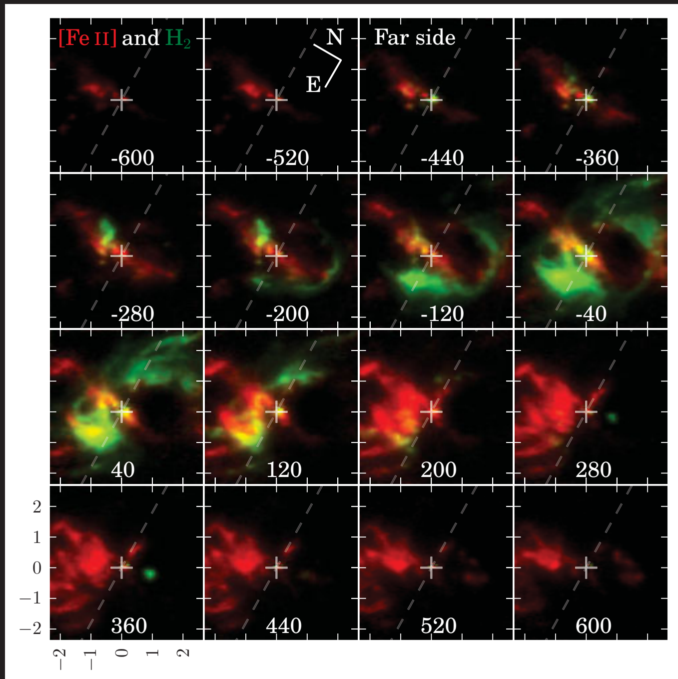

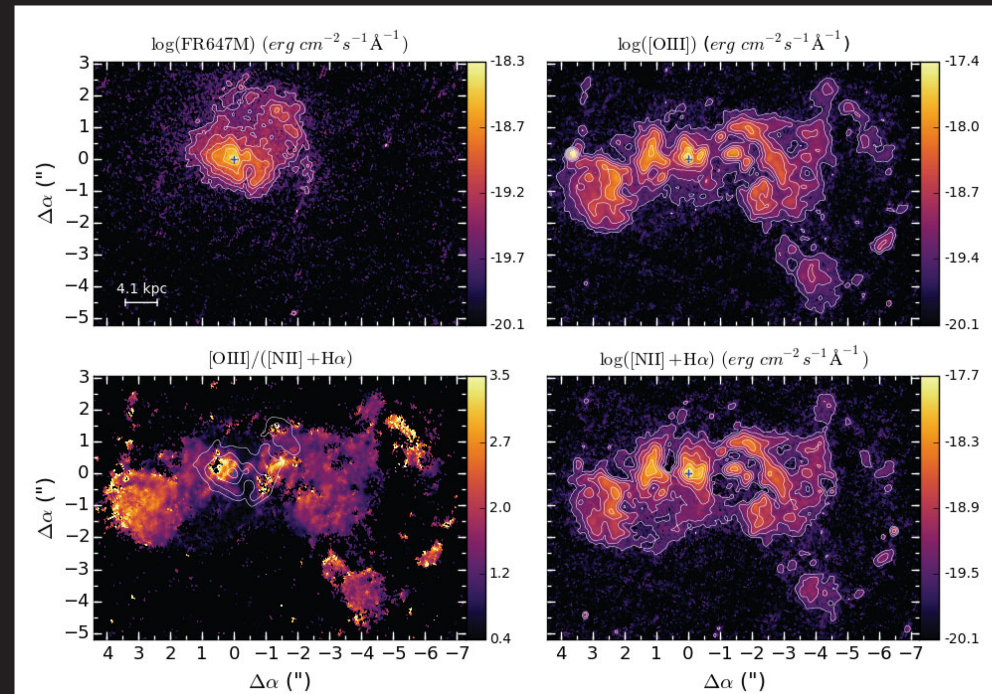

Observational constraints on feeding and feedback of Active Galactic Nuclei

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Summary

- Motivation
- Inflows:
  - Theory and observations
  - Different scales
  - The crucial inner kpc: IFU observations
  - Summary of inflows
- Outflows:
  - The inner kpc; IFU observations
  - Summary of outflows

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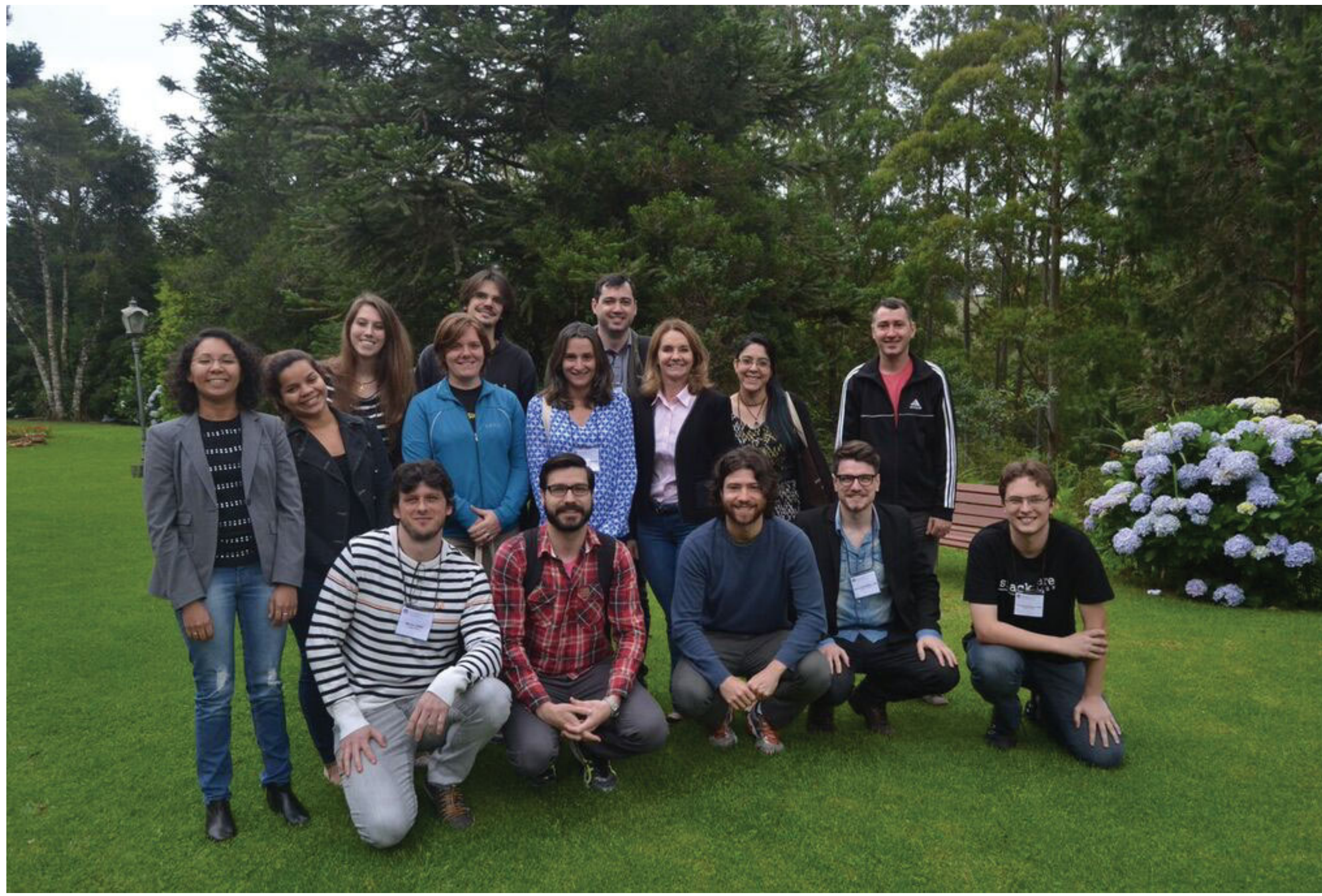


Feeding and feedback of Supermassive Black Holes (SMBH)

- Occur in Active Galactic Nuclei (AGN): fundamental phase in galaxy evolution
- Why? Madau & Dickinson 14: SMBH is connected to galaxy growth
- How? Feeding and Feedback of SMBH

Madau & Dickinson 2014:

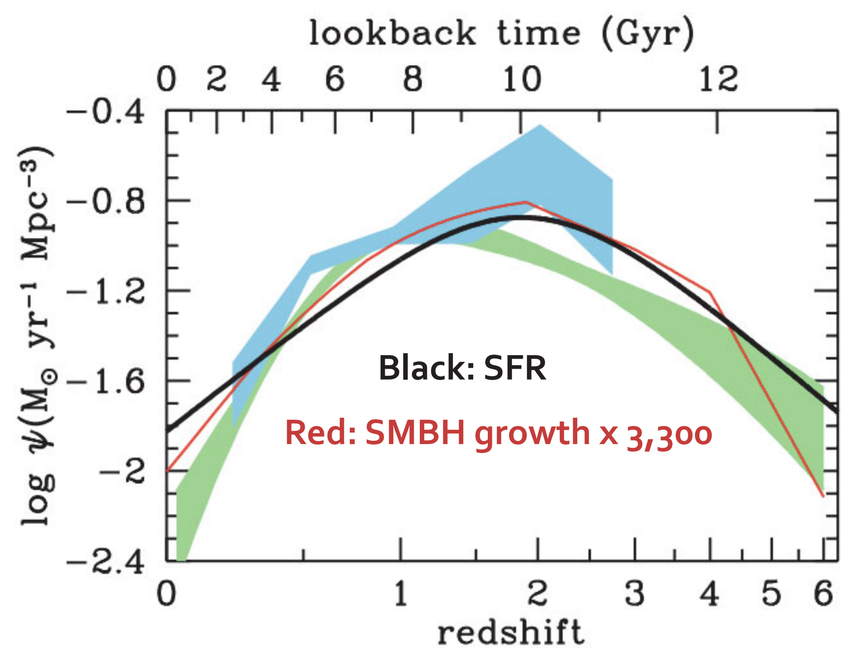
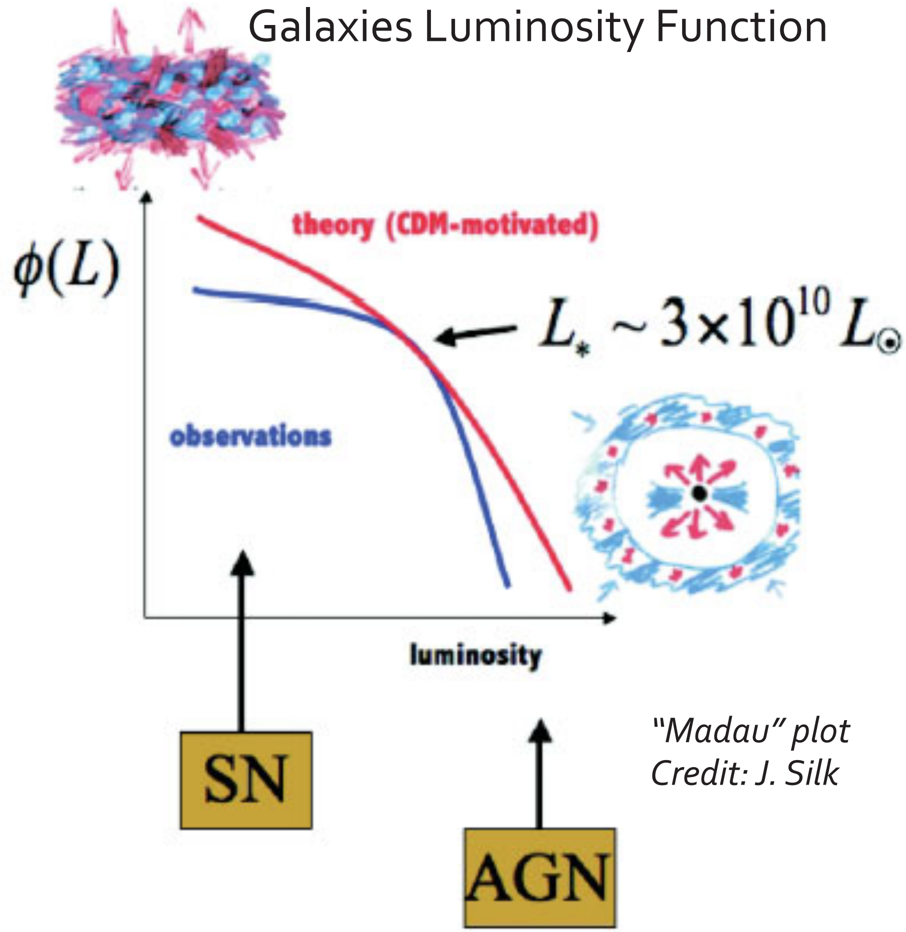


Figure 15: Comparison of the best-fit star formation history (*thick solid curve*) with the massive black hole accretion history from X-ray [*red curve* (Shankar et al. 2009); *light green shading* (Aird et al. 2010)] and infrared (*light blue shading*) (Delvecchio et al. 2014) data. The shading indicates the $\pm 1\sigma$ uncertainty range on the total bolometric luminosity density. The radiative efficiency has been set to $\epsilon = 0.1$. The comoving rates of black hole accretion have been scaled up by a factor of 3,300 to facilitate visual comparison to the star-formation history.

