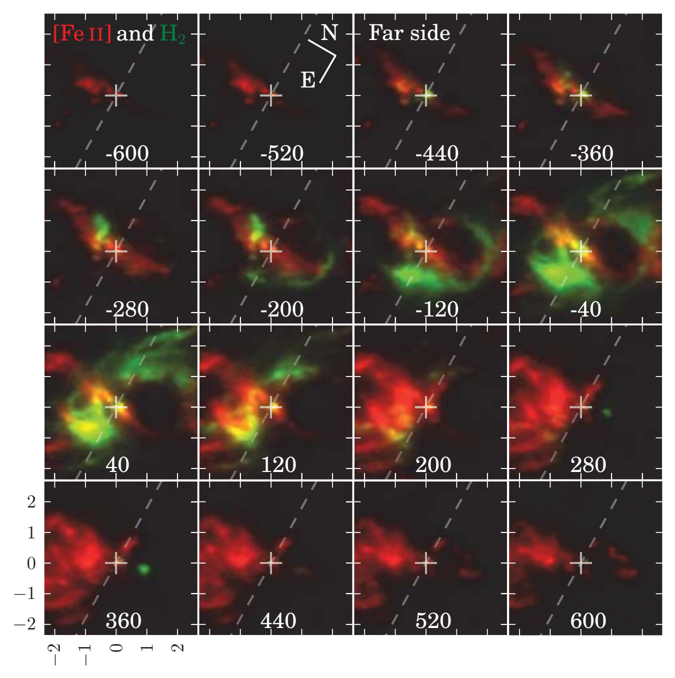
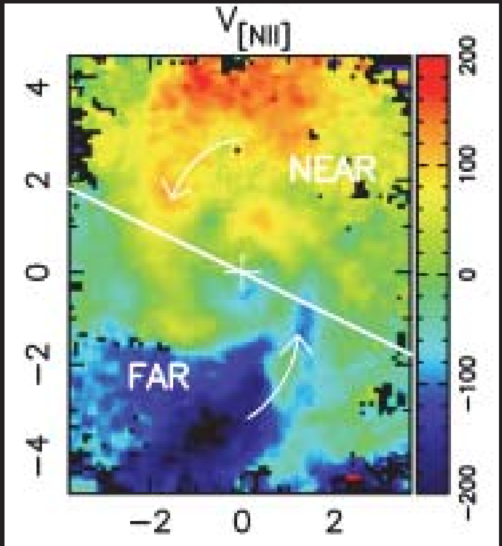
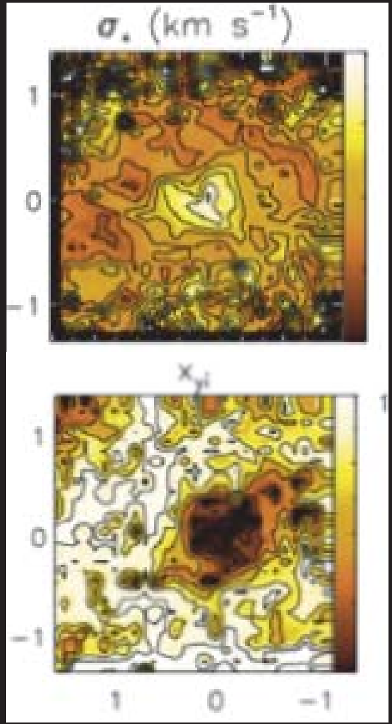
Outflows



Inflows



Stellar Population



Active Galactic Nuclei in 3D (Integral Field Spectroscopy): Feeding and Feedback Processes

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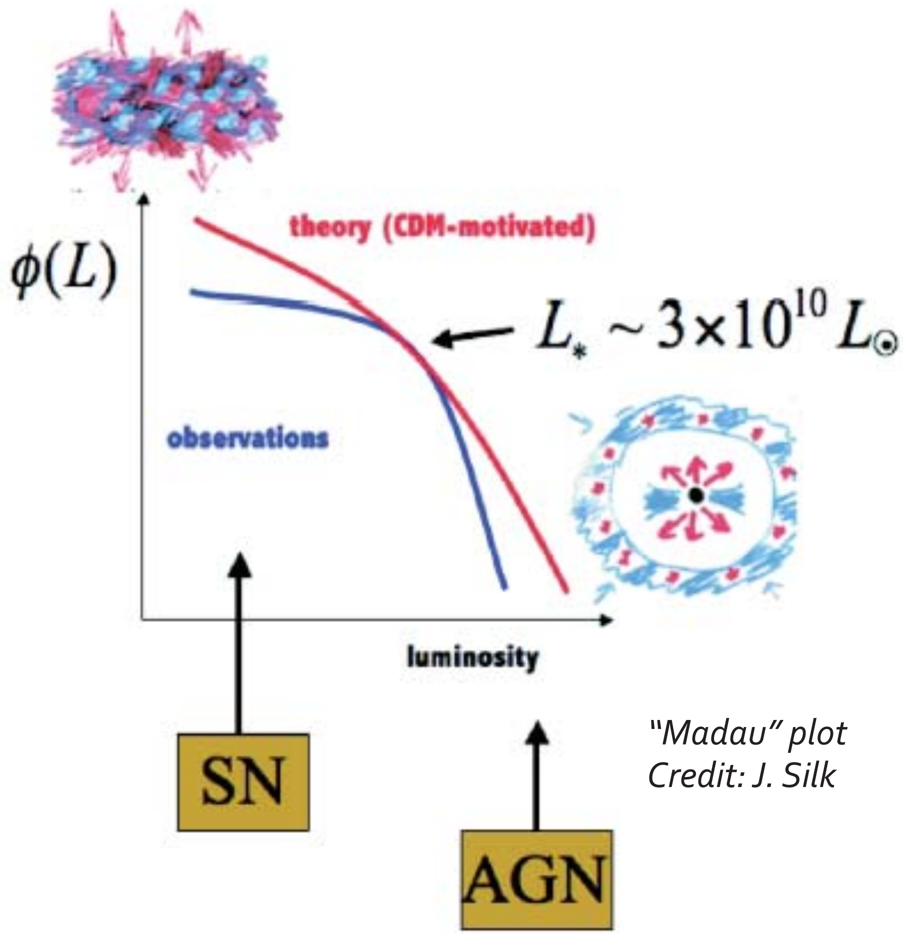
Motivation: feeding and feedback in AGN

- Nuclear activity: fundamental phase in galaxy evolution -> SMBH growth
- Feeding of SMBH is necessary to trigger nuclear activity
- Cosmological models without feedback do not reproduce galaxy luminosity function
- Low L end: feedback from supernovae
- High L end: feedback from Active Galactic Nuclei (Bower et al. 2012)
- Benson et al. 2003; Hopkins et al. 2006; DiMatteo et al. 2008



"Madau" plot
Credit: J. Silk

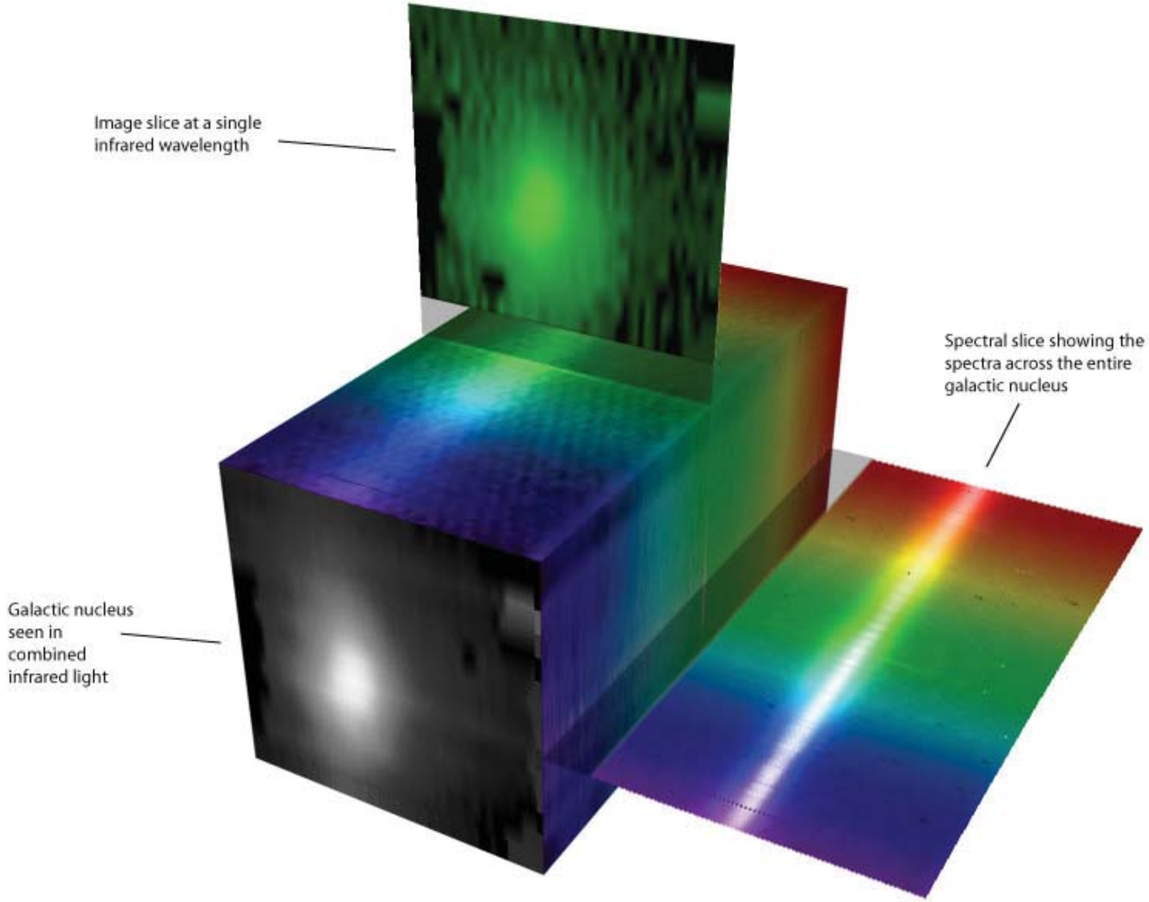
Goals: constrain feeding and feedback processes in AGN

