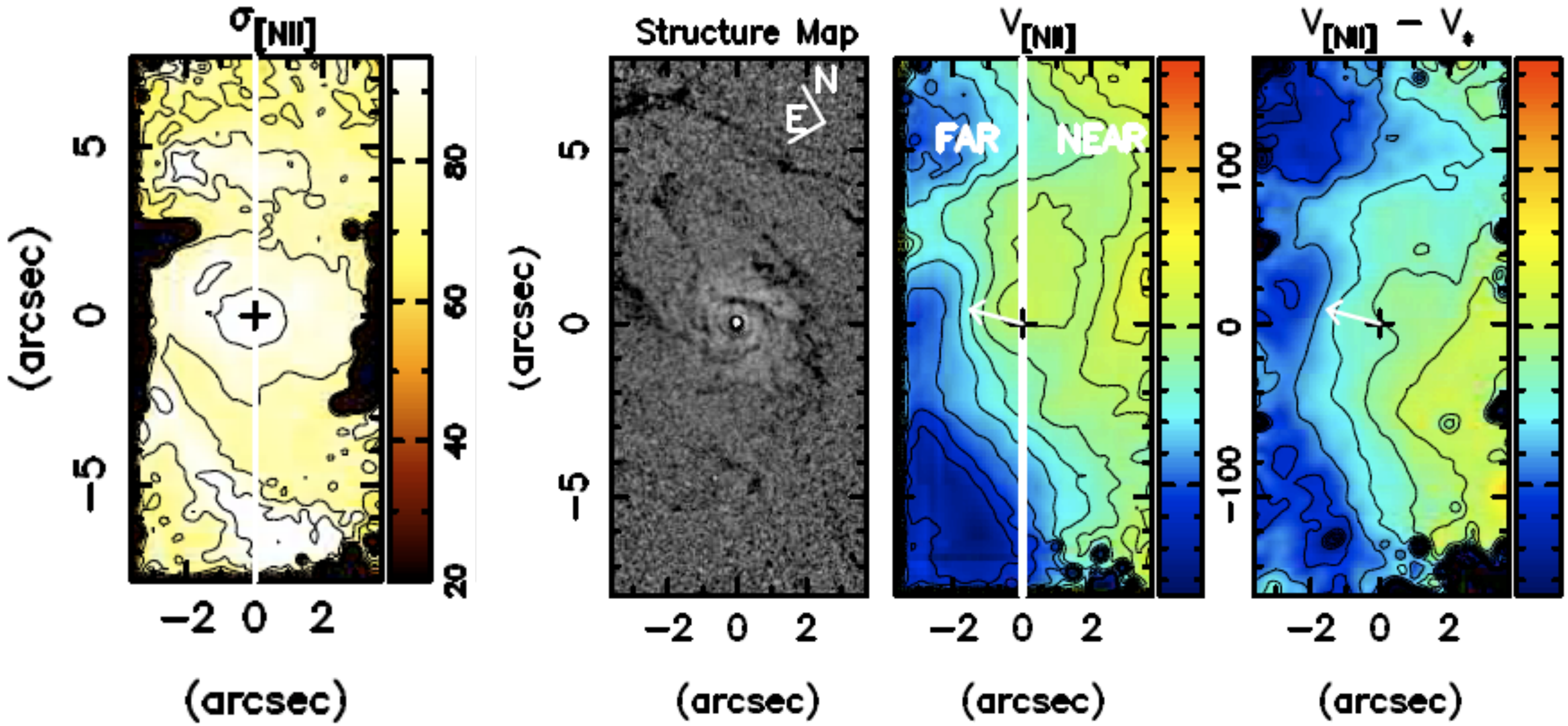


Gas kinematics

Stellar kinematics

Gas kinematics distinct from stellar: “rotation axes” perpendicular to each other.

Kinematics: M81 (Schnorr-Muller et al. 2010)