Motivation: feedback

- Feedback from AGN: outflows, jets, radiation
- -> Necessary to reproduce galaxy luminosity function
- Theory: Benson et al. 2003; Hopkins et al. 2006; Di Matteo et al. 2008, Bower et al. 2012
- Prescriptions used in models: not well constrained

Galaxies Luminosity Function



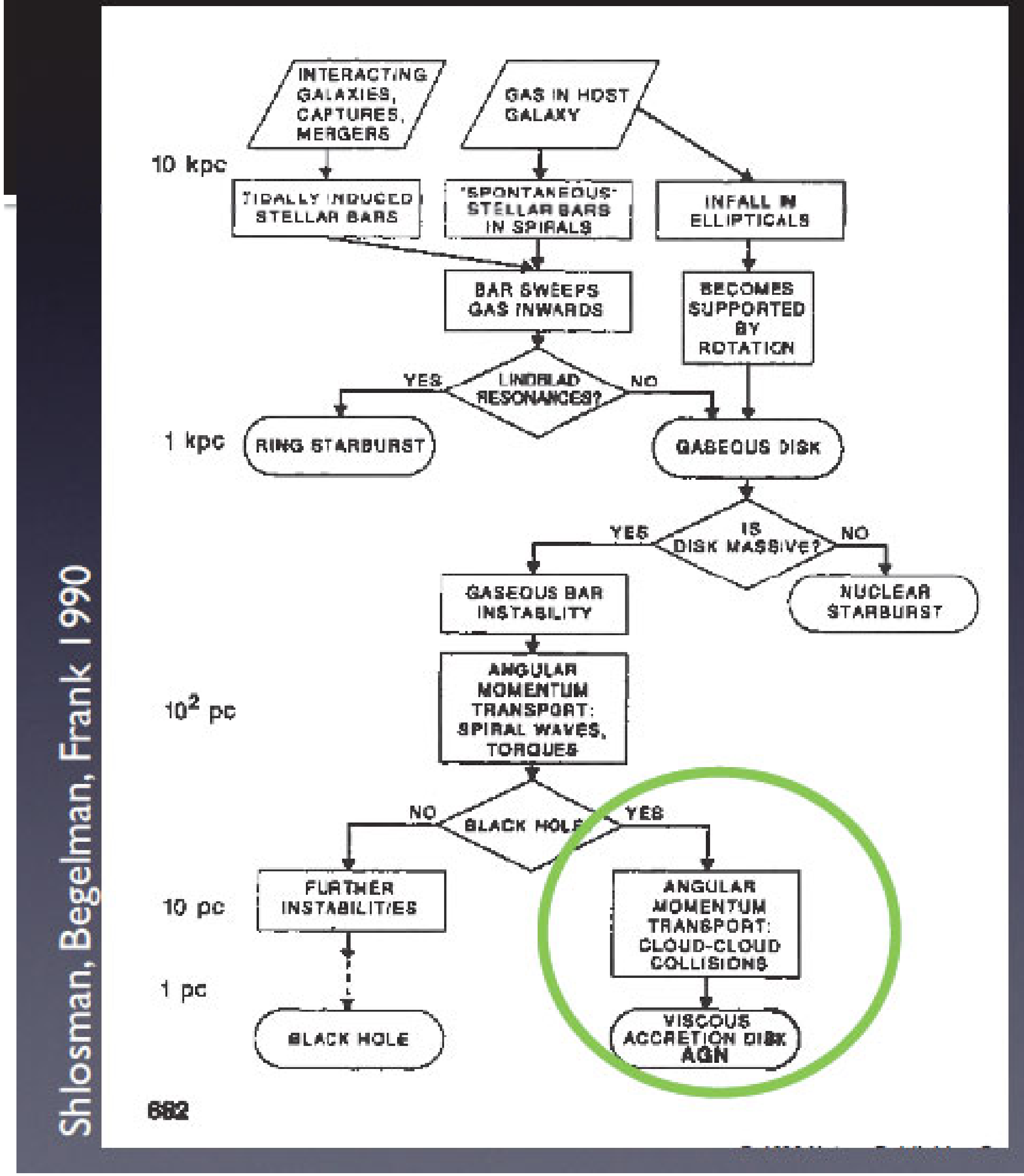
"Madau" plot
Credit: J. Silk

How to constrain feeding and feedback processes in AGN

- Feeding of SMBH -> *(1) map and quantify gas inflows*
- Bulge grows via formation of new stars -> *(2) map the circumnuclear stellar population and its kinematics*
- Feedback of SMBH -> *(3) map and quantify gas outflows*

Feeding: Inflows

Models: Slosman+90



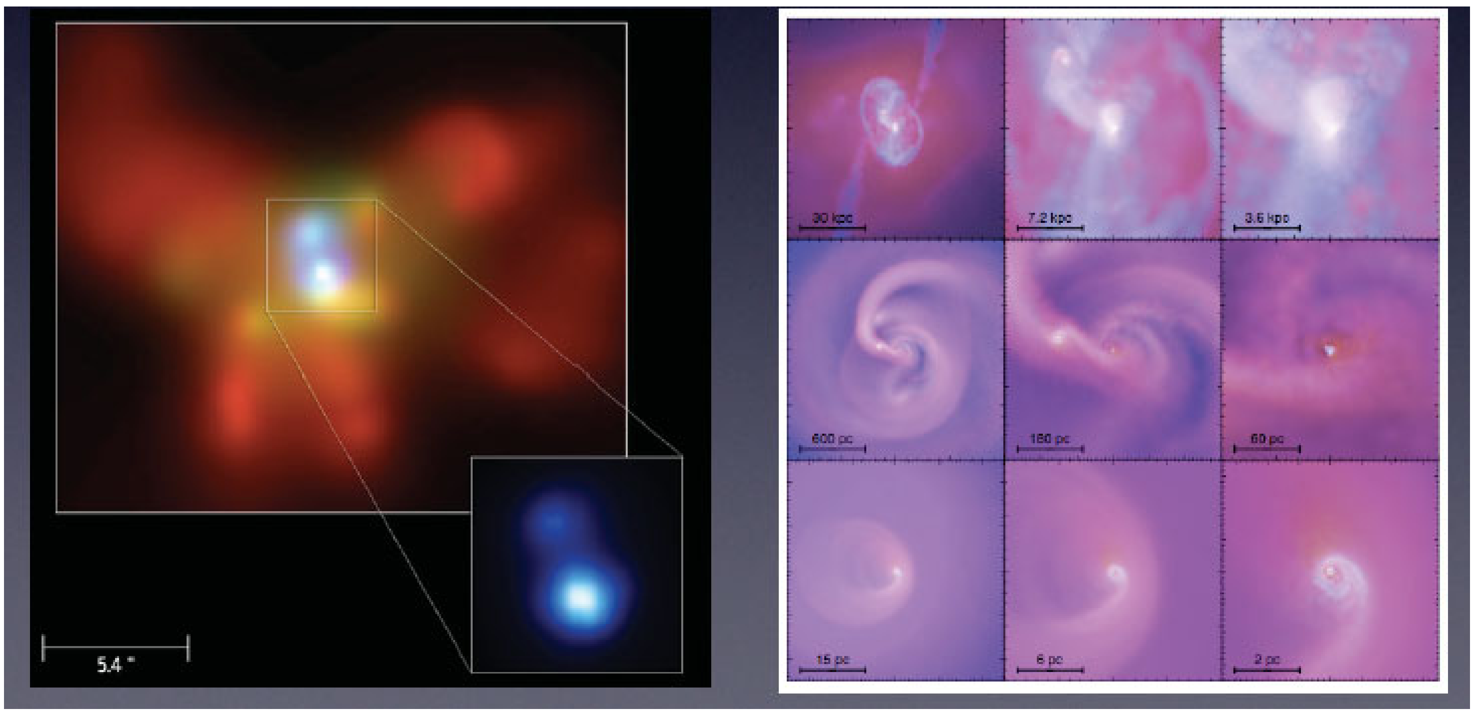
Removal of angular momentum:

Galaxy Interactions

“Bars within bars”

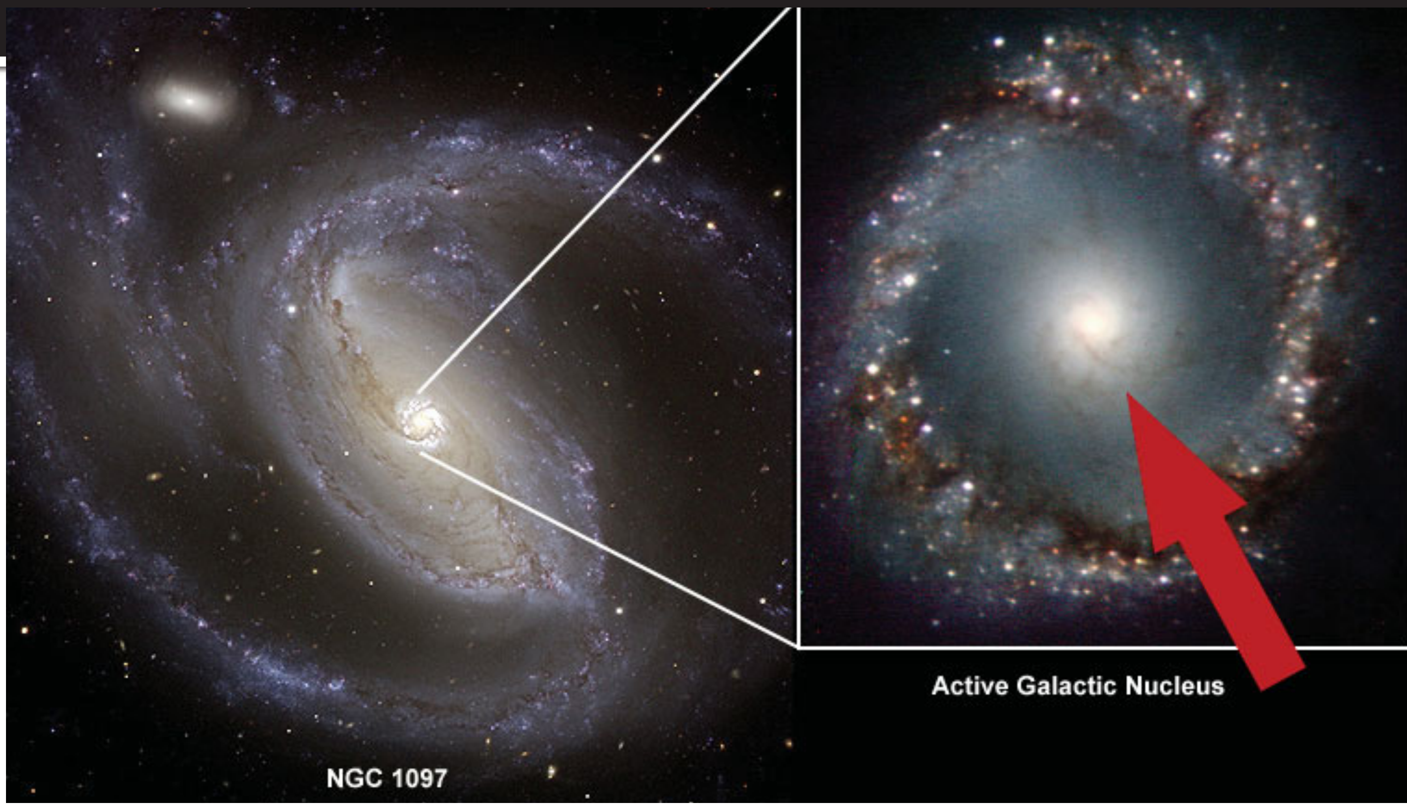
Extragalactic scales: role of mergers

- Model: Hopkins & Quataert 10:



- Observations: connection with star formation, not necessarily with AGN. Indirect connection as AGN connect with star formation?

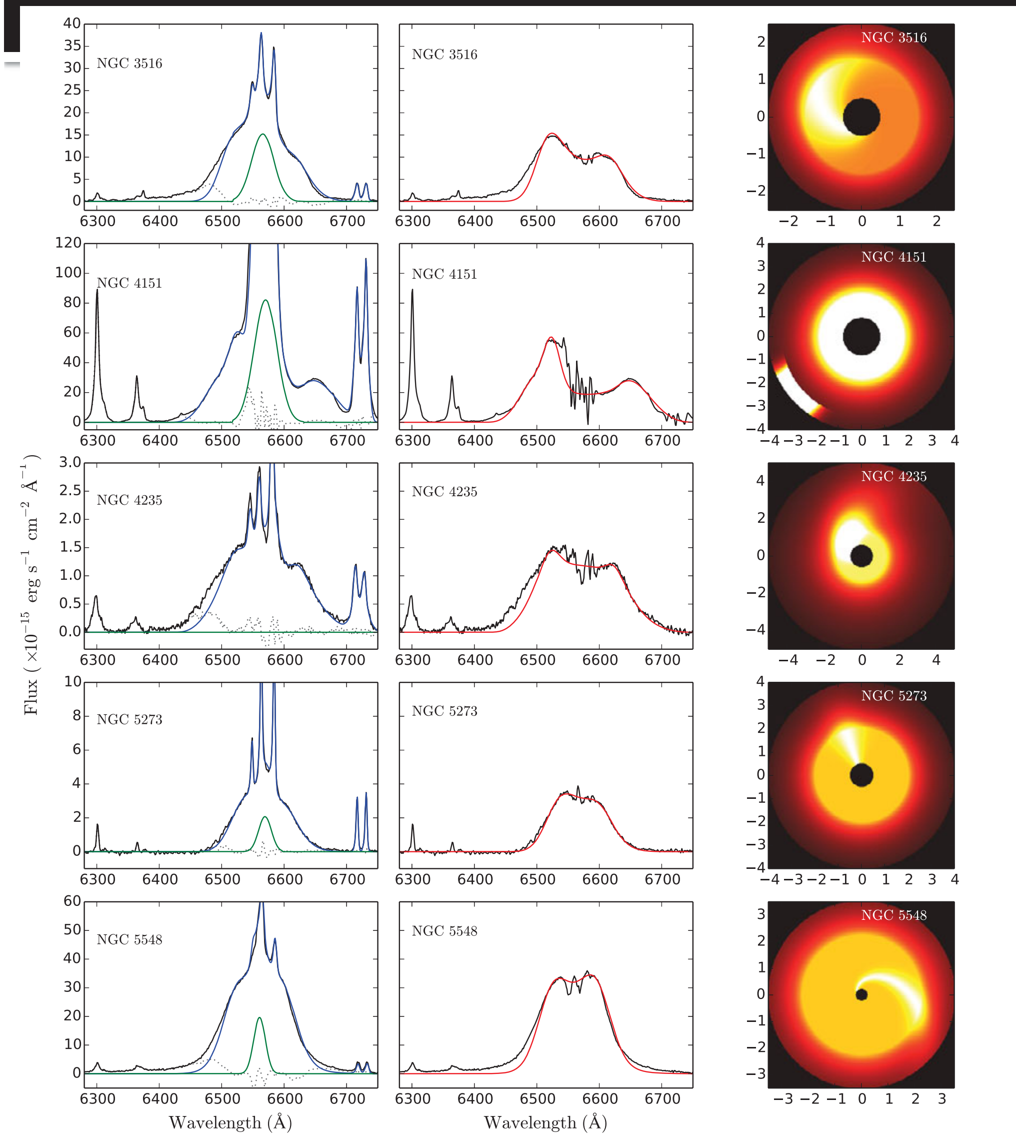
Galactic scales: bars



- Models: inflows along bars: stall at ~1kpc
- Observations: no clear connection with AGN.

→Time delay?