- Although peak of activity in the Universe at z~2, feeding and feedback processes which occur on ~100 pc scales only resolvable in nearby galaxies
- SMBH grows via gas inflow -> *(1) map and quantify gas inflows*
- Bulge grows via formation of new stars in the nuclear region -> *(2) map the circumnuclear stellar population and its kinematics*
- Feedback regulates the growth of SMBH and bulge -> *(3) map and quantify gas outflows*

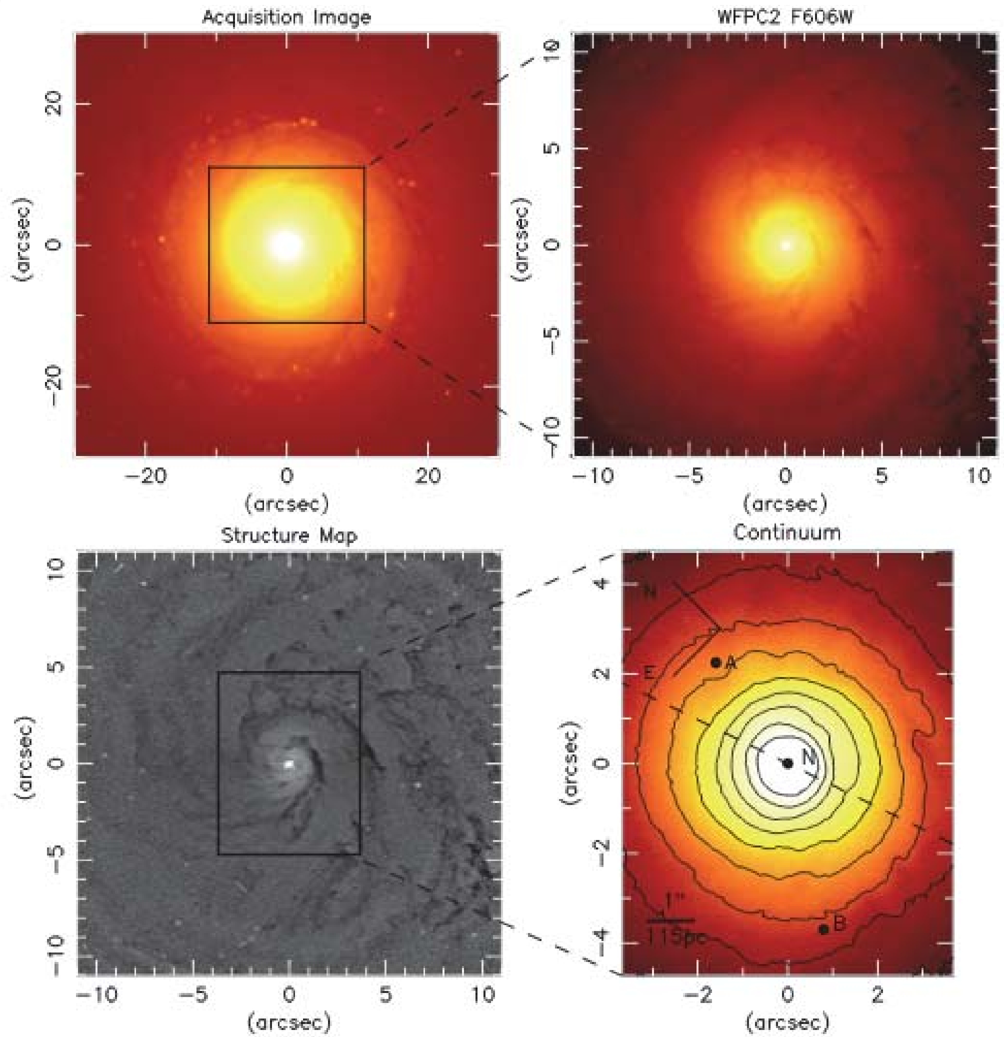
Data: Data cubes from Gemini IFUs

Optical: GMOS IFU
- FOV: 3.5″x5″ or 5″x7″
- Sampling 0.2″
- PSF ~ 0.6″
- R~2500

Near-IR
NIFS + ALTAIR (adaptative optics)
- FOV: 3″ x 3″
- Sampling: 0.04″×0.1″
- PSF ~ 0.1″
- R~5500, Z, J, H, K

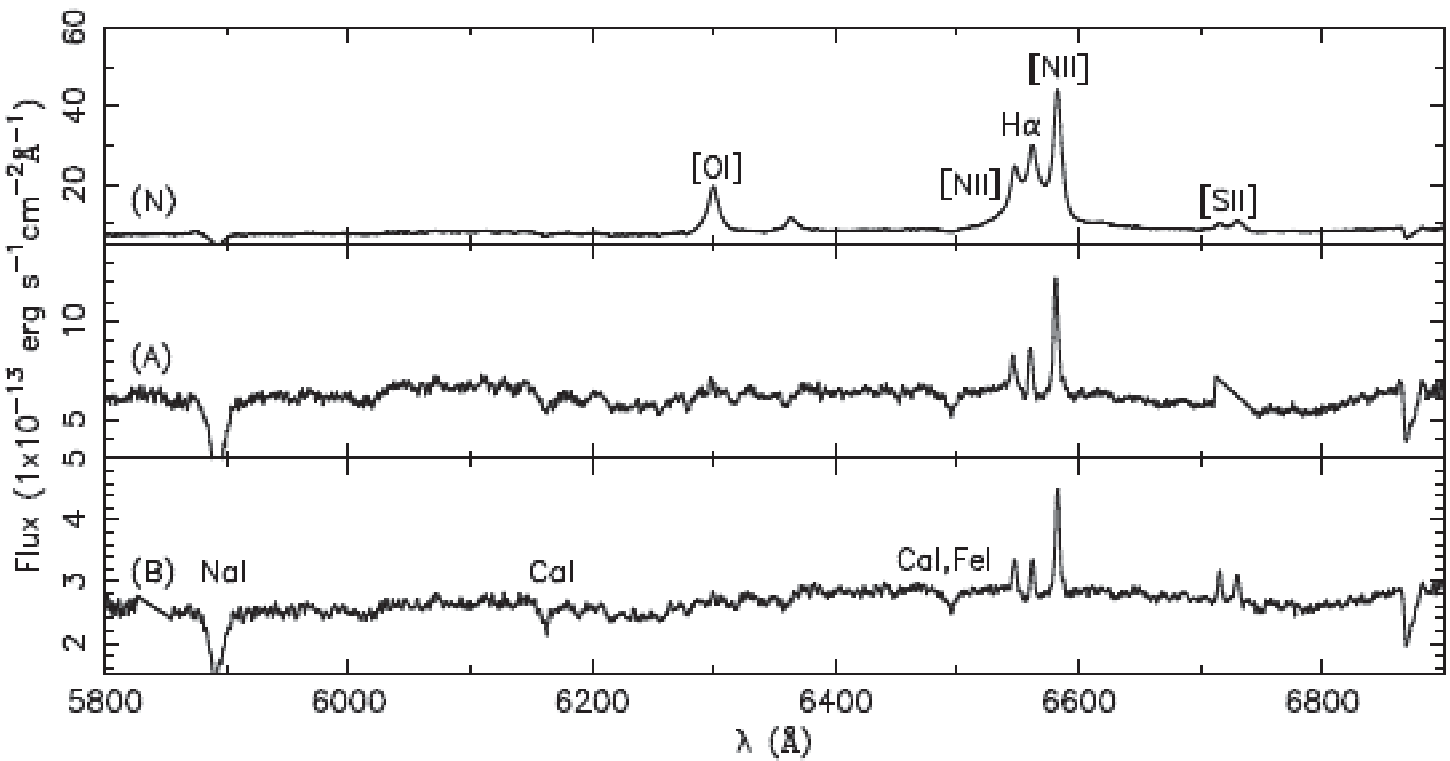


Inflows in NGC7213 (Schnorr Müller et al. 2014b)