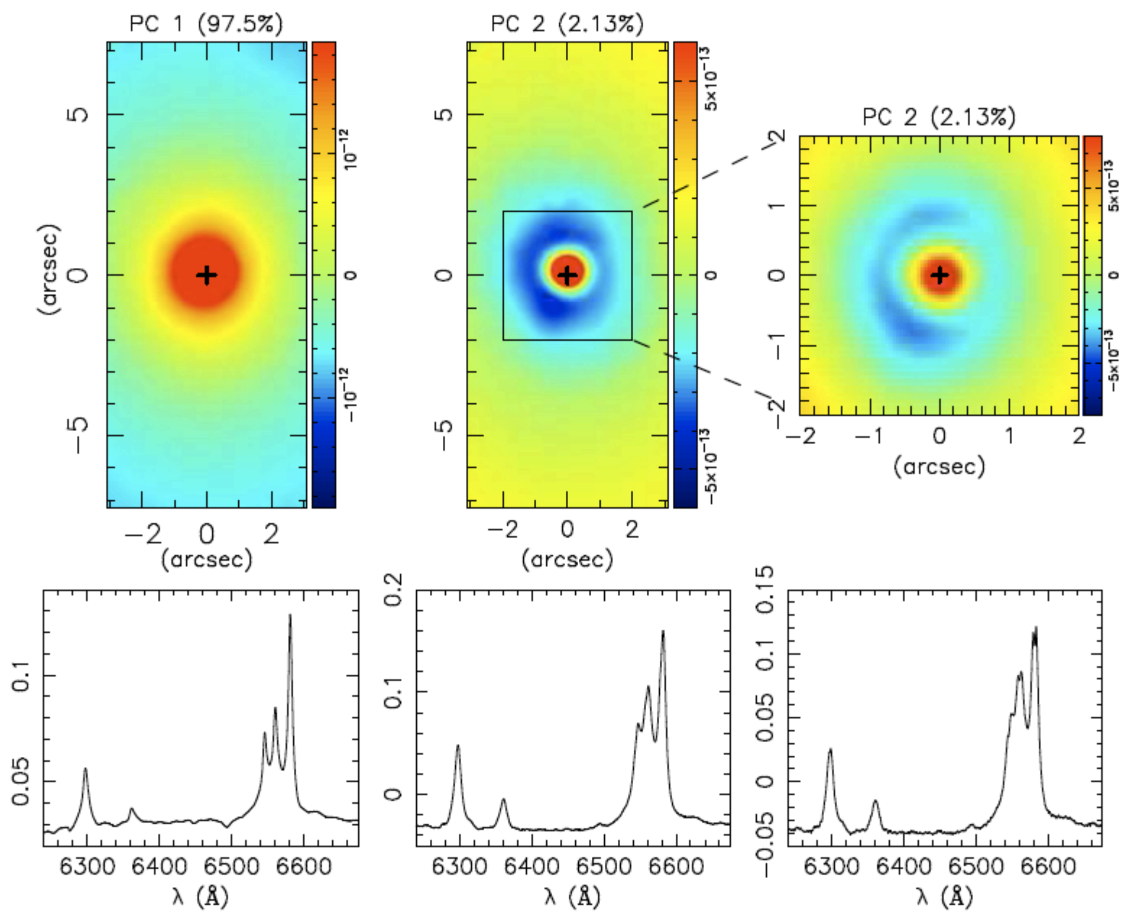
- Relation between velocity, velocity dispersion and structure map: shocks in the plane;
- If gas is in the plane, blueshifts in the far side → inflows towards the center

New Technique: PCA (Steiner et al. 2009)

Principal component analysis of spectral properties of each pixel:

"Tomograms" →

"Eigenspectra"→

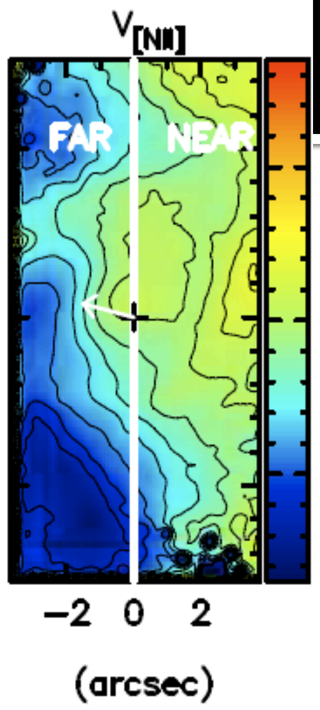


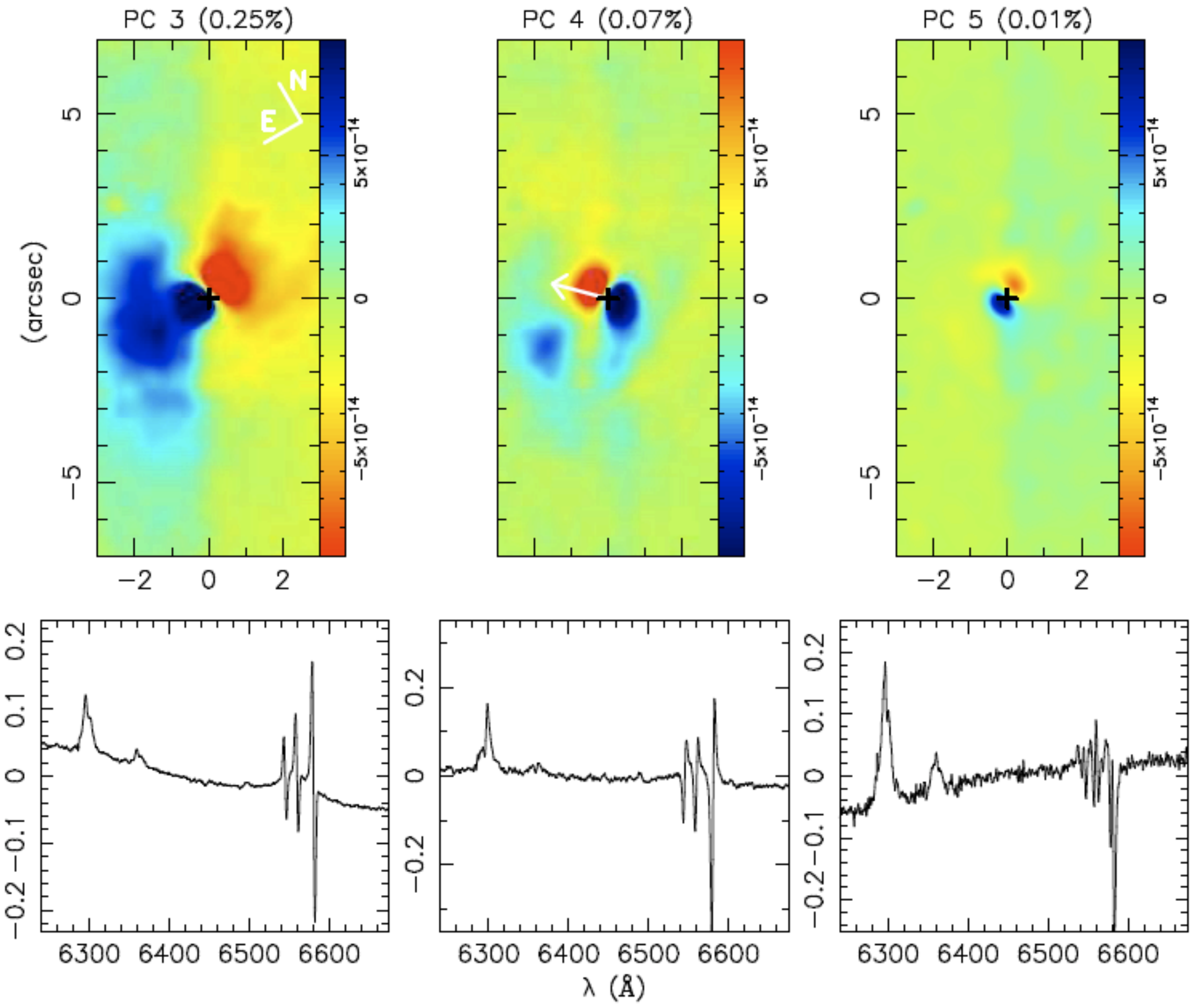
PC1: Principal comp.1 has most information

PC2: anti-correlation between gas emission and stellar continuum

PC2 in smaller FOV: unresolved double-peaks: bipolar outflow or rotation

PCA Results M81





PC3: rotating disk being fed along minor axis

PC4: bi-polar outflow related to radio jet (arrow)