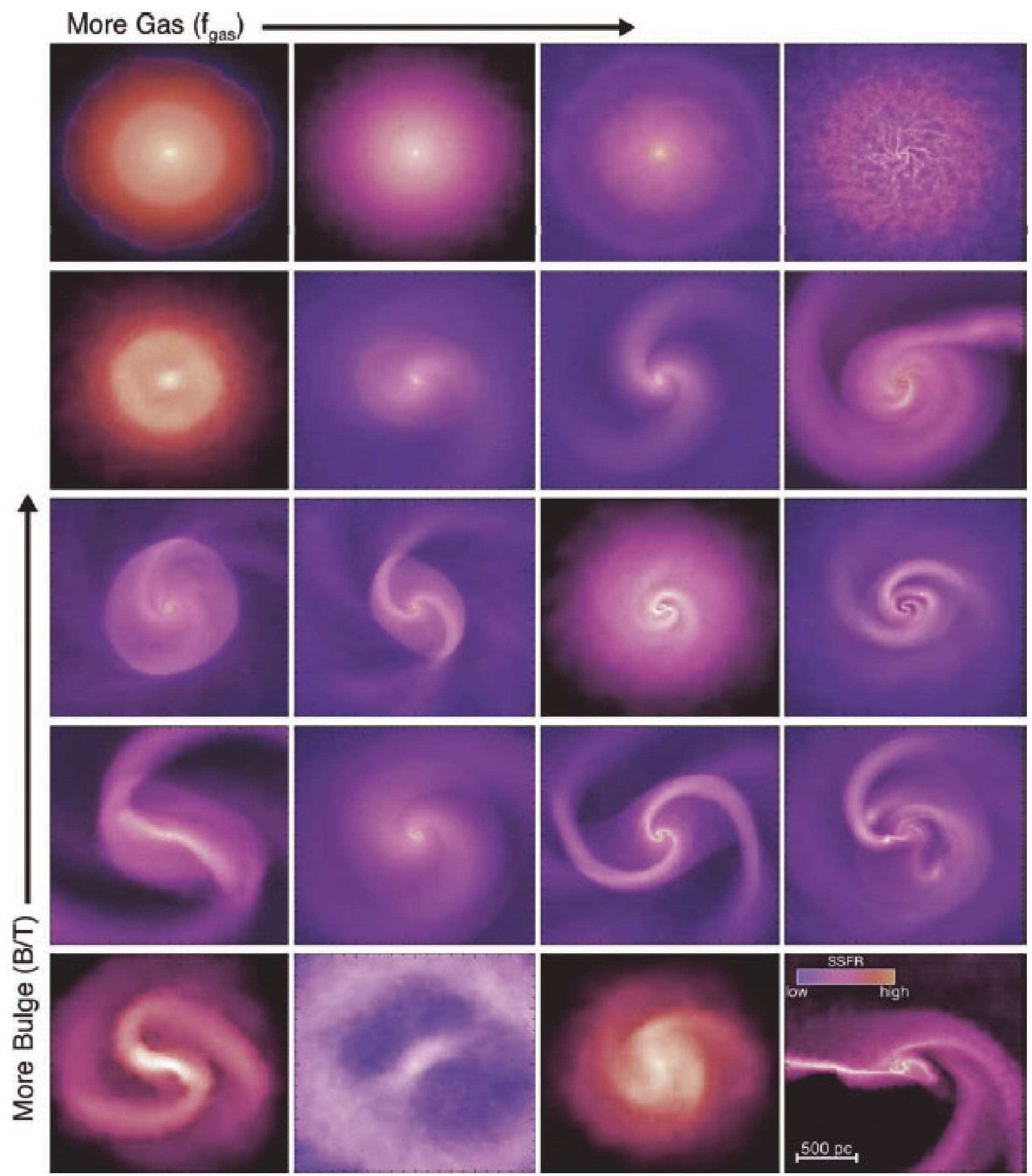
Sub-pc scales: BLR & accretion disk



- Broad Line Region: observations and models imply flattened structure connected with accretion disk(Pancoast+14; Storchi-Bergmann+16)

- Accretion disk

Inner kpc



Models:
Hopkins & Quataert 10

Key processes occur on ~100 pc scales: nuclear spirals and bars

Resolvable in nearby AGN

Nearby AGN

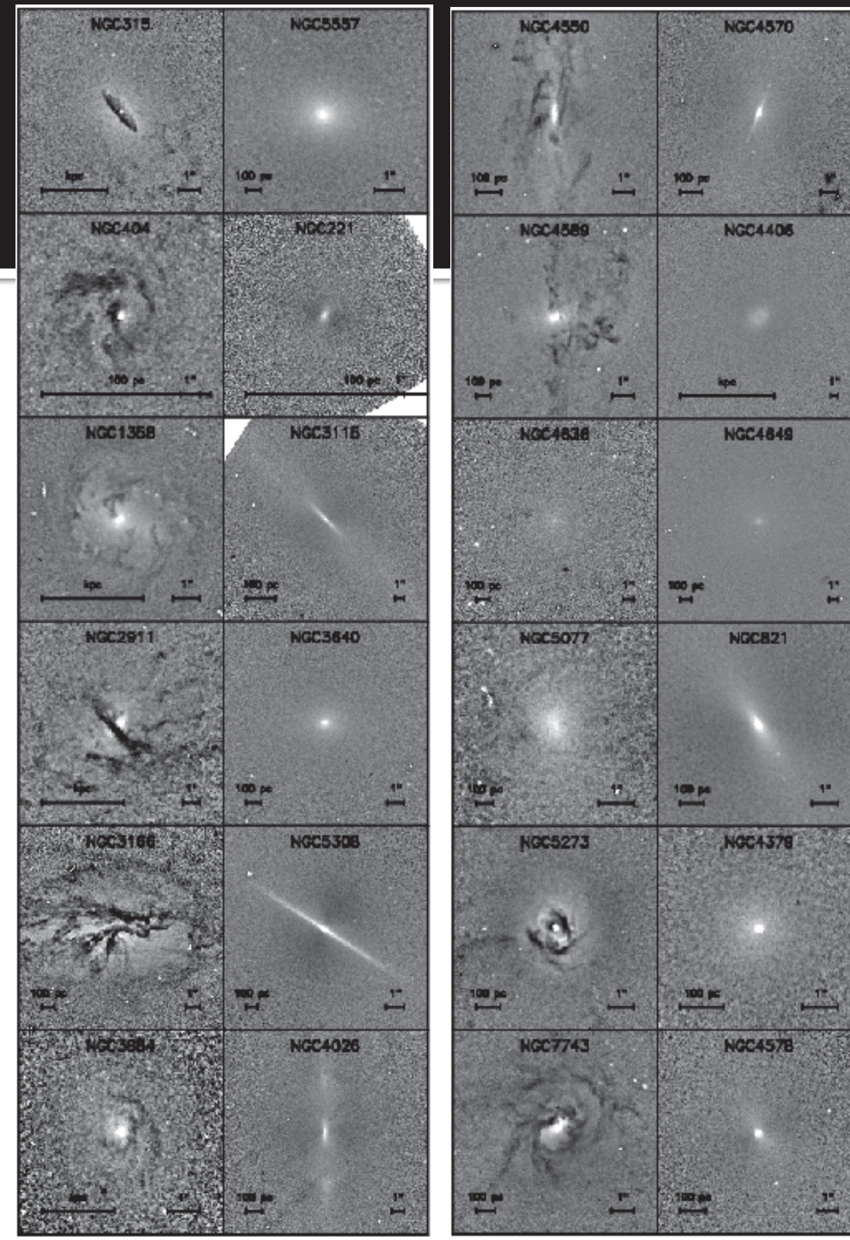
- Typical AGN accretion rates ~ 10^{-3} $M_{\odot} yr^{-1}$
- Could be provided by mere mass loss of bulge stars (e.g. H08,+13, Davies+14, Rosario+17)
- Yet an AGN triggering mechanism seems to be needed…

Observations: images

HST F606W images of inner kpc (Simões Lopes +07, Malkan +98,Martini+03) :

- Dusty nuclear spirals in all early-type AGN;
- In only 25% of control sample;

-> Nuclear spirals correlated with AGN: channels to feed the SMBH (Maciejewski 04, van de Ven & Fathi 10; Piñol-Ferrer+12; Hopkins & Quataert 10)

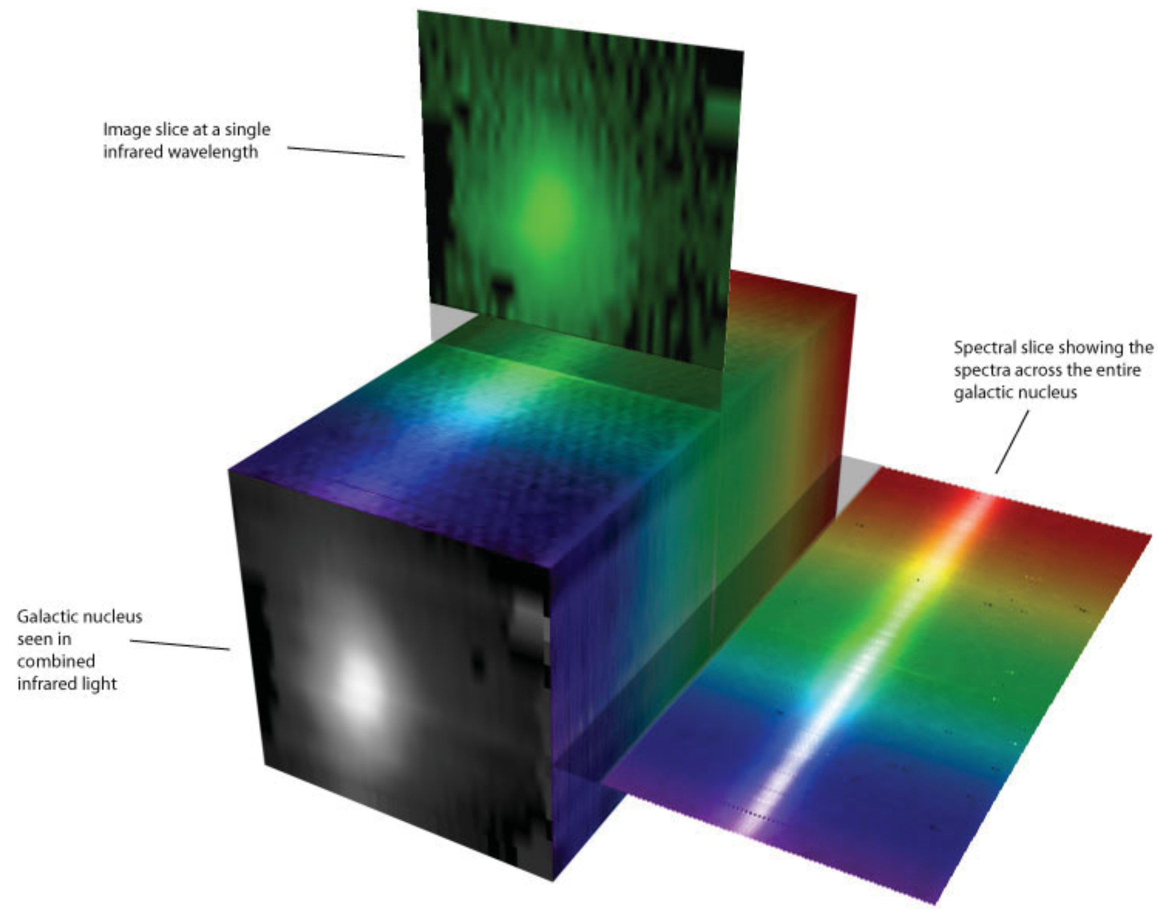


active non-active active non-active

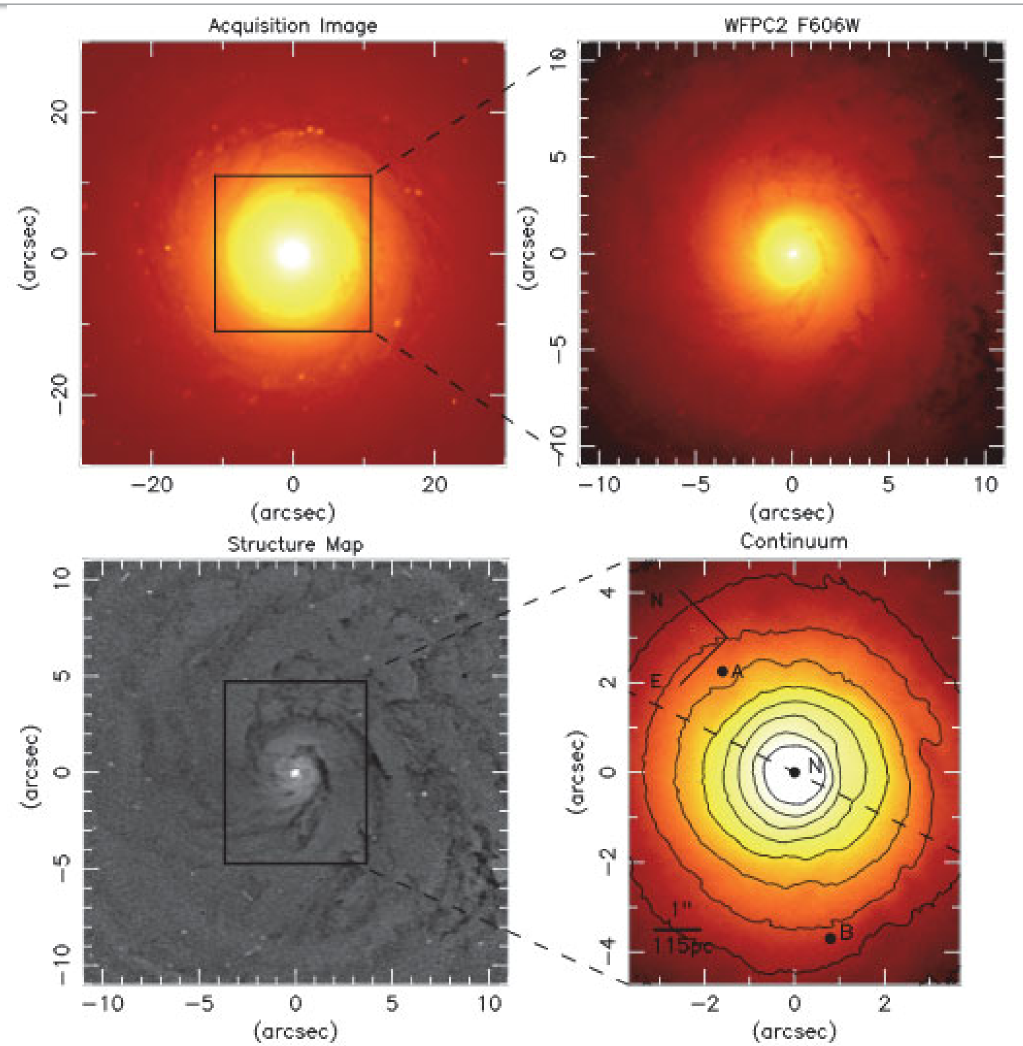
Observations: Kinematics (Gemini)

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

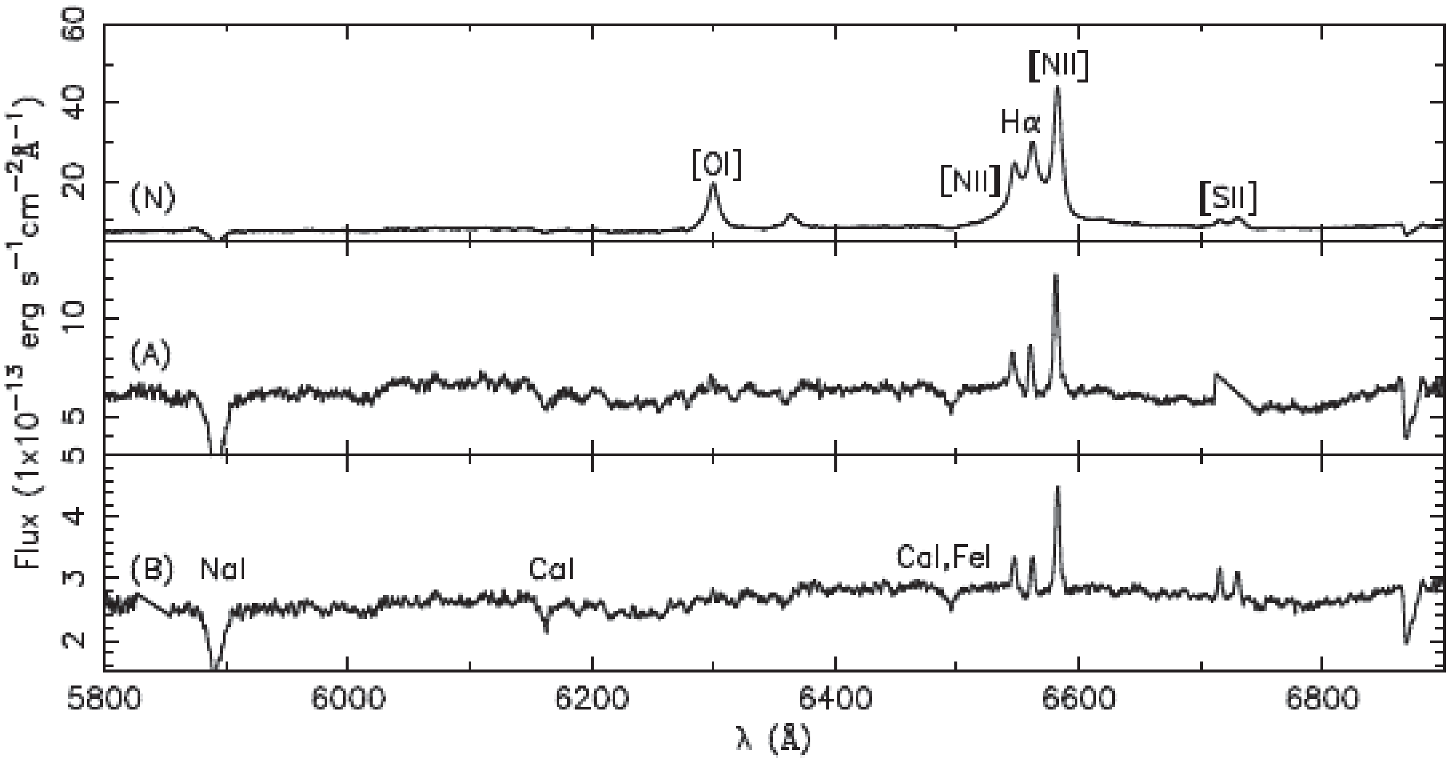


Inflows in ionized gas: NGC7213 (Schnorr Müller +14)