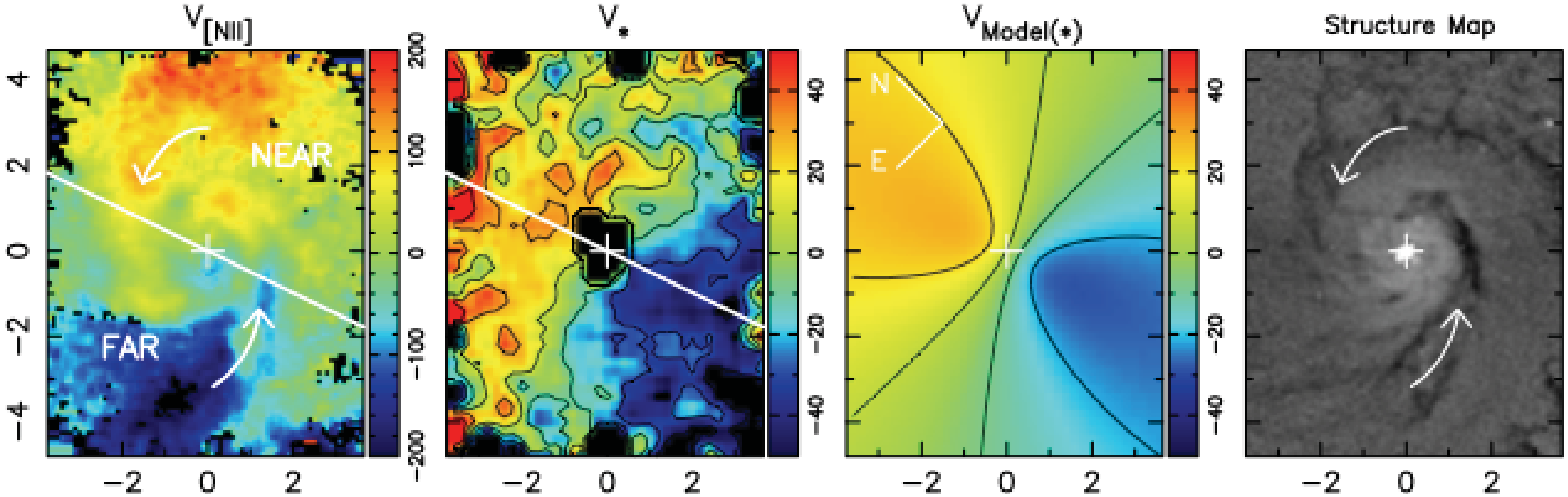
- Sa, LINER/Seyfert 1
- GMOS-IFU
- 0.7 kpc x 1 kpc
- Nuclear spiral
- 0.6”=60 pc

Sample spectra NGC7213 (Schnorr Müller et al. 2014b)



- Stellar kinematics from absorption spectra (pPxf, Cappellari & Emsellem 2004)
- Gas kinematics from emission lines

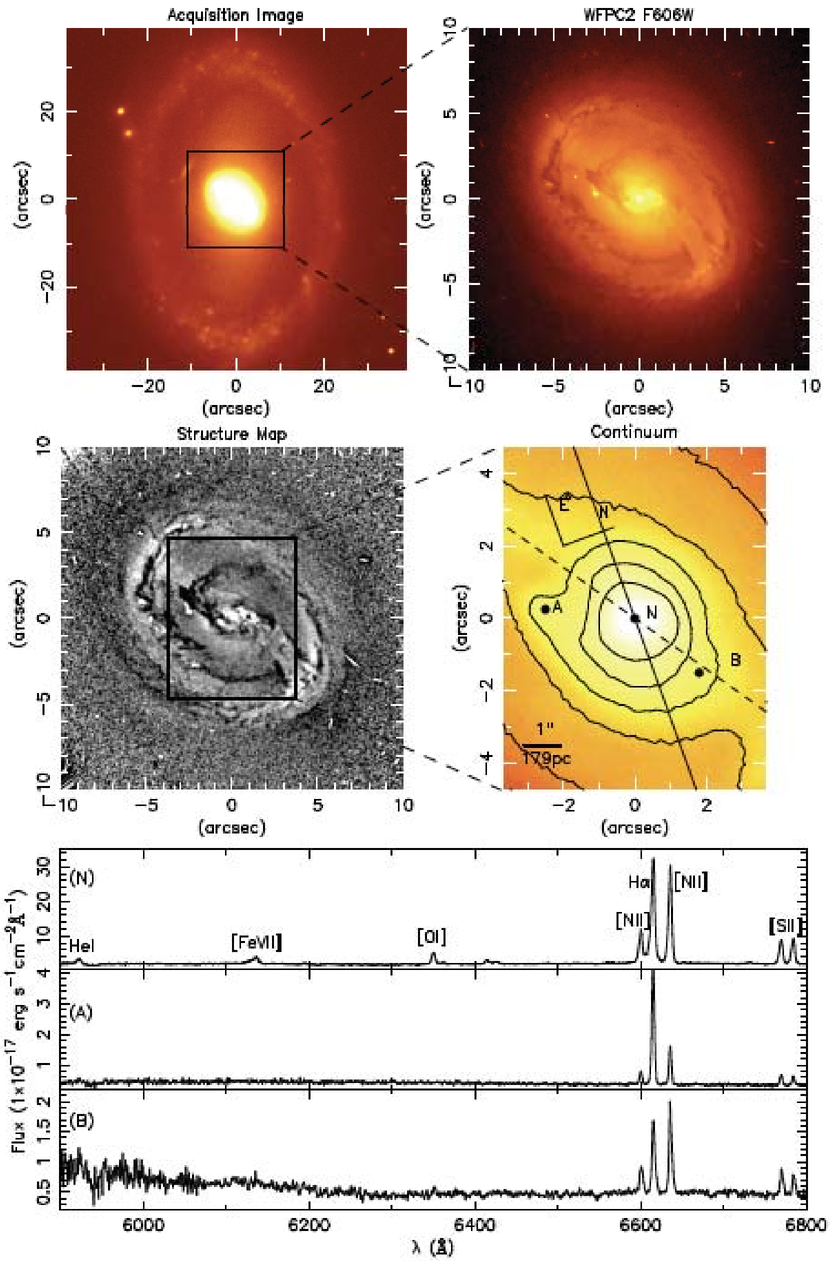
Inflows in NGC7213 (Schnorr Müller et al. 2014b)



Gas kinematics *Stellar kinematics*

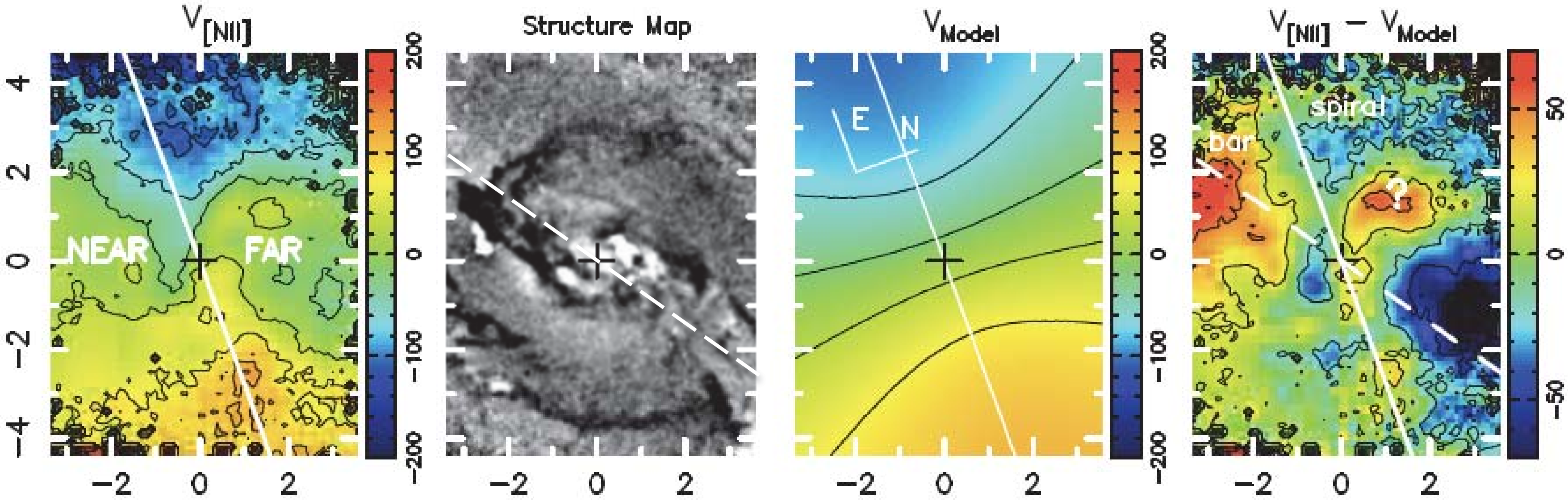
- Stellar kinematics: rotation, close to face on
- Ionized gas kinematics: rotation + streaming along spiral arms (inner 400pc); blueshifts in the far side and redshifts in the near side -> inflow
- Mass of ionized gas: 1.3 x 10^8 $M_\odot$; inflow rate: 0.4 $M_\odot yr^{-1}$ at 300 pc, 0.1 $M_\odot yr^{-1}$ at 100 pc