PC5: more of the disk

PCA Results M81

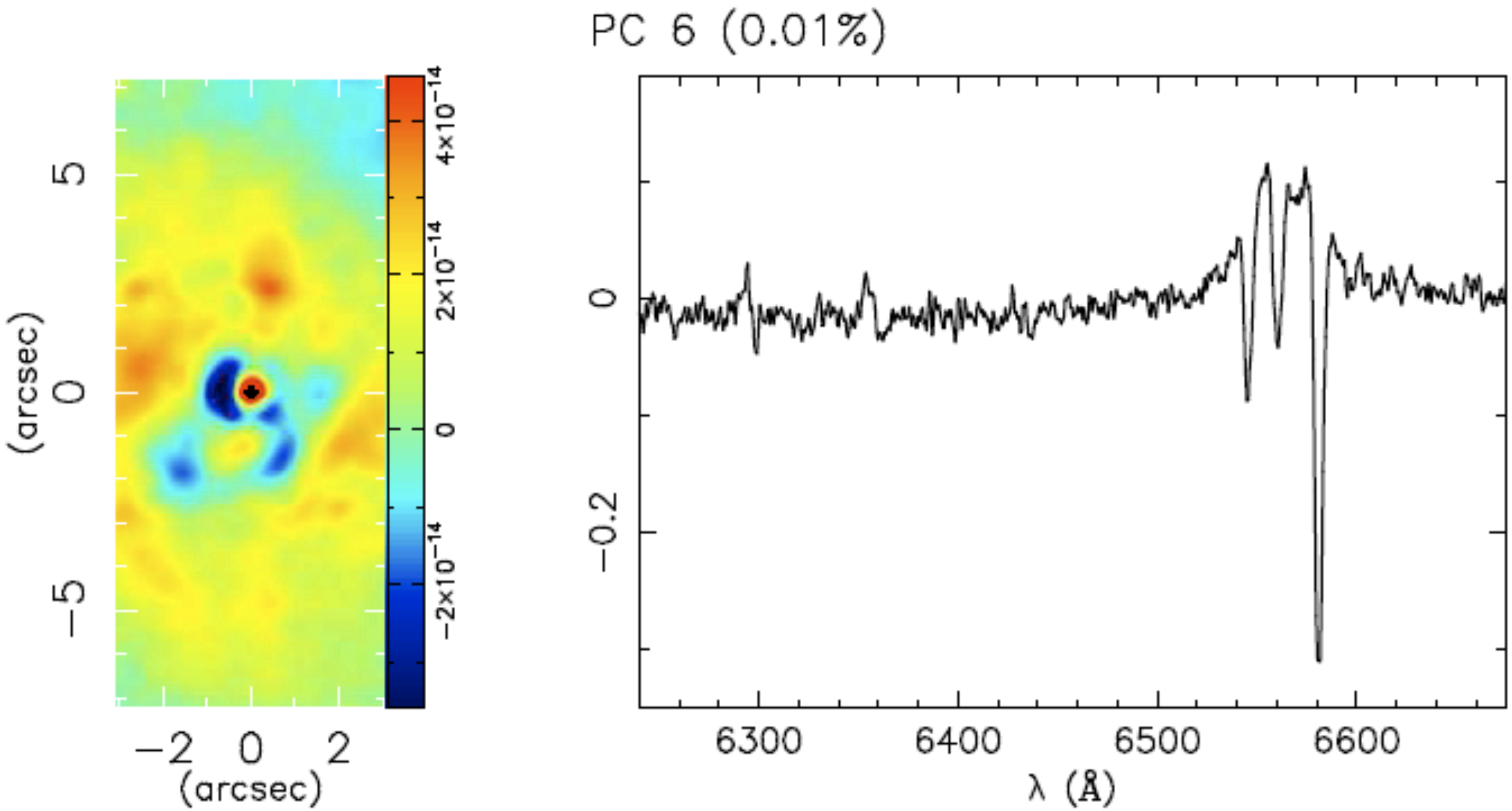
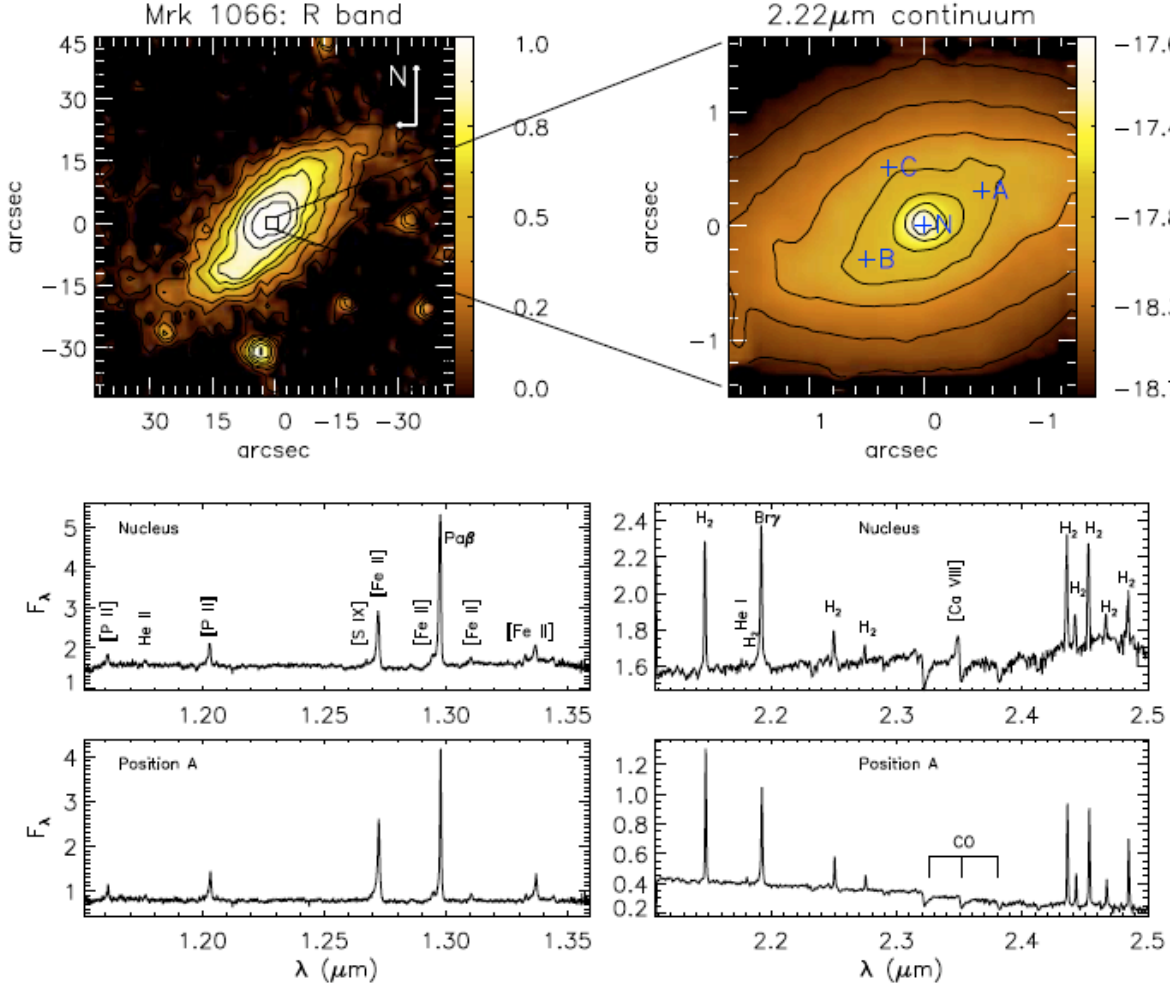


Figure 12. Left: Tomogram of PC 6; right: eigenvector 6, showing the broad Hα component.