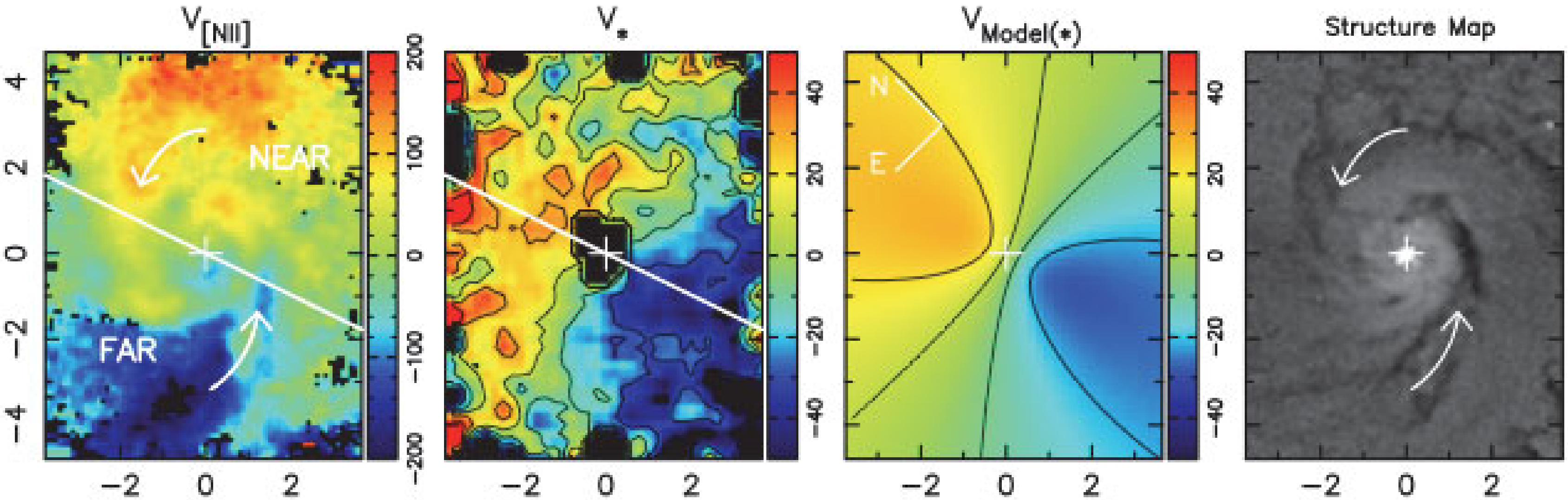
- Sa, LINER/Seyfert 1
- GMOS-IFU
- 0.7 kpc x 1 kpc
- Nuclear spiral
- 0.6"=60 pc

Sample spectra NGC7213 (Schnorr Müller +14)



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

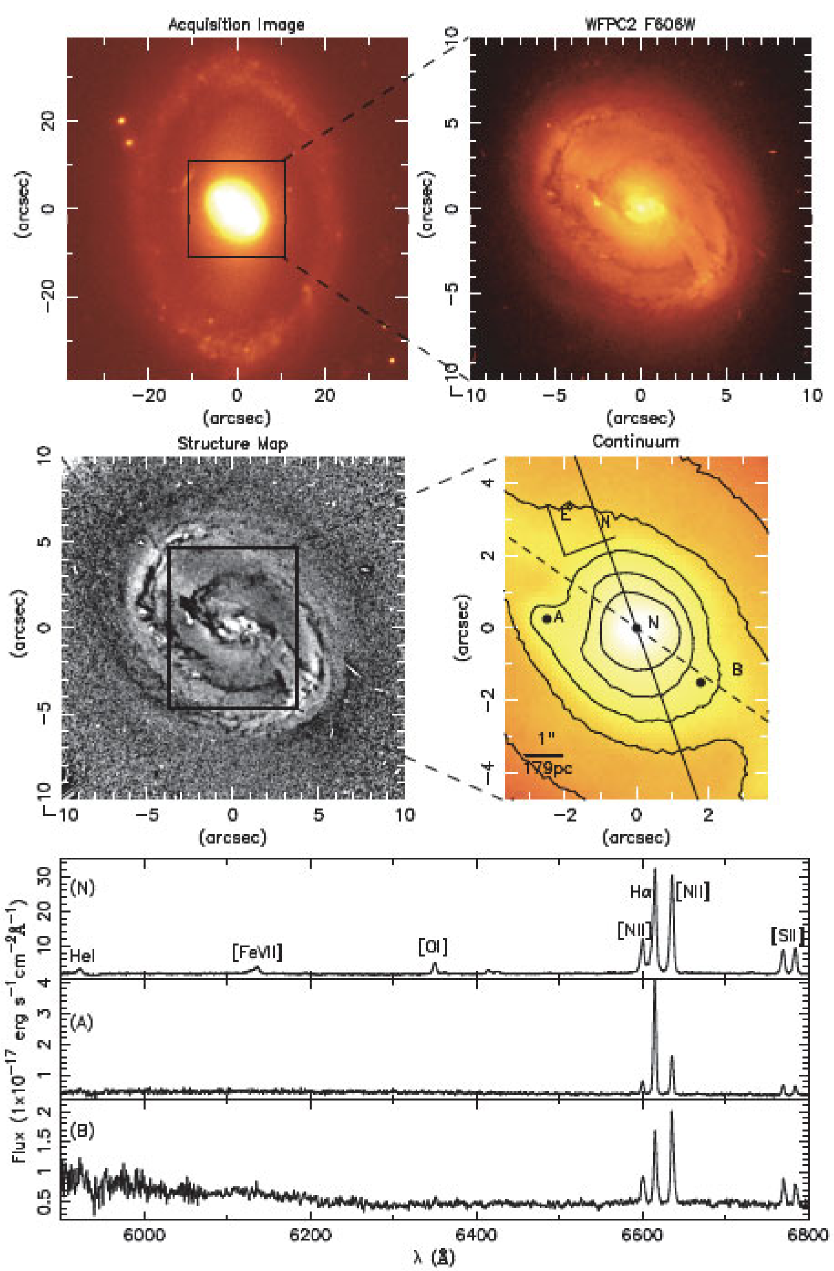
Inflows in NGC7213 (Schnorr Müller+14)



Gas kinematics *Stellar kinematics*

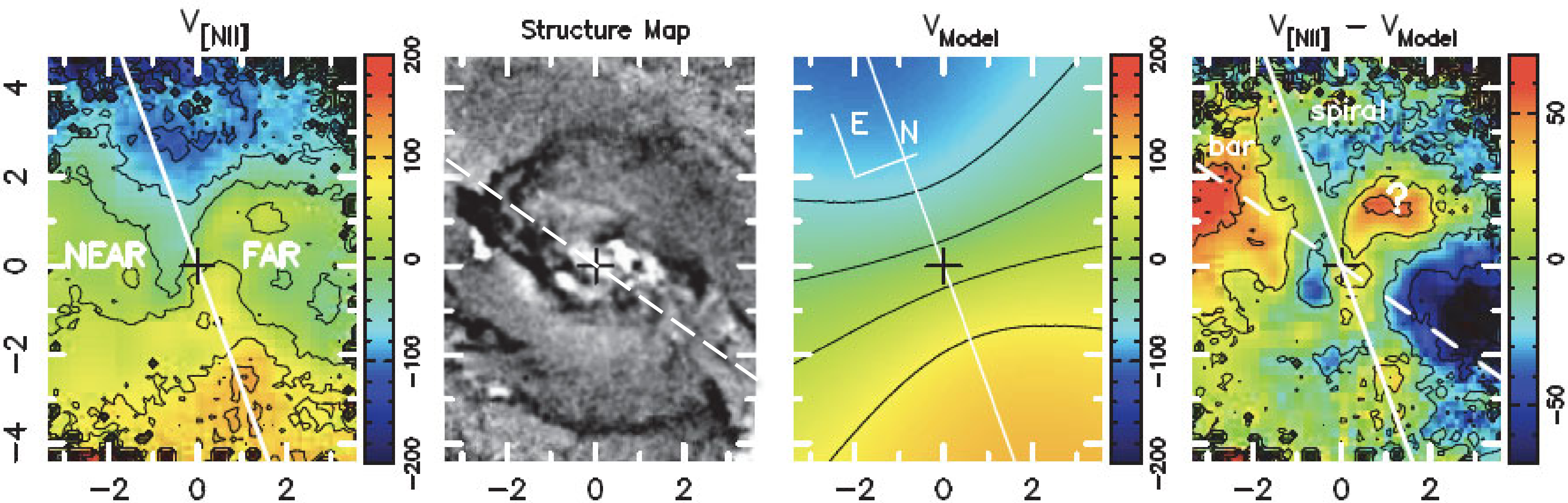
- Stars: rotation
- Ionized gas: rotation + distortions correlated with spiral dust structures: blueshifts in the far side and redshifts in the near side -> inflow
- Mass of ionized gas: 1.3 x 10^8 $M_\odot$;
- Mass inflow rate: 0.4 $M_\odot yr^{-1}$ at 300 pc, 0.1 $M_\odot yr^{-1}$ at 100 pc; Schnorr Müller+16;

Inflow along nuclear bar in NGC3081
Schnorr Müller +16)



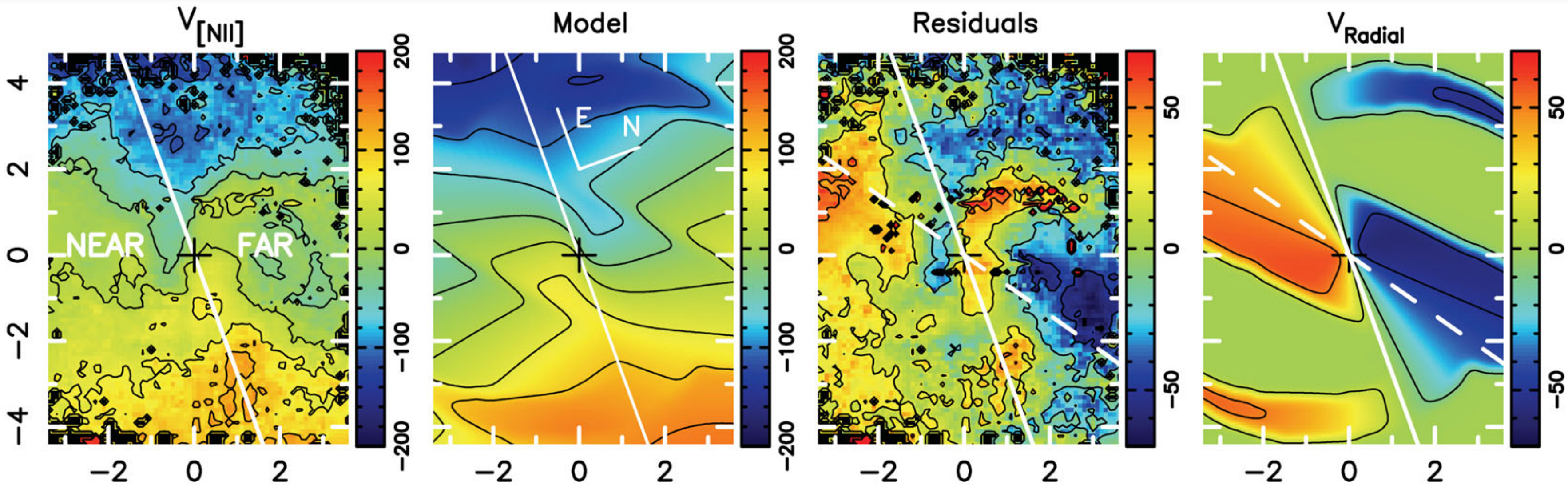
- SABO/a, Sy 2
- GMOS-IFU
- 1.25 x 1.80 kpc
- 0.6”=100 pc
- Nuclear bar (~1kpc)

Inflow along nuclear bar in NGC3081
(Schnorr Müller +16)



- 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 $M_\odot yr^{-1}$

Rotation + inflow model (Shape, Steffen et al. 2014)



- Model of rotation in disk plus radial inflow with v=80 km/s in bar and spiral arms
- Did not model outflow

Minor merger fueling AGN in Mrk509 (Fisher +15)