Inflow along nuclear bar in NGC3081
Schnorr Müller et al. 2015)



- SABO/a, Sy 2
- GMOS-IFU
- 1.25 x 1.80 kpc
- 0.6"=100 pc
- Nuclear bar (~1kpc)

Inflow along nuclear bar in NGC3081
(Schnorr Müller et al. 2015)



- Gas velocity field: rotation + distortions correlated with nuclear spiral and bar
- Subtraction of rotation model: large residuals -> inflows along the bar + compact nuclear outflow
- Total ionized gas mass: 3 x 10^8 $M_{\odot}$;
- Ionized gas mass inflow rate along the bar: <~ 0.1 $M_{\odot} yr^{-1}$

Minor merger fueling AGN in Mrk509 (Fisher et al. 2015)

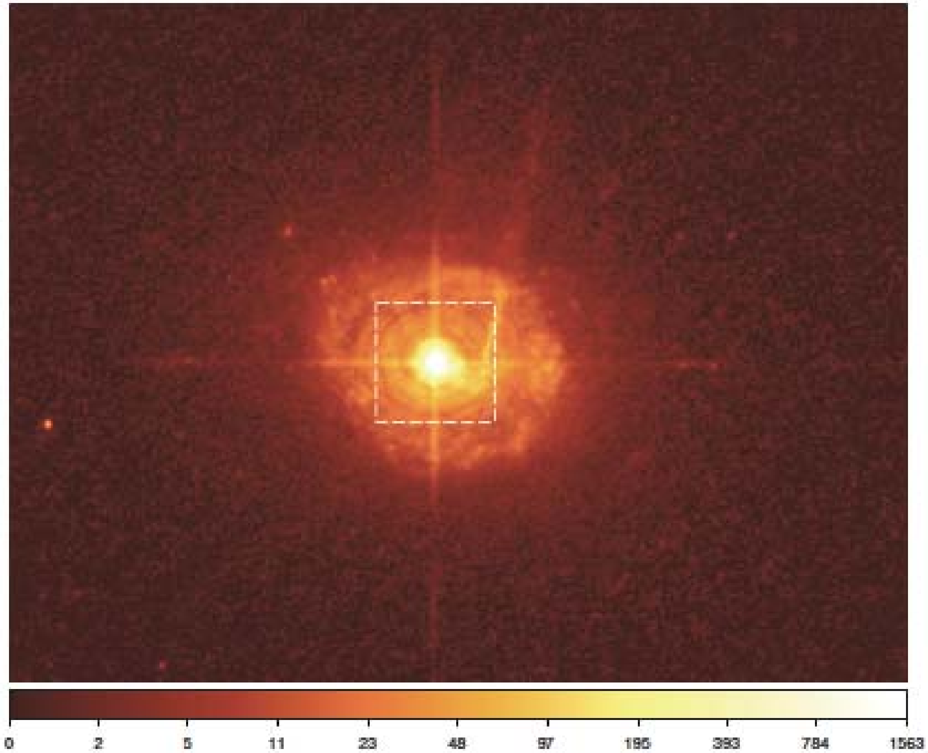
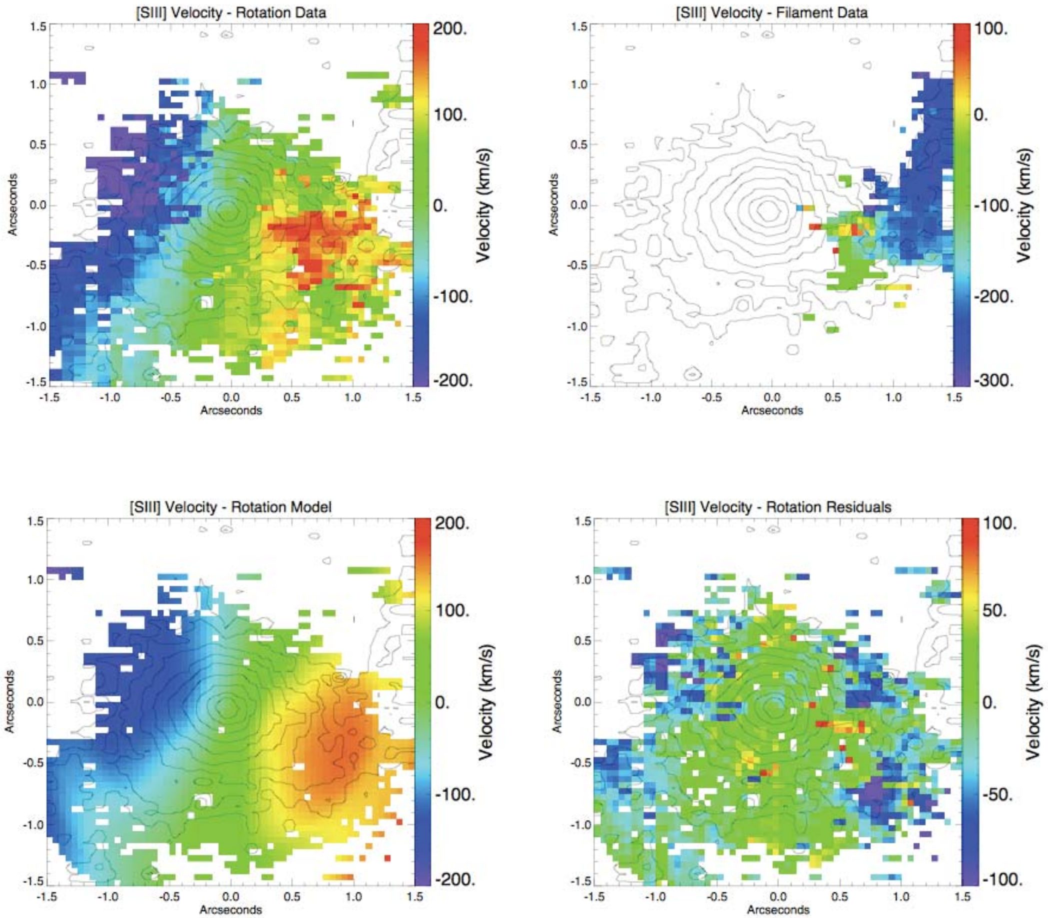


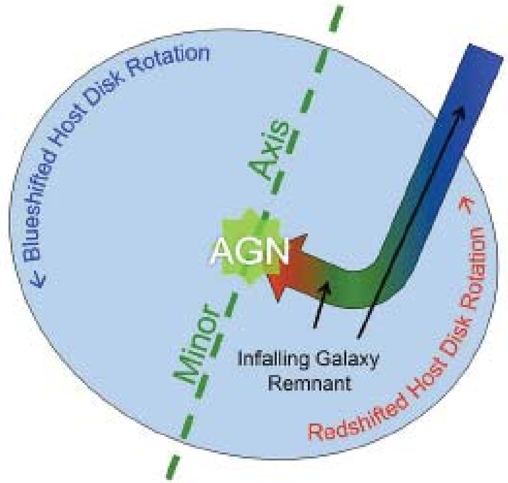
Fig. 1.— *HST* FQ508N narrow-band image of Mrk 509 showing primarily [O III] emission. The filament can be seen to the right of the nucleus, extending from northwest to southeast before making a 90° turn toward the nucleus. Starburst activity can be seen in a ring around the nucleus at a radius of ~ 3″. The dashed box shows the 3″ × 3″ field of view observed with NIFS.