Kinematics: Mrk1066 (Riffel et al. 2010)

- NIFS J and K: 3″x3″ (700x700 pc^2)
- Stellar (CO) and gas kinematics (Paβ, [Fe II], H_2)
- Channel maps

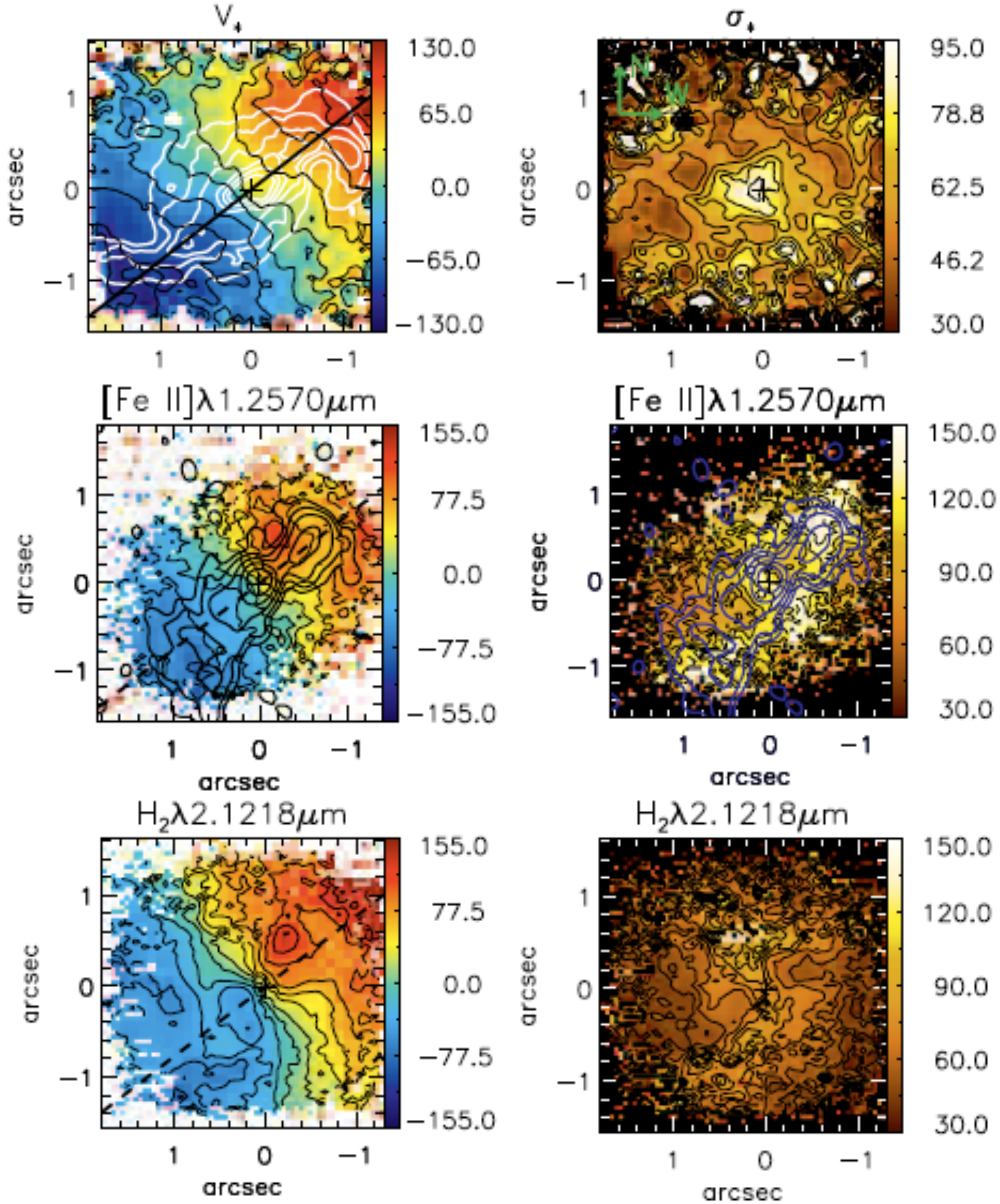


Mrk 1066