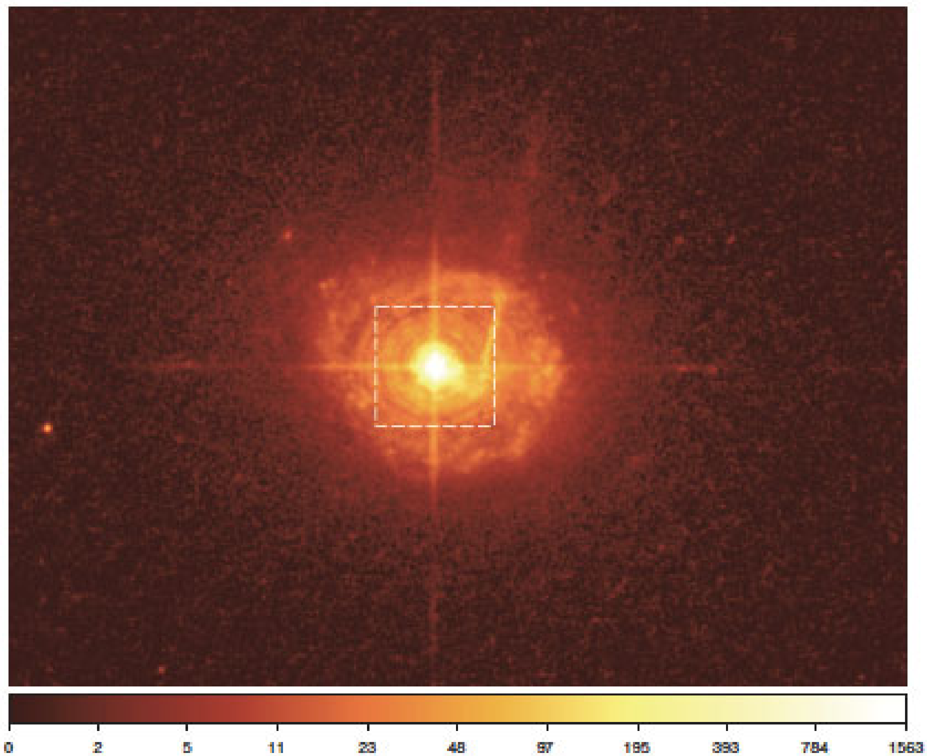
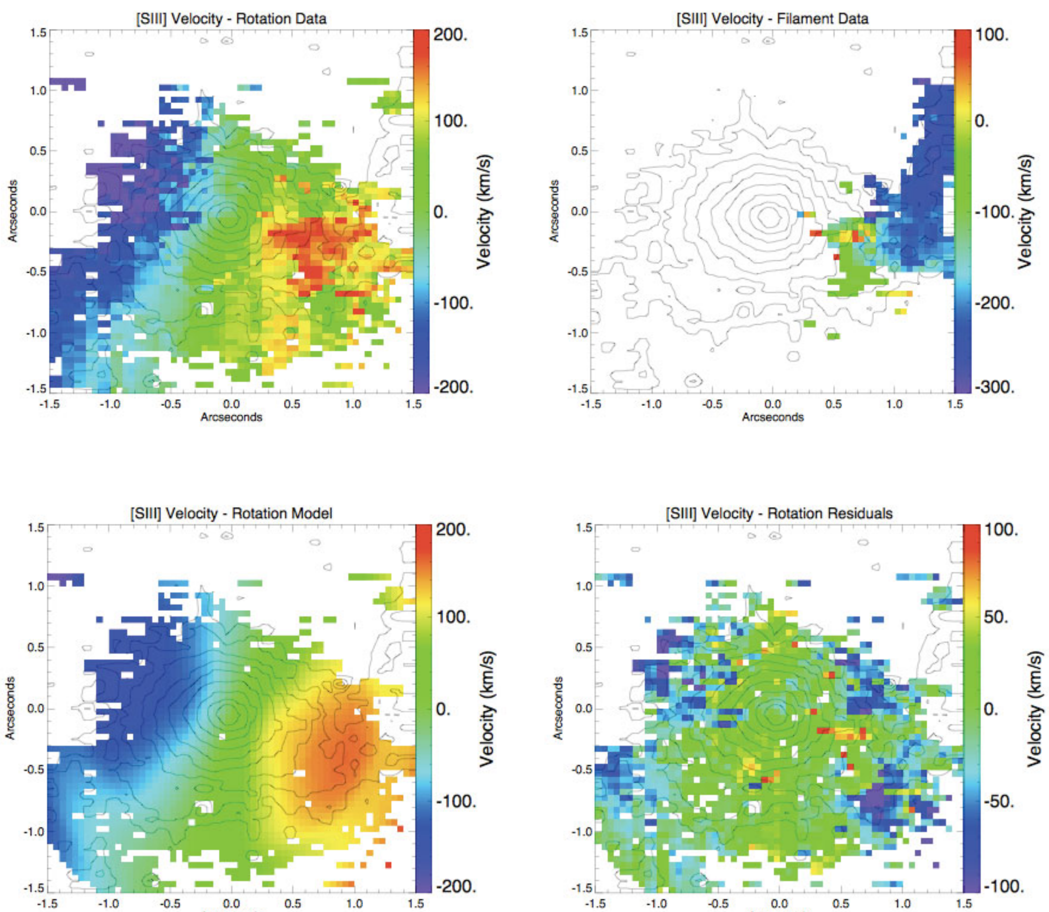


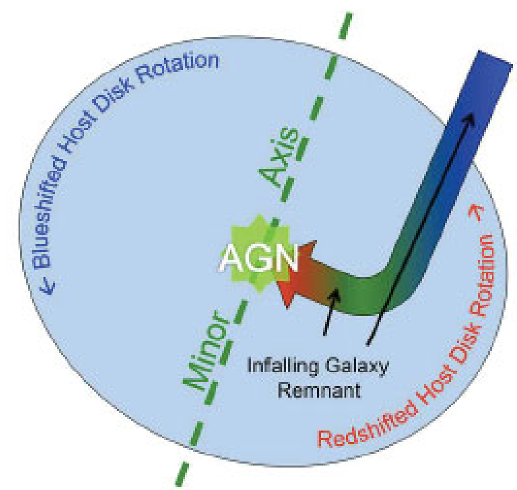
Fig. 1.— *HST* FQ508N narrow-band image of Mrk 509 showing primarily [O III] emission. The filament can be seen to the right of the nucleus, extending from northwest to southeast before making a 90° turn toward the nucleus. Starburst activity can be seen in a ring around the nucleus at a radius of ~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

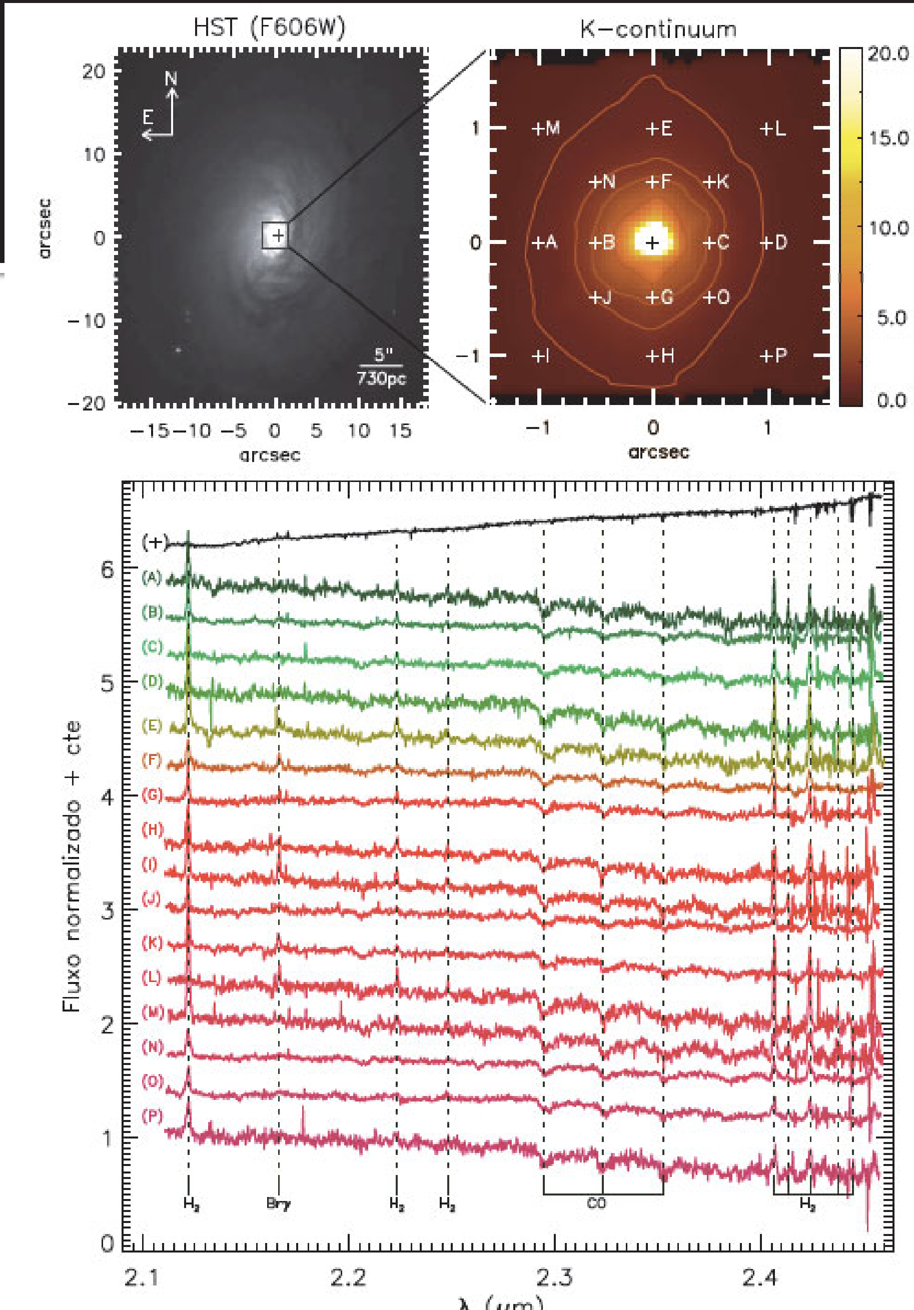
Mrk509 (Fisher et al. 2015): scenario



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

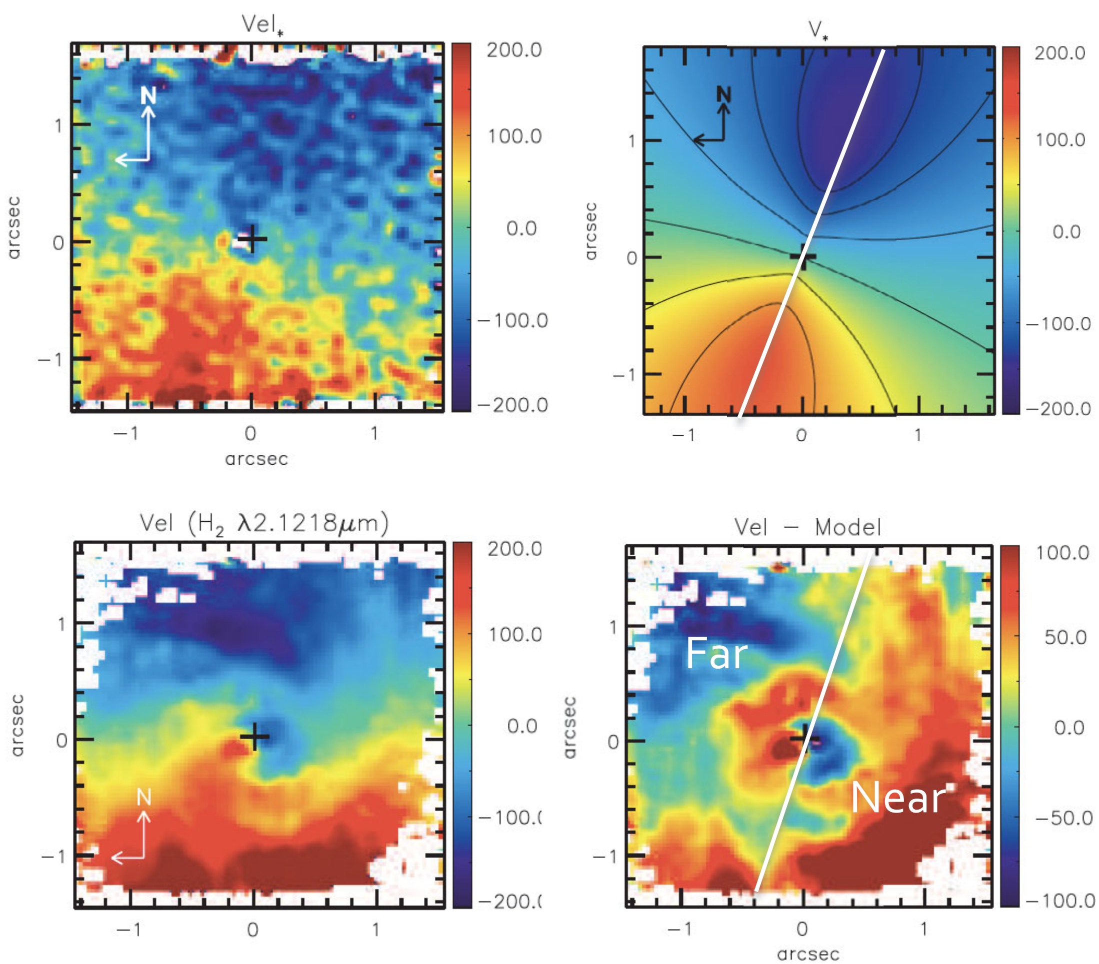


Inflows in molecular gas



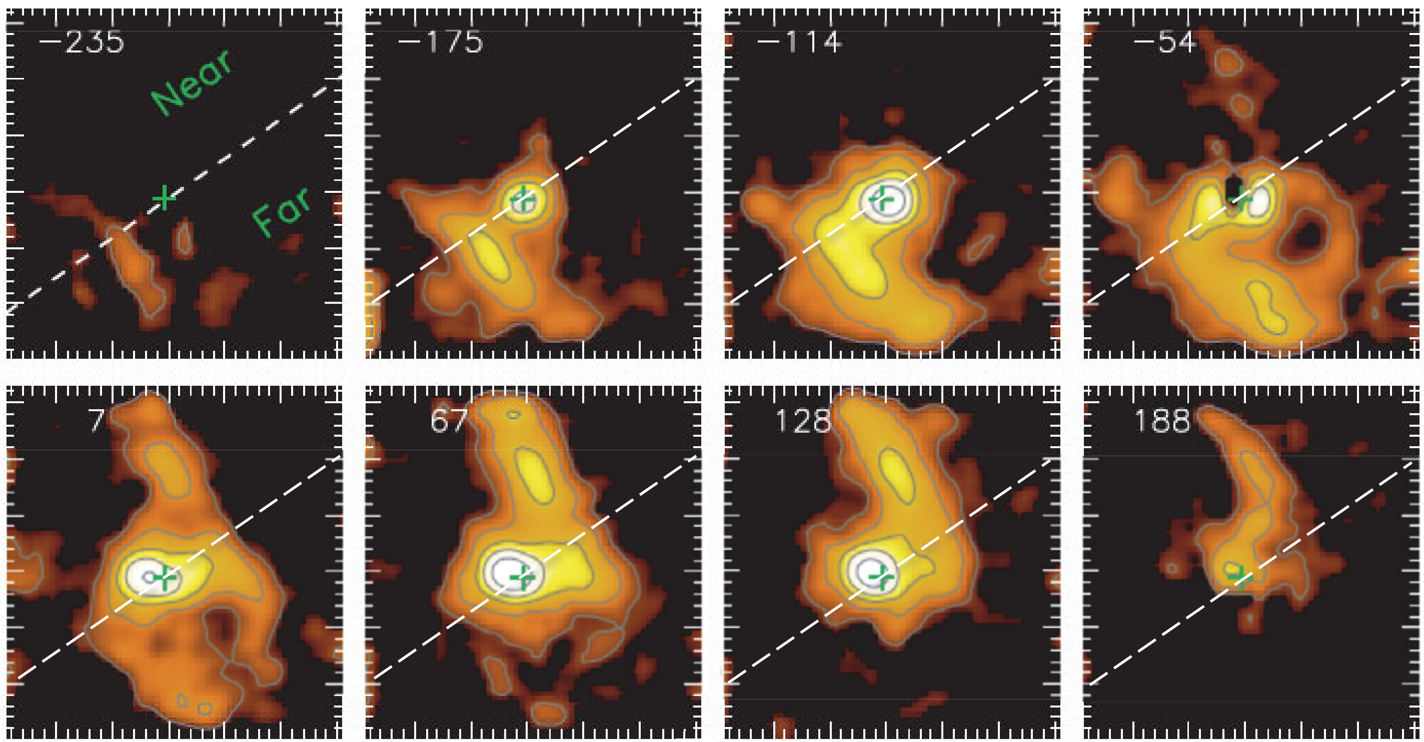
- Diniz+15: NGC2110
- SO, Sy 2
- FOV= 450 pc x 450 pc
- 0.1"=15 pc
- NIFS, K band
- Stellar (CO) and H2 kinematics

NGC2110: centroid velocity



- Stellar velocity field: rotation
- H2 velocity field: rotation + distortions at ~200 pc spiral arms
- Closer to the center: outflow
- Hot (2000K) H2 mass ≈ 1400 $M_\odot$
- Cold H2 mass (Mazzalay +12) ≈ $9.9 \times 10^8\ M_\odot$
- Surface density ≥ 710 $M_\odot\ pc^{-2}$