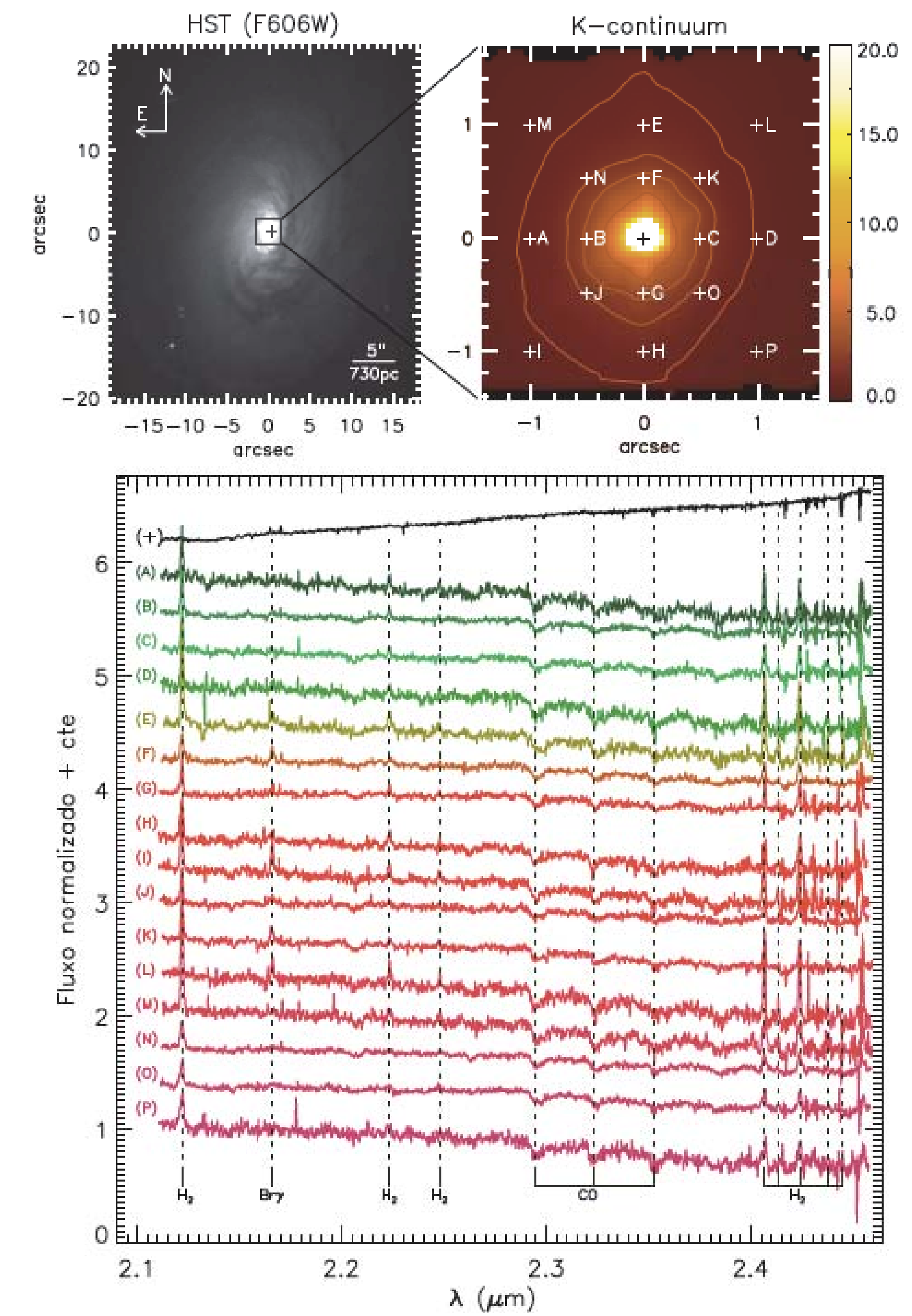
- Sy 1 galaxy at z=0.0346
- 1"= 700 pc
- Filament in [OIII] and continuum
- STIS spectrum of filament: redshift close to the nucleus: inflow?
- NIFS observations to check

Mrk509 (Fisher et al. 2015): scenario



- Gas in the disk: rotation
- Infalling filament: blueshifts then decelerates and turns towards the nucleus



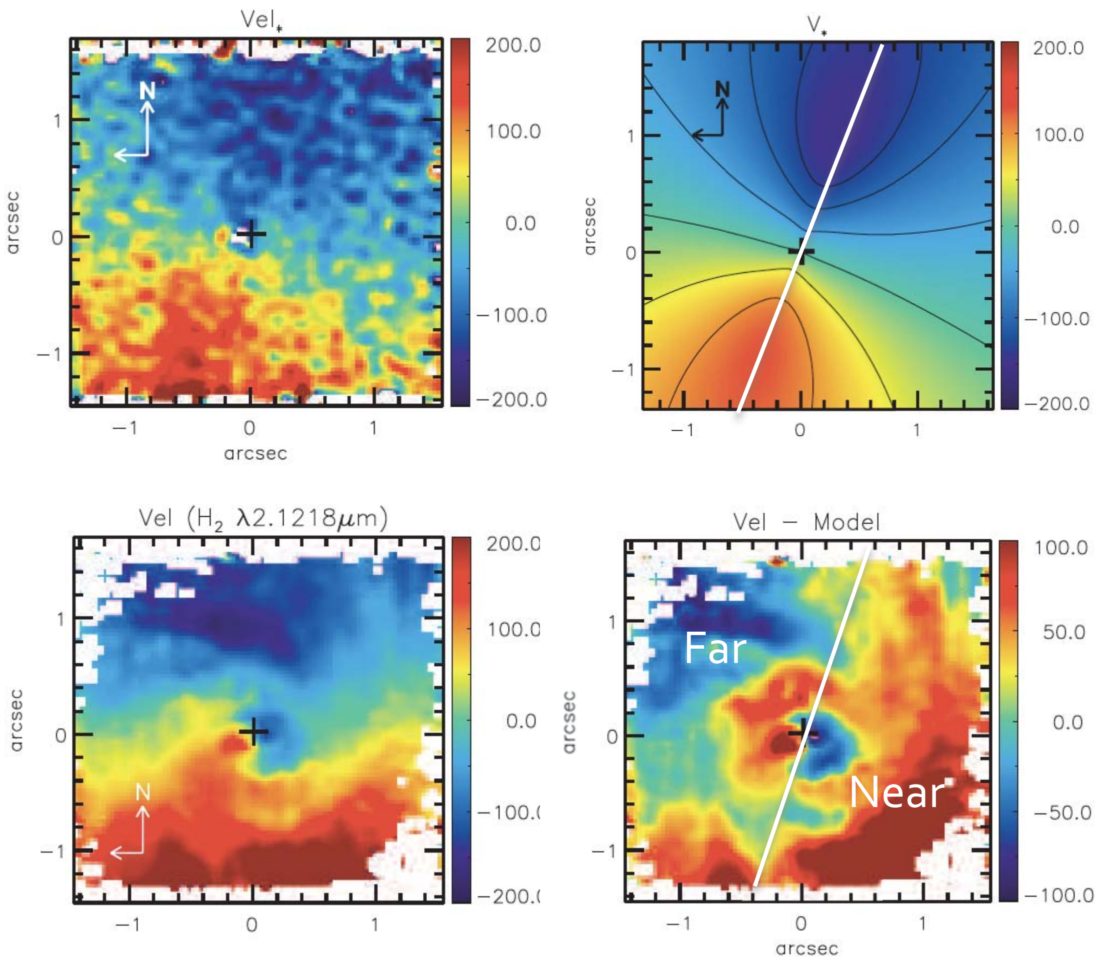


NGC2110

(Diniz et al. 2015)

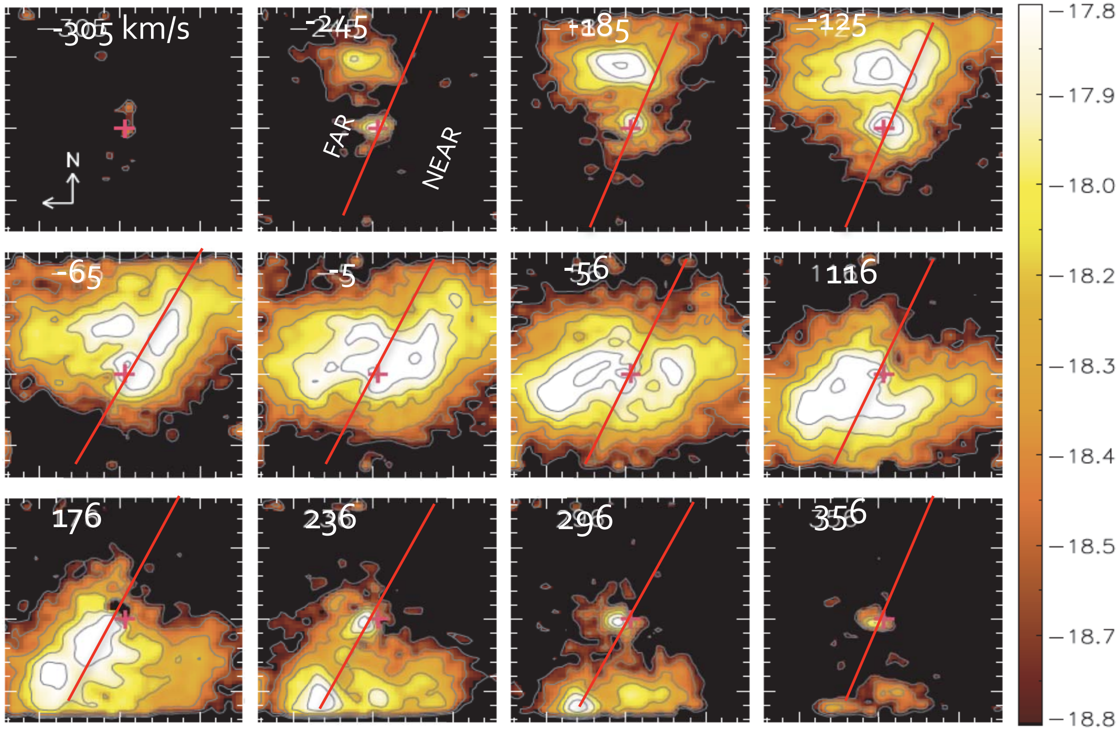
- SO, Sy 2
- FOV= 450 pc x 450 pc
- 0.1″=15 pc
- K-band spectra: stellar and H2 kinematics
- Channel maps in H_2 (R=5300)