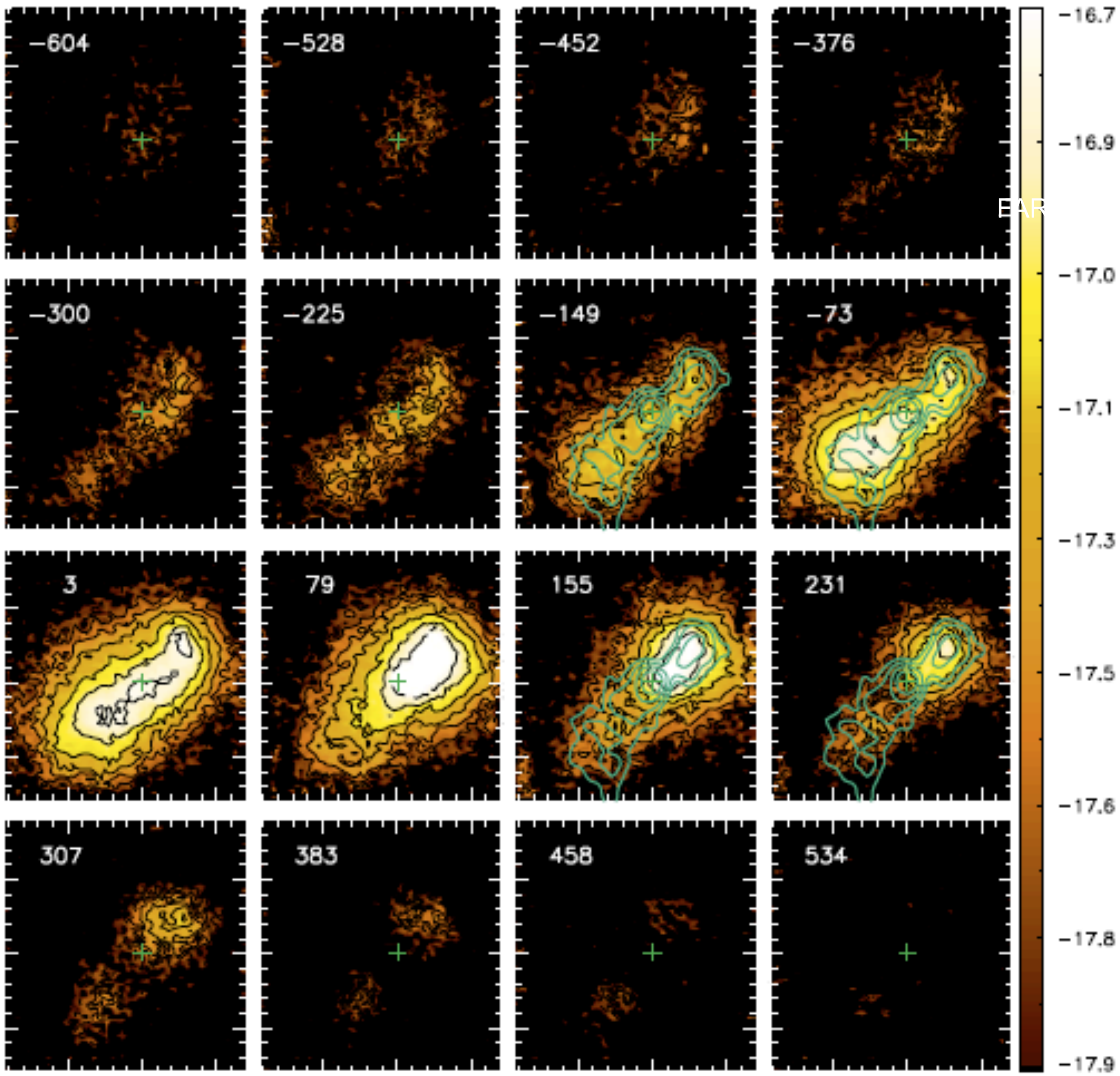
(Riffel et al. 2010)

- Stars: →
rotation; low-σ ring
~250 pc

- Gas:
(i) [Fe II], high σ: →
rotation + outflows
along radio axis;
(ii) H_2, low σ: compact disk
(100 pc) fed by spiral
arms →