H2 channel maps in Mrk79 (Riffel+13)



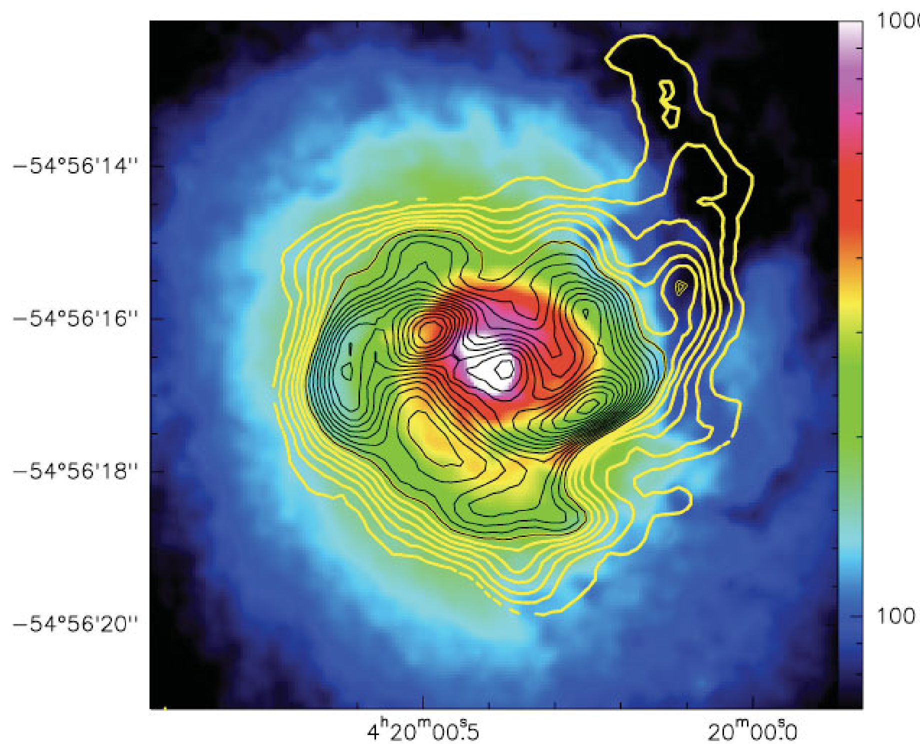
- Within inner ~600 pc: blueshifts in far side, redshifts in near side -> inflow
- Mass inflow rate: ~ 4 x 10^{-3} $M_{\odot}$ yr^{-1}, but should be dominated by cold gas

Other:

- More nuclear spirals or compact molecular gas disks: Fathi+06, Storchi-Bergmann+07, Riffel+08,+09, Hicks+09, Schnorr Müller+11, Riffel+11a, 11b; Hicks+13,Shoenell+14

- Cold molecular gas: IRAM PdBI: Garcia-Burillo+12 (NUGA group)

- ALMA: Combes+13, Combes+14: spiral in CO emission correlated with dust spiral in HST F606W image of Sy1 NGC1566 →



Summary: inflows

- Inflows in nuclear spirals, bars and disks, capture of dwarf companion; observed in H^+ and H_2;

- Inflow velocities ~ 100 km/s;

- Inflow rates ~0.1 – few $M_\odot yr^{-1}$: 10^2-10^3 times the AGN accretion rate

- Estimated total gas masses in inner kpc ~ 10^7 - 10^9 $M_\odot$

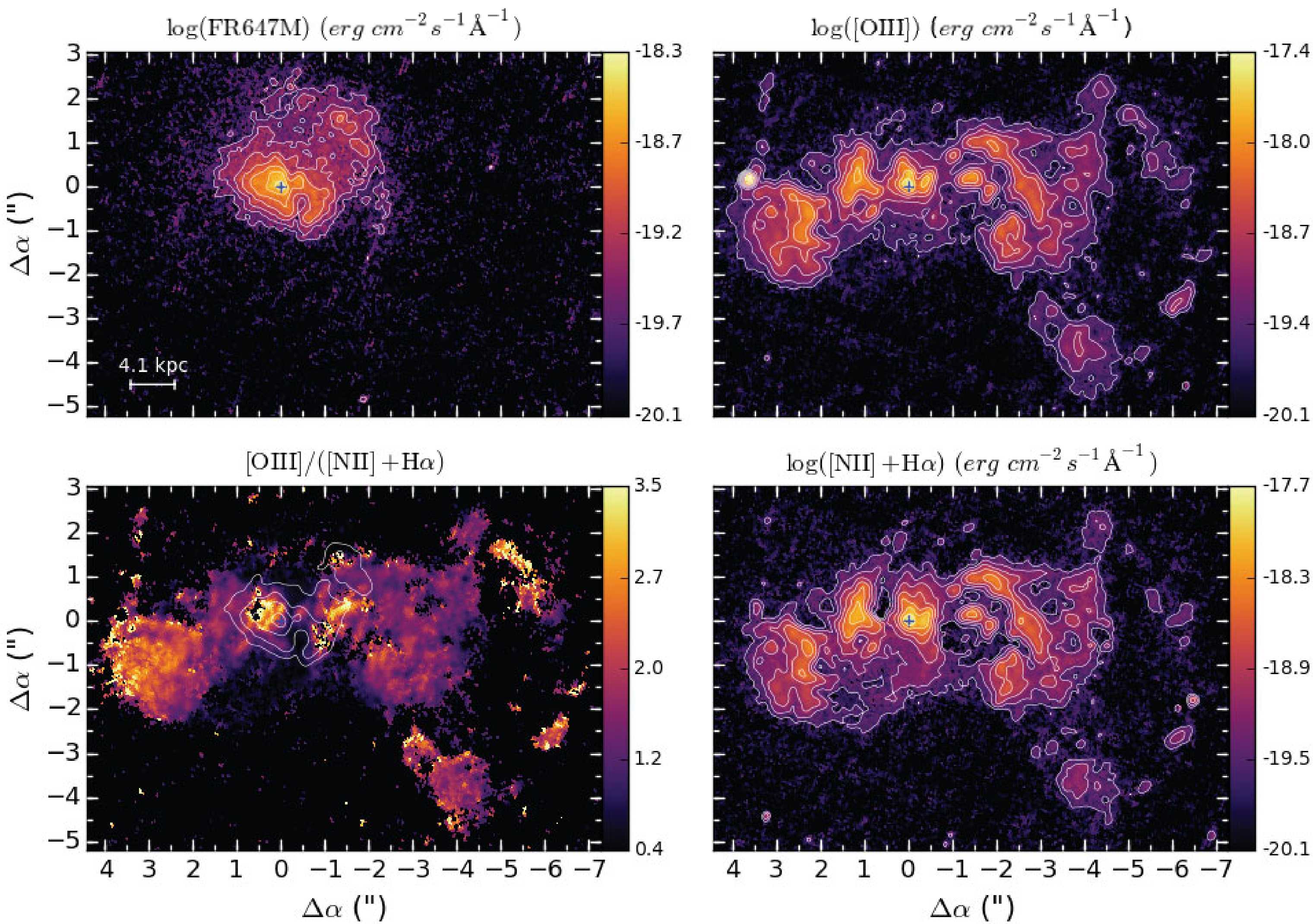
Summary: inflows

- Surface mass densities: 100 – 7000 $M_{\odot}pc^{-2}$ -> KS law -> SFR ~ 0.1 – 10 $M_{\odot}yr^{-1}$ -> gas will form stars (observed in many cases)

➢ co-evolution: **SMBH at 10^{-3} $M_{\odot}yr^{-1}$ and bulge at 1 $M_{\odot}yr^{-1}$**

➢ **The new frontier: the inner ~10pc-> higher sensitivity and angular resolution → GMT IFUs**

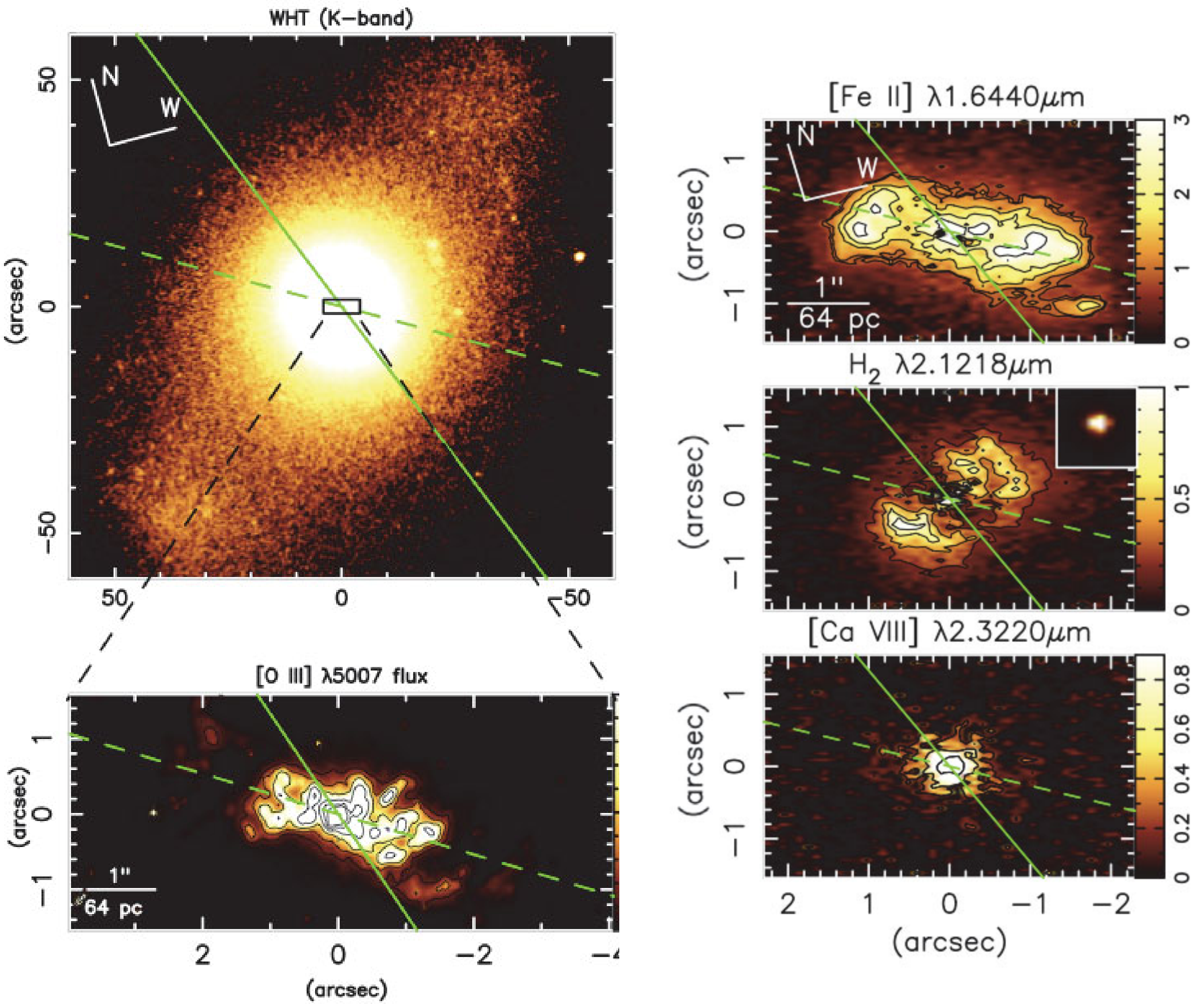
Feedback



log(FR647M) (erg cm^-2 s^-1 Å^-1)
log([OIII]) (erg cm^-2 s^-1 Å^-1)
[OIII]/([NII] +Hα)
log([NII] +Hα) (erg cm^-2 s^-1 Å^-1)
4.1 kpc
Δα (")
-18.3
-18.7
-19.2
-19.7
-20.1
-17.4
-18.0
-18.7
-19.4
-20.1
3.5
2.7
2.0
1.2
0.4
-17.7
-18.3
-18.9
-19.5
-20.1

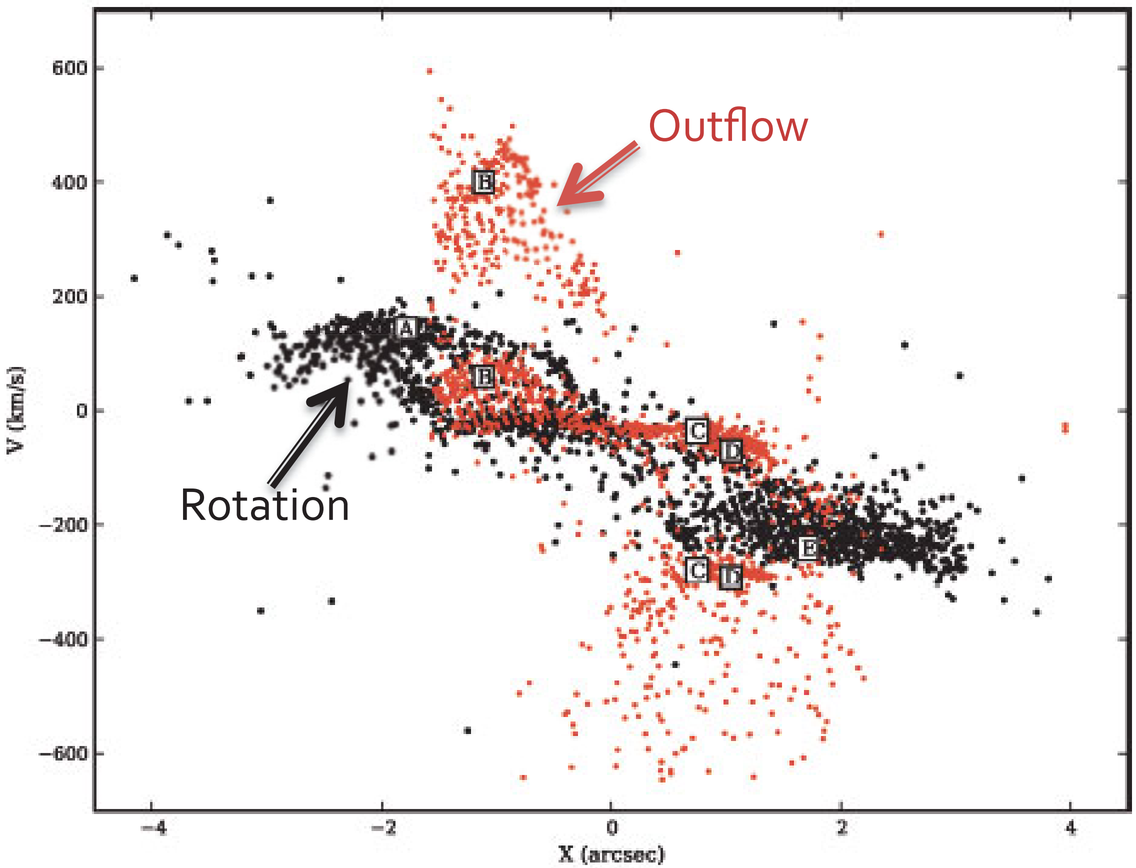
Outflow in NGC4151 (log L[OIII]= 42.2)

(NIFS, Storchi-Bergmann+09,+10)



- SABab, Sy 1.5
- 1″: 64 pc
- [FeII] : ioniz. cone, ~ 100 pc
- H_2 : along bar; 50 pc, avoids cone
- Coronal lines: barely resolved