NGC2110: centroid velocity



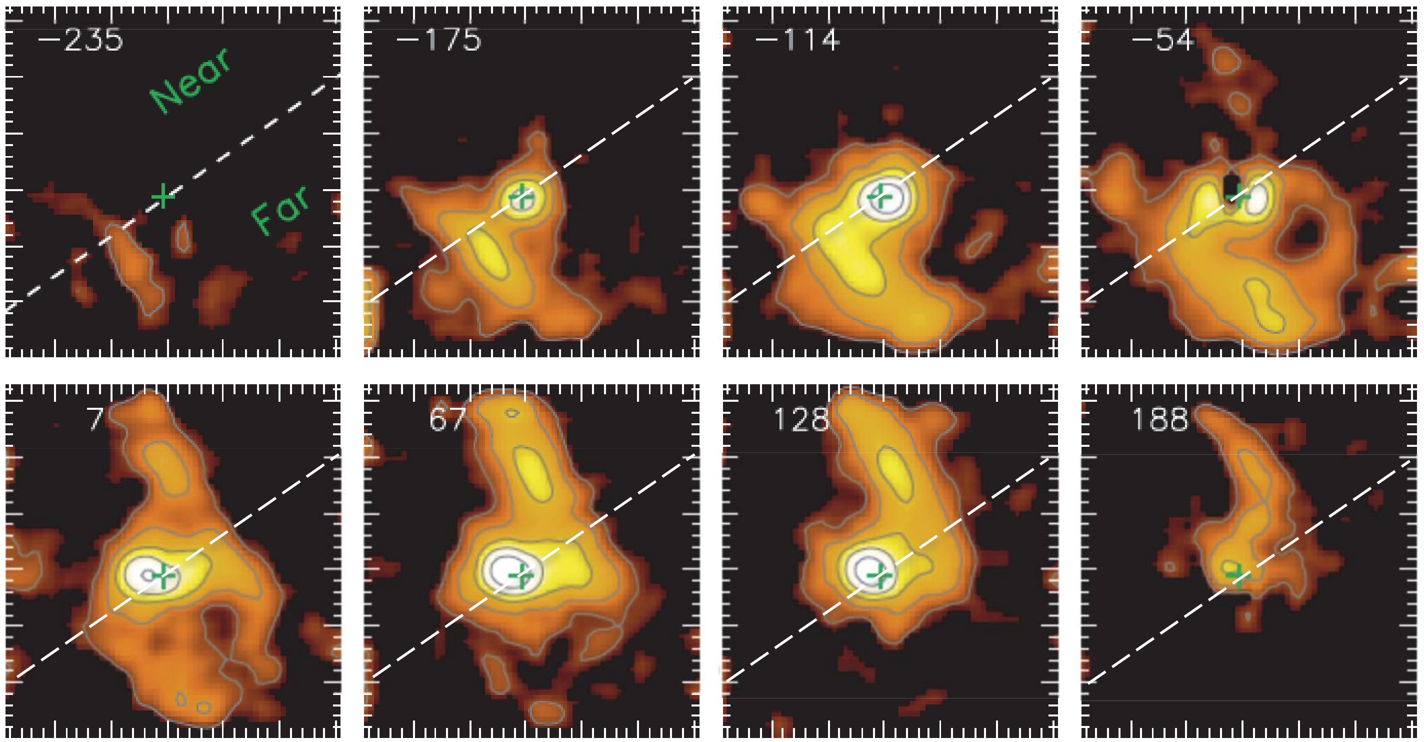
- Stellar velocity field: rotation
- H_2 velocity field: rotation + streaming along ~200 pc spiral arms
- Subtraction of stellar velocity field -> inflow
- Closer to the center: outflow?
- Hot (2000K) H_2 mass ≈ 1400 $M_\odot$
- Cold H_2 mass (Mazzalay +12) ≈ 9.9 x 10^8 $M_\odot$
- Surface density ≥ 710 $M_\odot$ pc^{-2}

NGC2110 H2 channel maps



- Confirming more blueshifts in far side and more redshifts in near side -> inflows
- Hot H2 mass inflow rate ≈ 4 x 10^{-4} $M_{\odot}$ yr^{-1}
- Cold H2 inflow rate ≥ 40 $M_{\odot}$ yr^{-1}
- (using conversion to cold ≥ 10^5, Dale+05,Mazzalay+12)

H2 channel maps in Mrk79 (Riffel, Storchi-Bergmann & Winge 2013)



- Spiral arms within inner ~600 pc: blueshifts in far side, redshifts in near side. If gas is in the plane -> inflow
- Mass inflow rate: ~ 4×10^{-3} $M_\odot$ yr^{-1} x 10^5 (Dale+05, Mazzalay+12) ≥ 400 $M_\odot$ yr^{-1}!!!

Other inflows:

NGC1097 – nuclear spiral: Fathi et al. 2006

NGC6951 – nuclear spiral: Storchi-Bergmann et al. 2007

M81 – nuclear spiral: Schnorr Müller et al. 2011

NGC4051 – nuclear spiral: Riffel et al. 2008

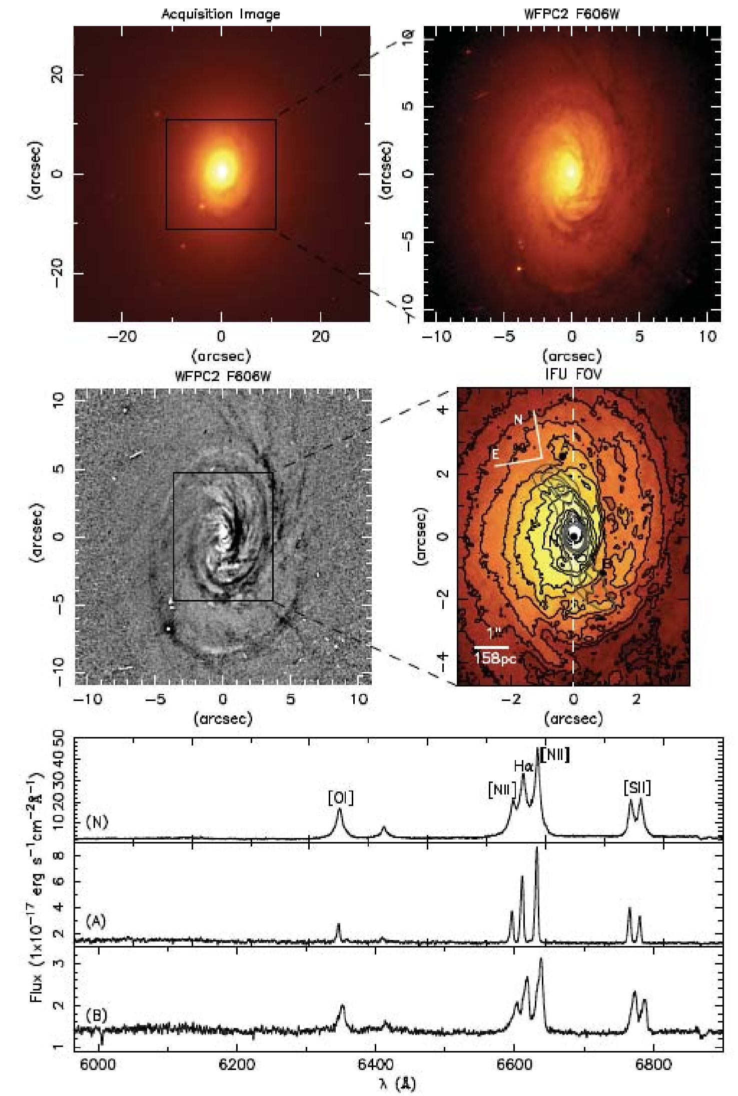
NGC7582 – inflow from nuclear ring: Riffel et al. 2009

Mrk1066 – nuclear spiral + compact disk: Riffel et al. 2011

Mrk766 – compact H2 disk: Shönell et al. 2014

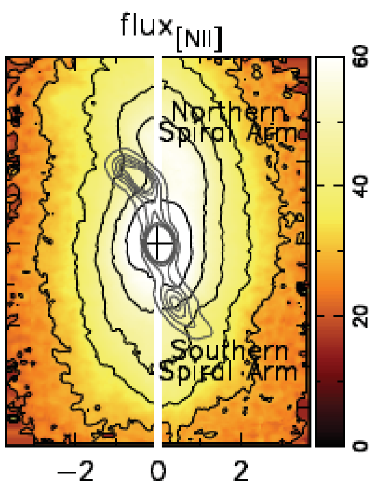
- Near-IR: H2 in inflow and/or rotation

Outflow in NGC2110 (GMOS-IFU, Schnorr Müller et al. 2014a)



- SO galaxy
- 1″= 160 pc
- Radio jet extending by ~4″ (~600pc)