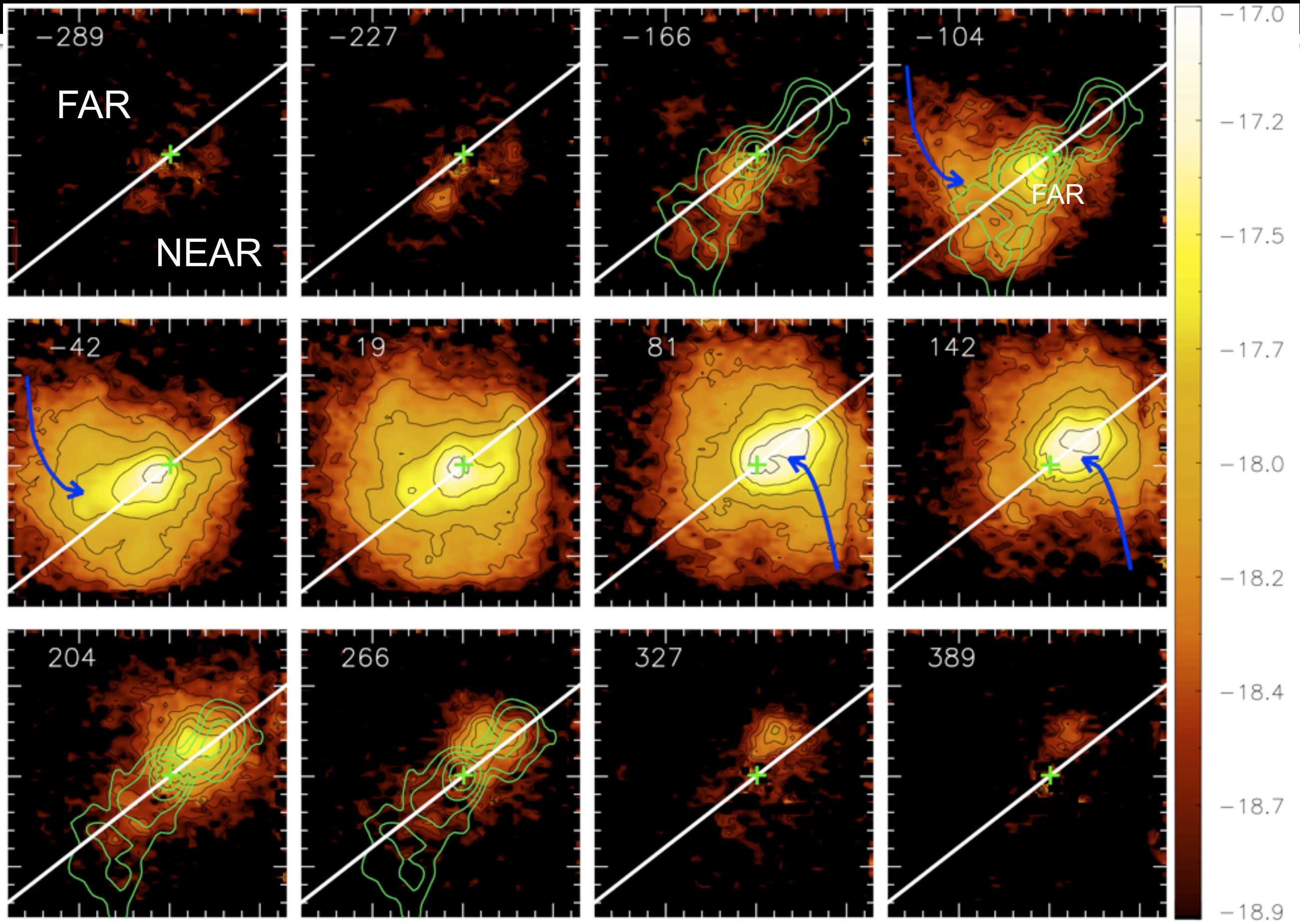


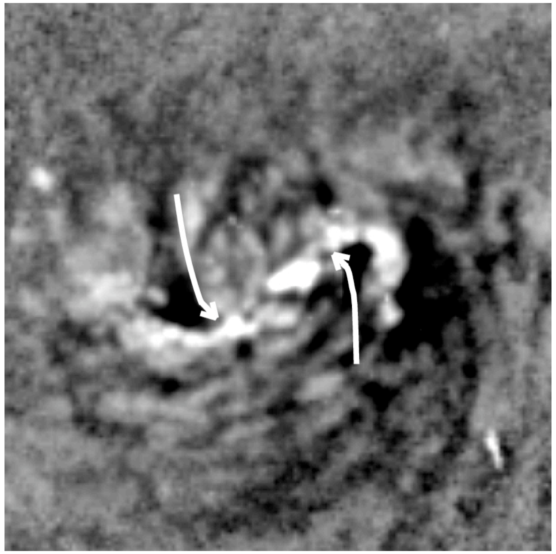
Mrk 1066: [Fe II] channel maps (Riffel et al. 2010)



- High velocities;
- Correlation with radio jet (green contours);
- Outflows in ionized gas of $6x10^{-2}M_{sun}\ yr^{-1}$

Mrk 1066: H_2 channel maps (Riffel et al. 2010)