Outflows in NGC4151



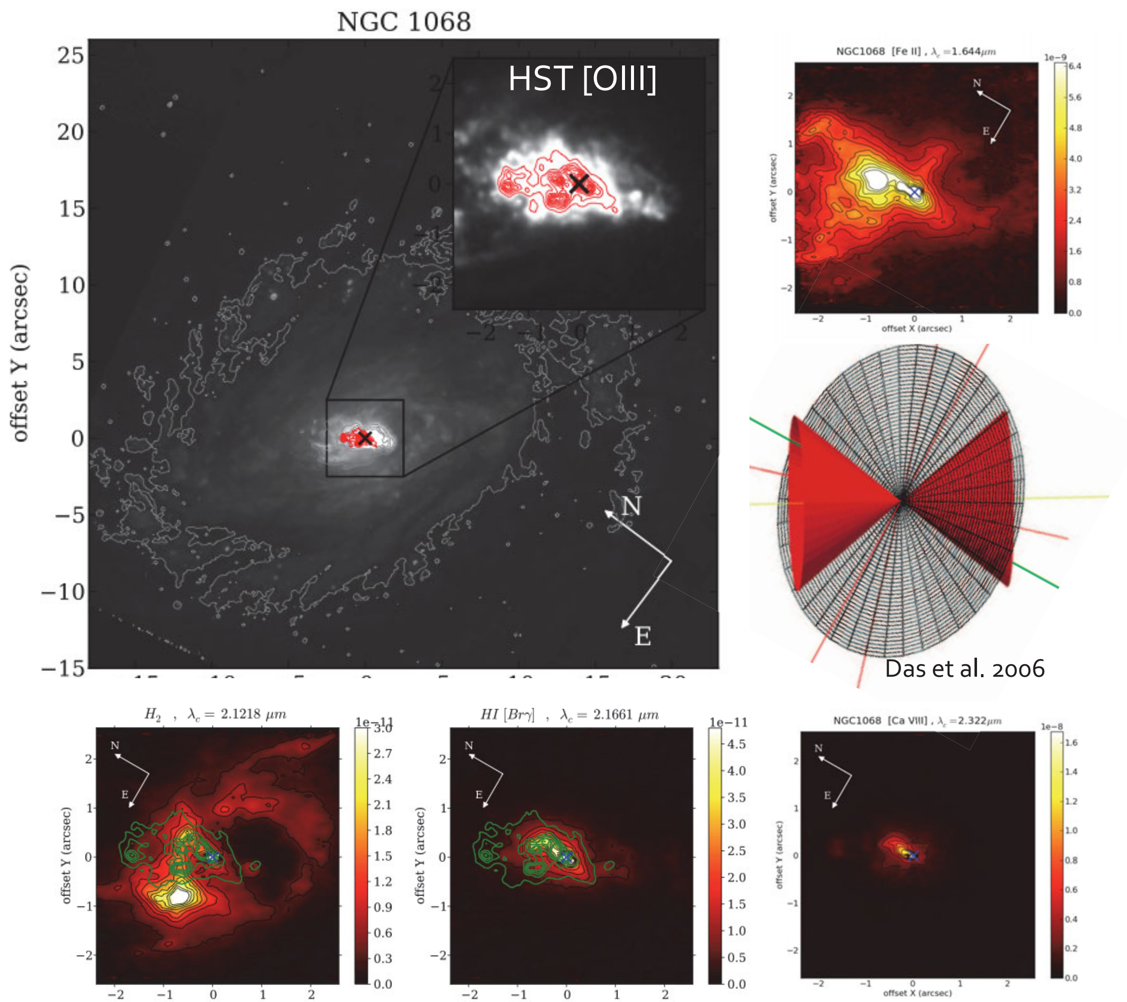
Outflow restricted to inner 2": 130 pc

Outwards: rotation

-> Lower resolution data could be interpreted as the outflow being more extended

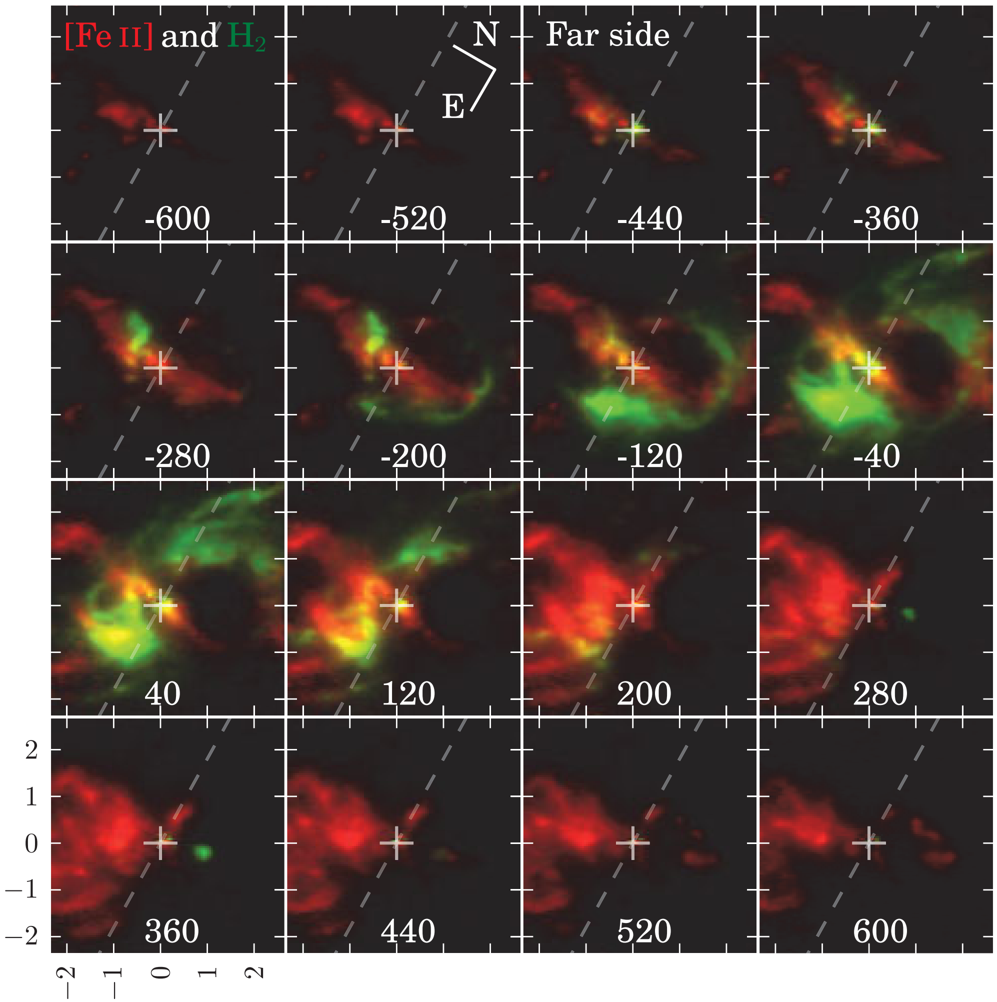
Outflows in NGC 1068 (log L[OIII]= 41.5)

(NIFS, Barbosa+14)



- Sb, Seyfert 2
- 500 pc x 500 pc
- 1"= 64 pc
- [FeII]: 250 pc from nucleus
- H_2: 100 pc (radius) off-centered ring

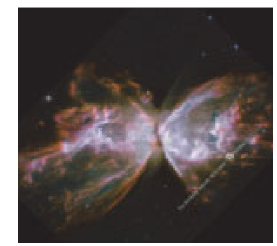
NGC1068 channel maps: [FeII] and H2



[Fe II]: outflows

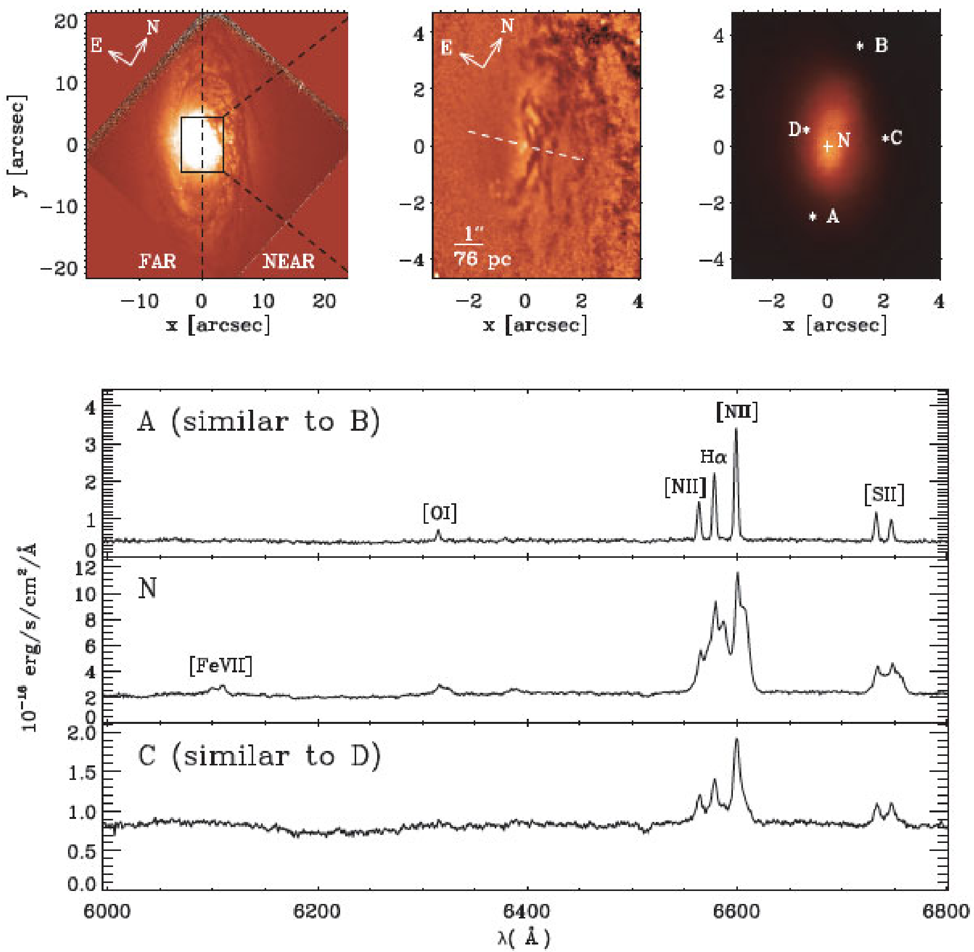
- Velocities up to 800 km/s
- Mass outflow rate: 4± 1 $M_\odot$ yr^{-1}

Hourglass shape as PN NGC6302



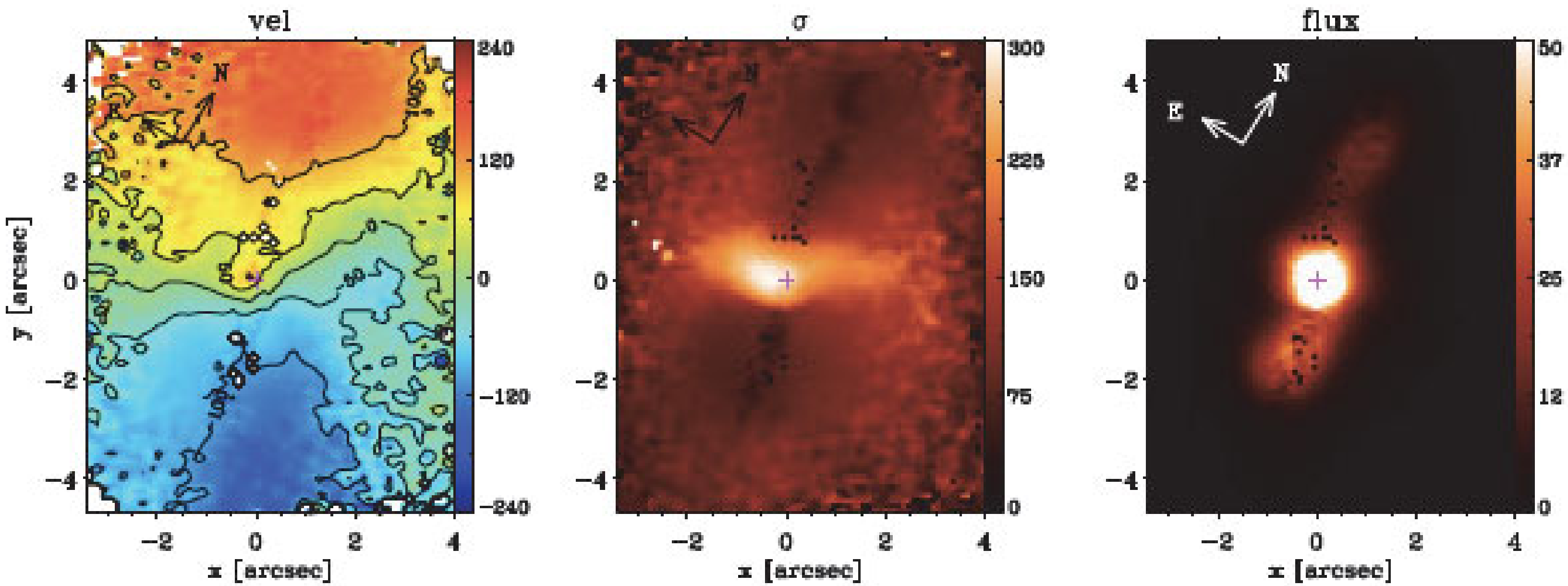
- Power of the outflow: ~ 0.1% L_{bol}
- Weak effect in the galaxy
- Extent of the outflow: 130 pc

Outflow in NGC1386 (log L[OIII]= 40) (GMOS, Lena+15)



- Sbc, Seyfert 2
- 500 pc x 500 pc
- 1″= 76 pc
- Complex line profiles within inner 1″-2″ (150 pc)

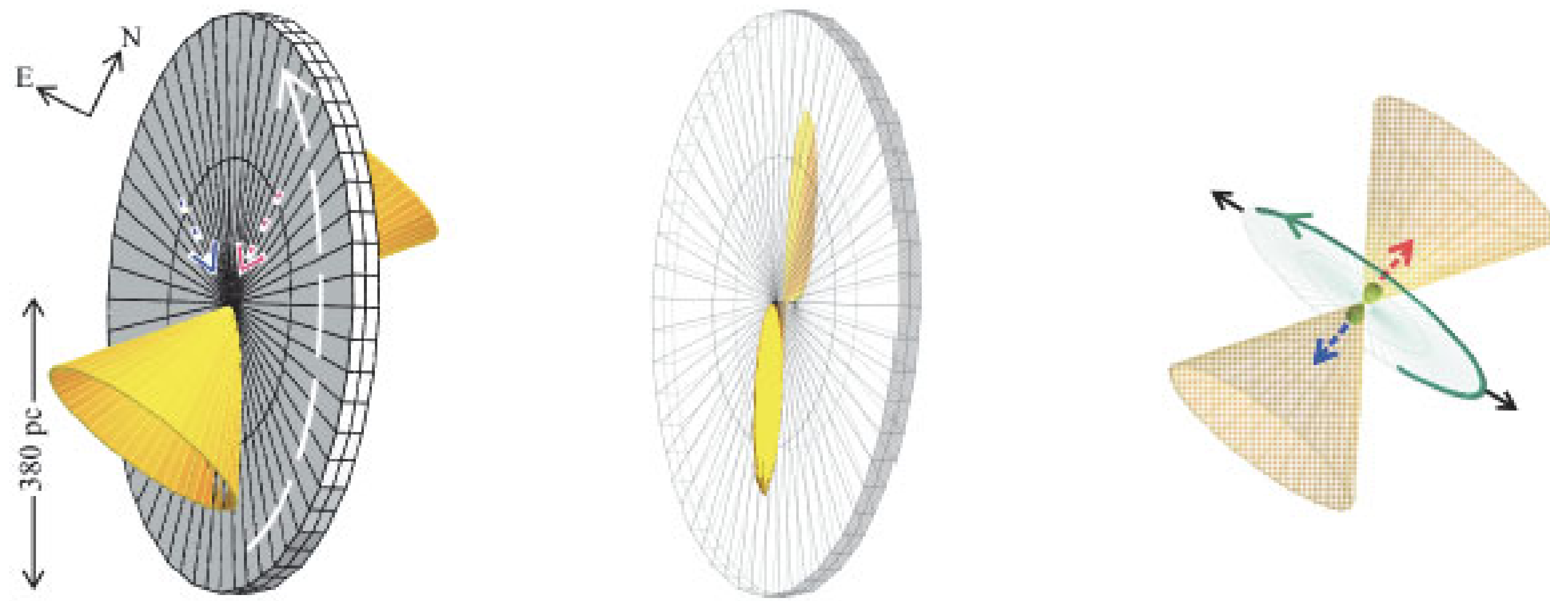
Outflow in NGC1386 (log L[OIII]= 40) (GMOS, Lena+15)