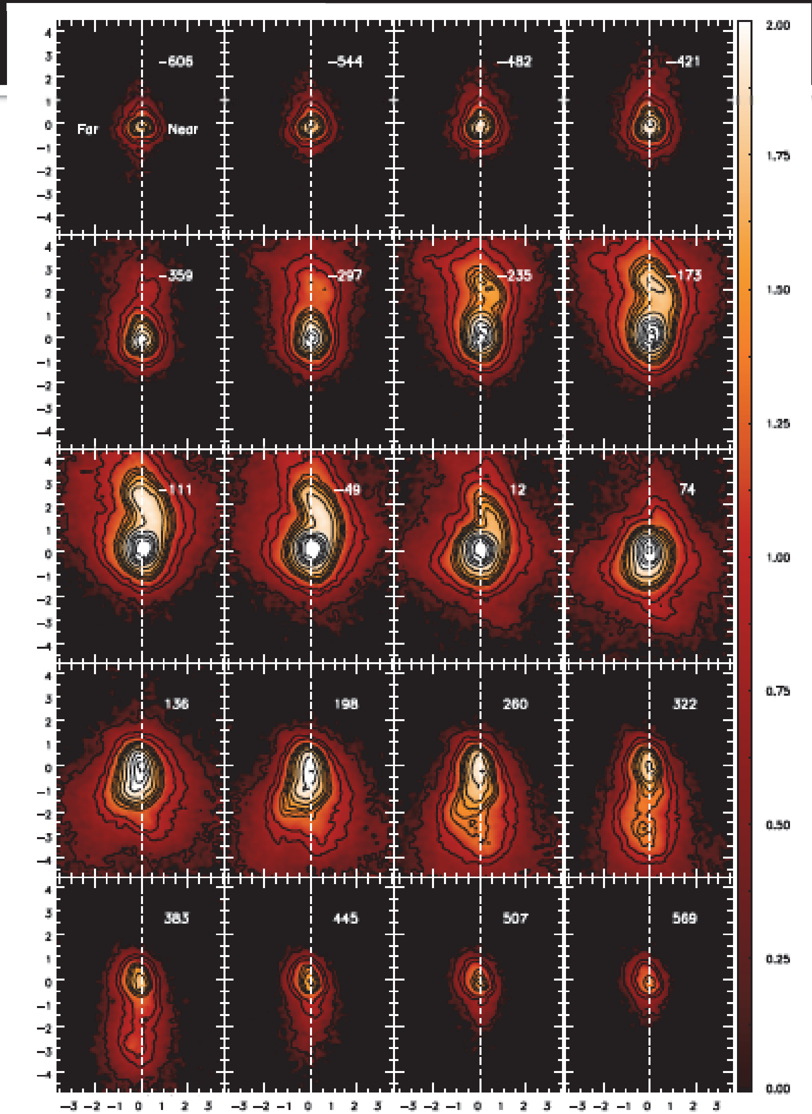
Line emission extending over the whole FOV (at least up to 800 pc)



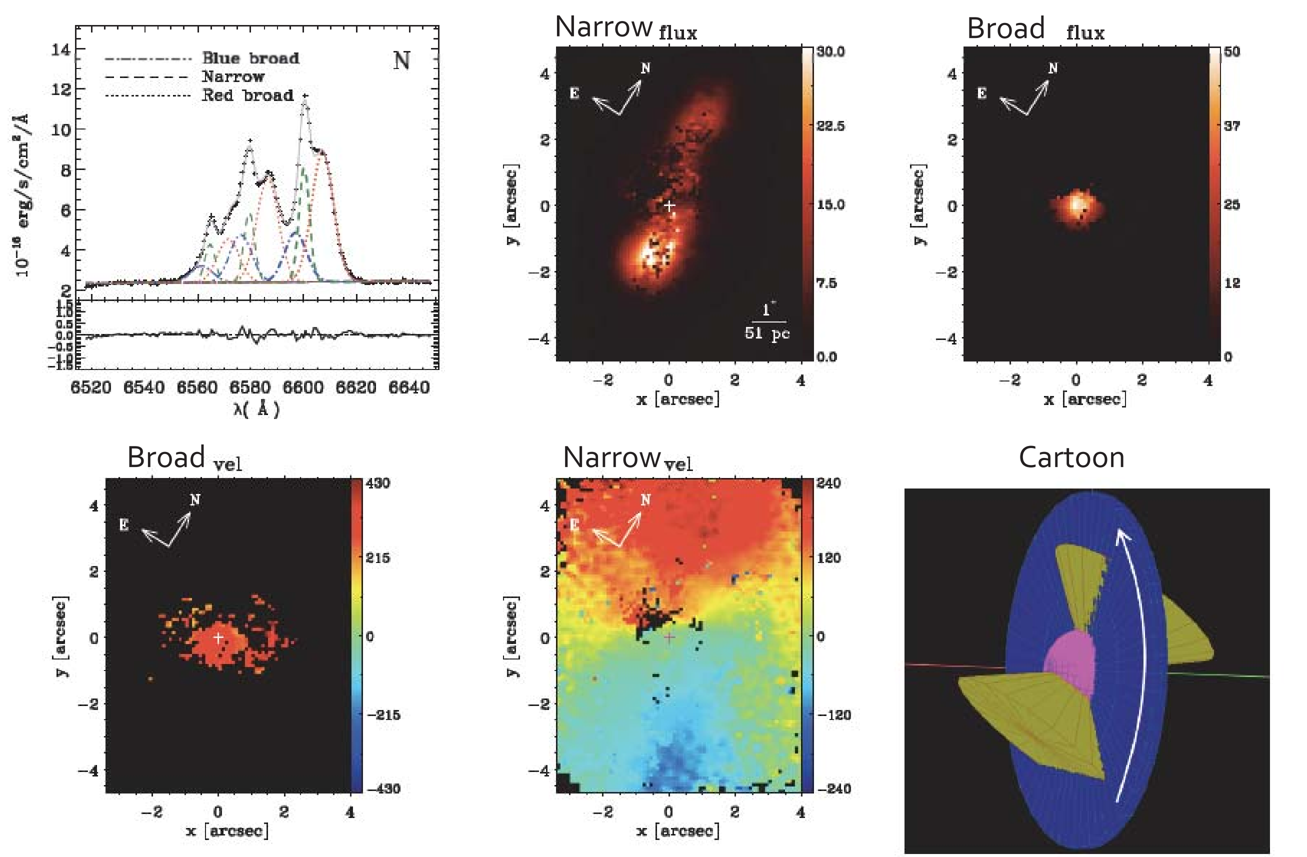
Kinematics: Compact Outflow

Several kinematic components, main:

- Extended emission: illumination/ ionization of gas rotating in the plane out to > 800 pc
- Outflow only in inner ~160 pc (barely resolved);
- Mass of ionized gas: 9.8 x $10^7 M_\odot$
- Mass outflow rate: ~0.9 $M_\odot$ yr^{-1}

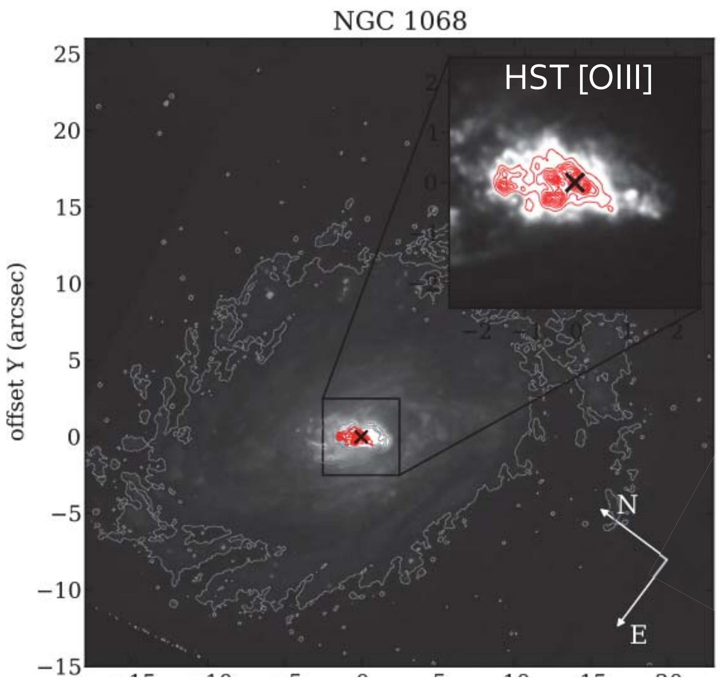


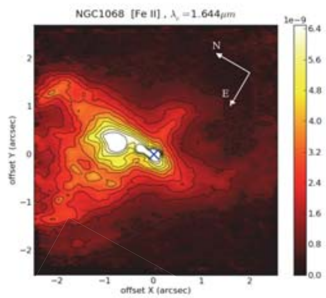
Outflows in NGC1386 (Lena et al. 2015)