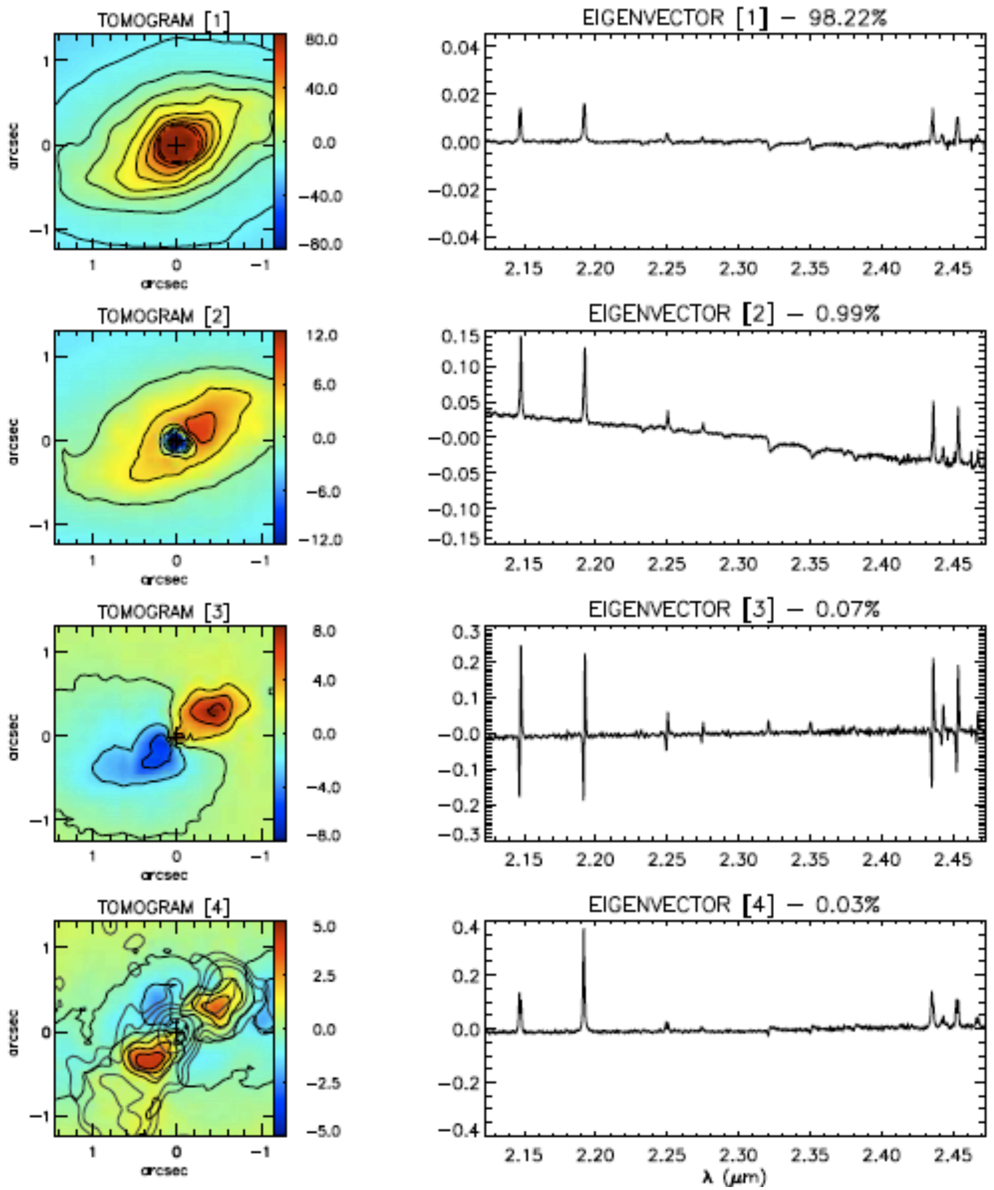




HST Optical structure map

Low velocities (low σ); rotation in the plane + inflows

Mrk 1066: K-band PCA



Blue nuclear continuum

Compact rotating disk

Bipolar outflow

Mass inflow rates along spiral arms

- In ionized gas: $$\Phi_{ion} = nN_e vAm_p f$$

n: number of arms; N_e: density; *v*: velocity; *A*= cross-section area of the arm; m_p: proton mass; *f*: filling factor

Typical values (NGC1097, NGC6951, M81):
n=2; N_e=100 cm-3; v=40 km/s; f=0.005, A=1 kpc^2

→ Φ_{ion}= 0.001 M_{sun} yr^{-1} in ionized gas

- In molecular gas: $$\Phi_{mol} = nN_{H_2} vAm_p f$$

For NGC4501, using the H2 flux F2.12 to obtain $N_{H_2}f$

→ Φ_{mol}= 4 x 10^{-5} M_{sun} yr^{-1} in warm molecular gas

Conclusions and final considerations

- Inflows on scales of 10 to few 100 pc mapped in ionized (HII) and molecular gas;
- Structure: nuclear spiral arms;
- PCA: compact nuclear disks (fed by inflows)
- Near-IR: H2 kinematics distinct from [Fe II] kinematics; when inflows not clearly seen, see rotation in a disk
- Mass inflow rates: ~ 10^{-3} M_{sun} yr^{-1} in ionized gas and smaller in warm molecular gas;

Conclusions and final considerations

- Actual mass inflow rate probably much larger, in neutral and cold molecular gas (estimates of total H2 mass of ~few 10^7 M_{sun}, e.g. Hicks et al. 2009; CO observations by NUA group)
- Dale et al. (2005): cold to warm molecular gas ratio: 10^5 - 10^7 → total inflow rate of ~ few M_{sun} yr^{-1}
- Simões Lopes et al. (2010): dust masses of nuclear spirals in this sample ~ 10^5 M_{sun}; for dust/gas ~ 10^{-2}, M_{gas} ~ 10^7 M_{sun}; if activity lasts 10^7 yr, inflow rate ~ 1 M_{sun} yr^{-1}
- Large Inflow rate: also triggers star formation, explaining excess of young to intermediate-age stars around AGN (Storchi-Bergmann et al. 2001, 2005; Cid Fernandes et al. 2004) and low velocity dispersion rings and disks (Mrk1066, Barbosa et al. 2006; Davies et al. 2007)