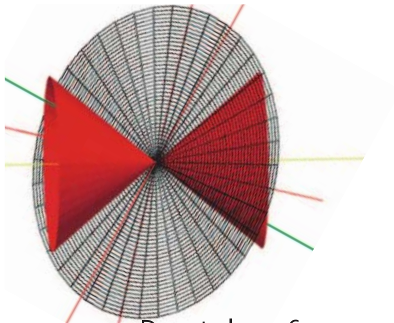


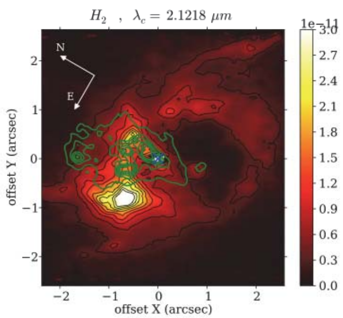
- Compact outflow within 40pc, but extended emission up to the borders of the field at ~200pc; mass outflow rate: ~ 0.1 $M_{\odot}$ yr^{-1}
- Kinematics of most extended emission: rotation in the galaxy plane -> illumination of gas rotating in the plane, not outflow

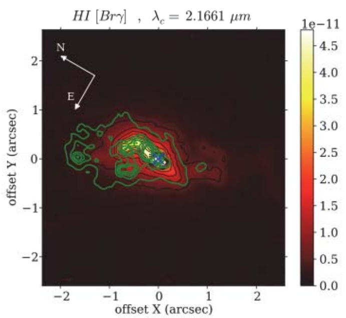
Outflows in NGC 1068 (NIFS, Barbosa et al. 2014)

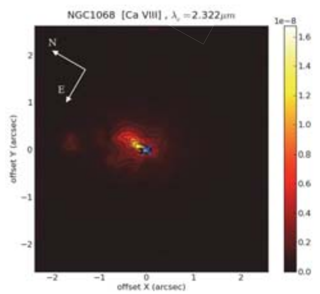






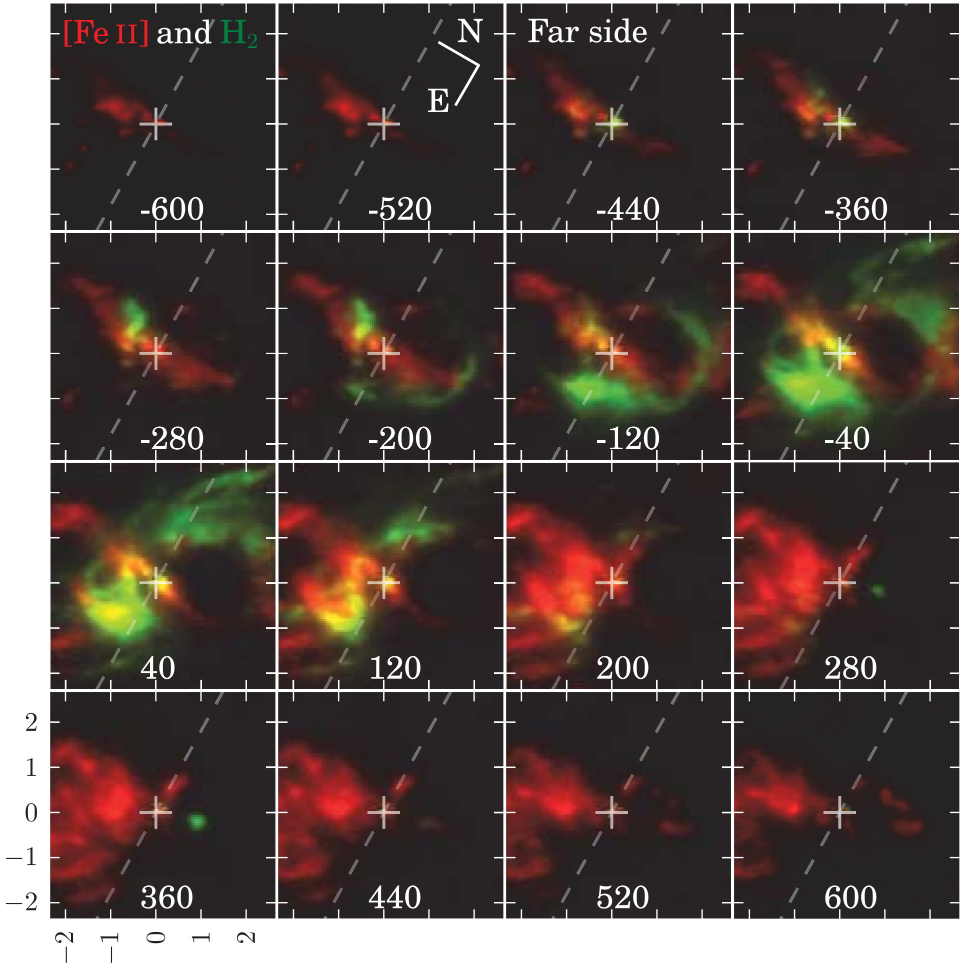






- Sb, Seyfert 2
- 500 pc x 500 pc
- 0.1"= 7 pc
- [FeII]: 250 pc from nucleus: broader than conical shape of [OIII]-> partial ionization zone;
- H_2: 100 pc (radius) off-centered ring

NGC1068 channel maps: [FeII] and H2



[Fe II]: outflows

- Velocities up to 800 km/s
- Mass outflow rate: 4± 1 $M_\odot$ yr^{-1}

H2 (green): decelerated expansion in the plane

- -200 km/s < v < +200 km/s
- Hot H2 mass ≈ 29 $M_\odot$
- Estimated cold H2 mass ≈ 2.1 x 10^7 $M_\odot$
- Garcia-Burillo+14, ALMA: for 50 pc < radius < 400 pc, outflow in H2 with mass 2.7±1 x 10^7 $M_\odot$
- Surface density >100 $M_\odot$ pc^{-2}

Other outflows

NGC5929 and NGC5899: Riffel et al. 2015

Mrk1066: Riffel et al. 2010

Mrk1157: Riffel et al. 2011

Arp102B: Couto et al. 2013

NGC5548: Schönell et al. 2015

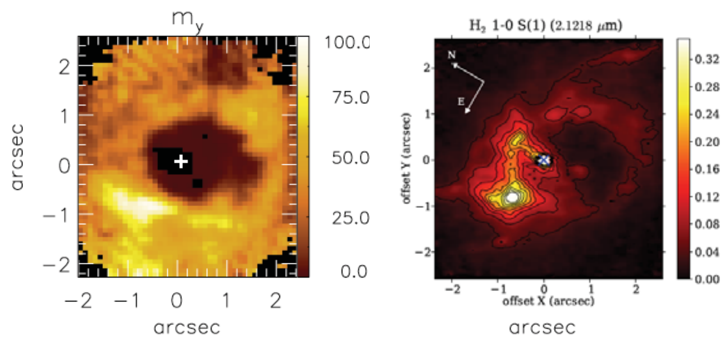
Summary and Conclusions: feeding

- Inflows in nuclear spirals, bars and disks, capture of dwarf companion; sometimes observed in H^+ and almost always in H2 (if not inflow, compact rotation);
- Inflow velocities 50 – 200 km/s; Inflow rates ~0.1 – few $M_\odot yr^{-1}$
- Estimated total gas masses in inner kpc ~ 10^7 - 10^9 $M_\odot$
- Surface molecular mass densities: 100 – 7000 $M_\odot pc^{-2}$ -> KS law -> SFR ~ 0.1 – 10 $M_\odot yr^{-1}$

➤ **co-evolution of SMBH and galaxy**

Summary and Conclusions: stellar population

- Young stellar population related to H2 in NGC1068 (Storchi-Bergmann et al. 2012):



- Possible evolutionary scenario (Storchi-Bergmann 2001, Davis 2007, others):

Mass inflow -> star-forming rings (with possible mild nuclear activity) -> nuclear activity (with intermediate age rings) ->

Co-evolution in the near Universe: SMBH growth + bulge growth (~10^{-3} $M_{\odot} yr^{-1}$ x ~ 1 $M_{\odot} yr^{-1}$)

Summary and Conclusions: outflows

- Outflows in ionized gas with velocities: 200 – 800 km s^{-1} and mass outflow rates of ~few $M_{\odot}$ yr^{-1}
- Geometry:

(1) hollow conical/hourglass (Fisher+13: ~ 1/3 of AGN)
(2) Compact or unresolved (inner 100-200 pc)

➔ **Possible evolution: compact bubble ("young" AGN) expanding to "open" conical/hourglass shape**

- Scenario: most extended emission due to illumination of gas rotating in the galaxy disk; only inner part is outflowing -> possible overestimation of power of the outflow by 1-2 orders of magnitude if it is assumed that all the gas is outflowing

Summary and Conclusions: outflows

- Power of the outflow in ionized gas: < 0.1% L_{bol} in the near Universe -> little effect on the galaxy (but maybe larger on other gas phases?)
- Future: expand studies to a complete sample including more luminous AGN -> look for correlations of geometry/extent/kinematics/mass outflow rate with AGN luminosity (MaNGA SDSS-IV, GMOS-IFU, NIFS)