Rotation in narrow component up to the border of FOV

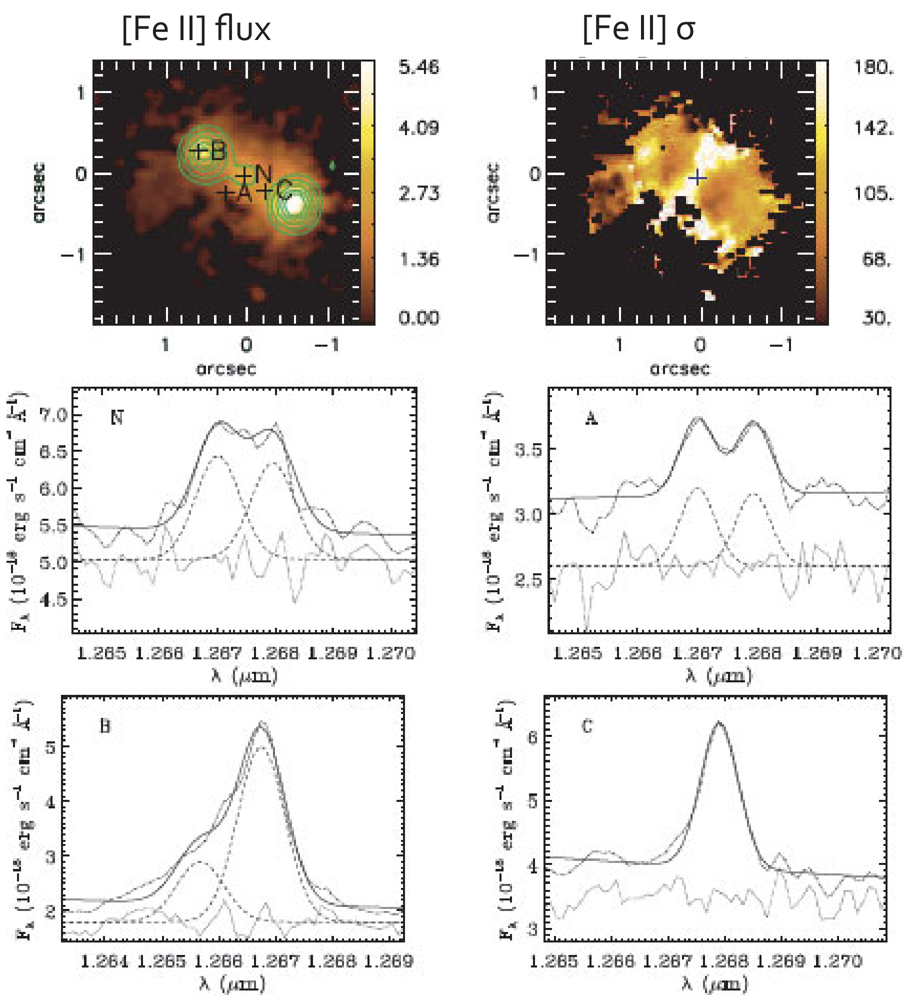
Double components in a region ~ perpendicular to ionization axis

Outflow in NGC1386: interpretation



- Extended emission: ilumination of gas rotating in the disk
- Compact outflow (150 pc) along ionization axis plus equatorial expansion
- Mass outflow rate: ~ 0.1 $M_{\odot}$ yr^{-1}; Power: 0.2% L_{Bol}

Outflow in NGC5929 (log L[OIII]= 40.5) (NIFS, Riffel +13,+15);



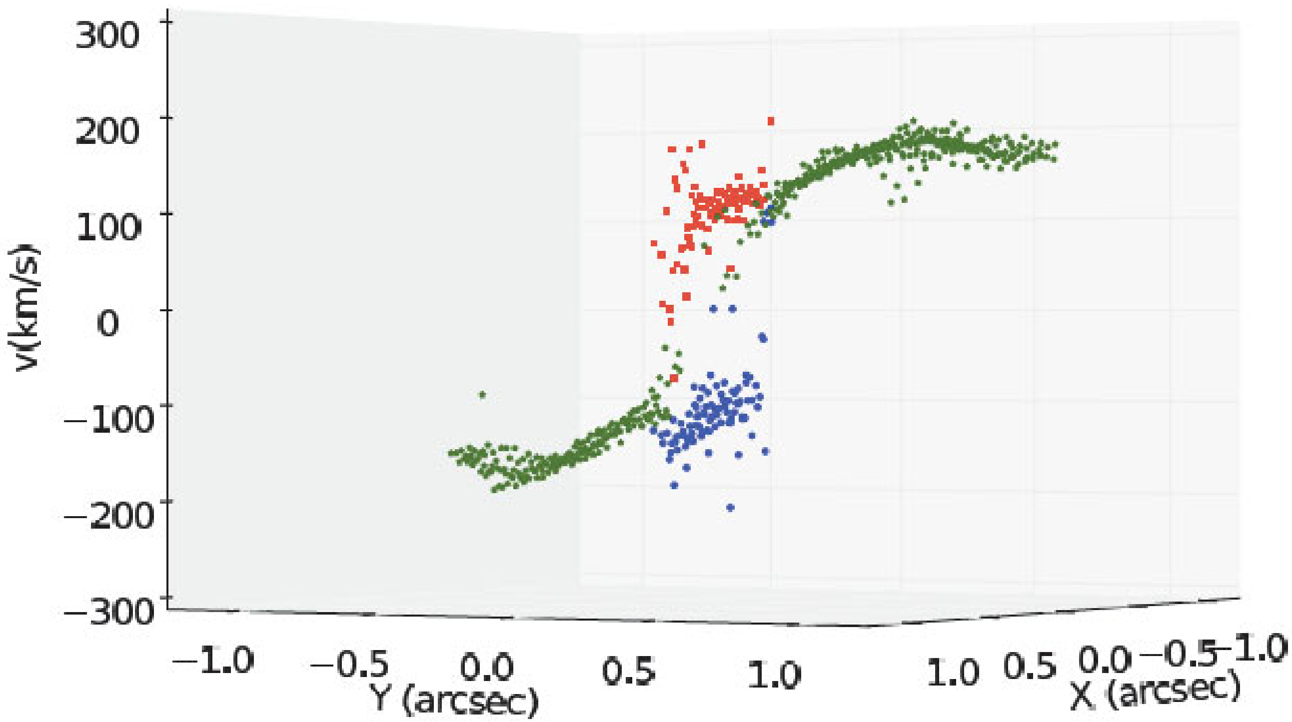
Sab pec, Sy 2, radio blobs

1″= 175 pc

High vel. Disp. perp. ioniz. axis: double lines

-> equatorial outflow: strip 50 pc x 250 pc

Outflow in NGC5929 (log L[OIII]= 40.5) (NIFS, Riffel +13,+15)



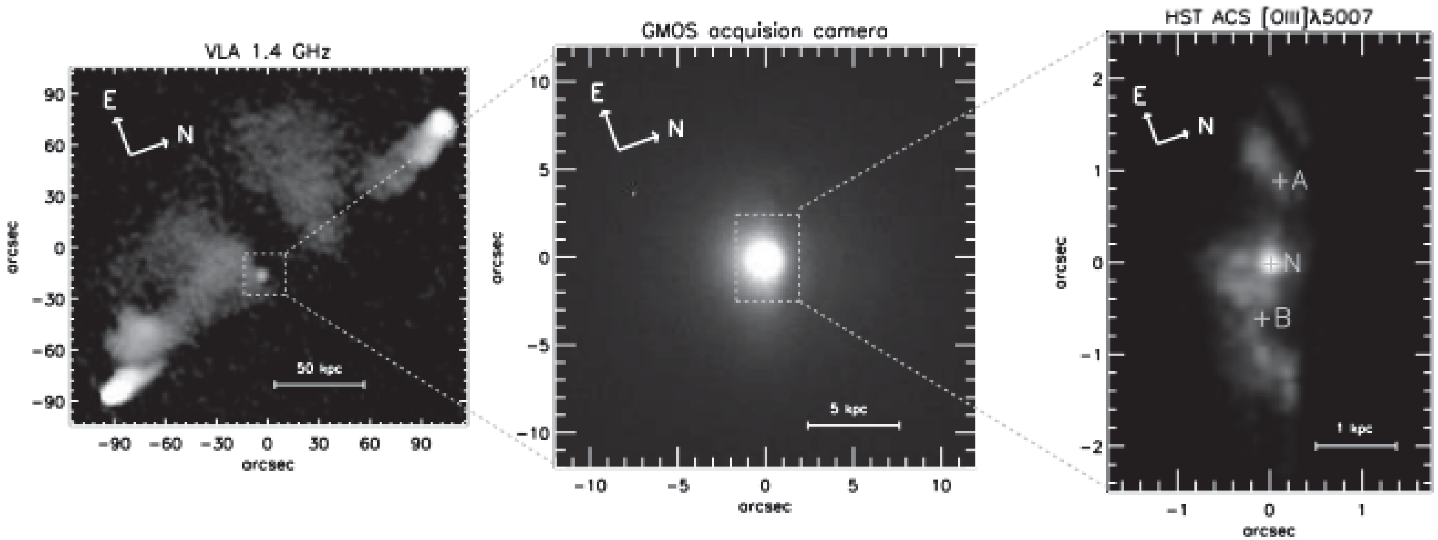
Equatorial outflow + rotation

Expansion of torus?

Mass outflow rate:

~ 0.4 $M_\odot$ yr^{-1}

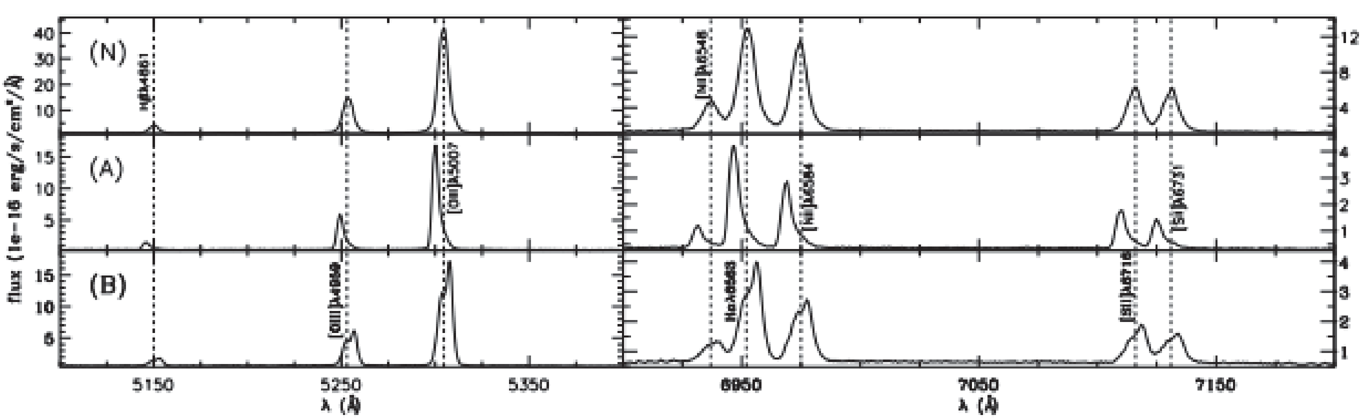
Outflow in radio galaxy 3C33
(log L[OIII]= 42.8) (GMOS, Couto+17)



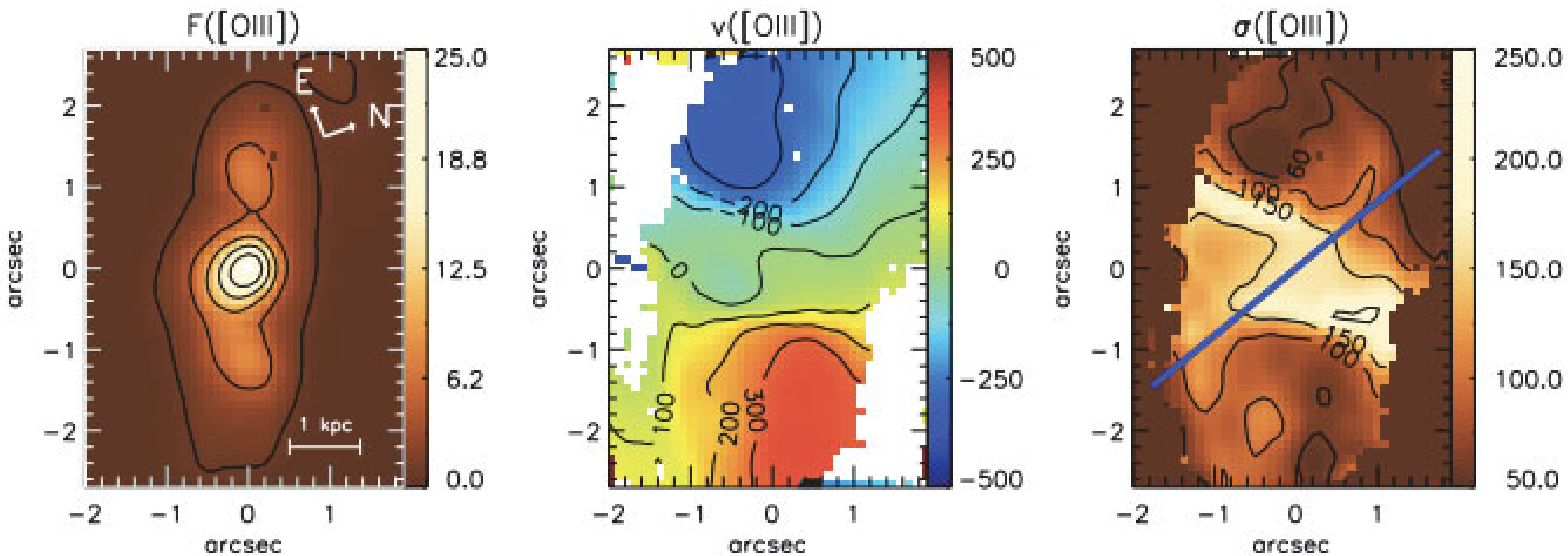
Radio gal.

FRII

1″=1.15 kpc

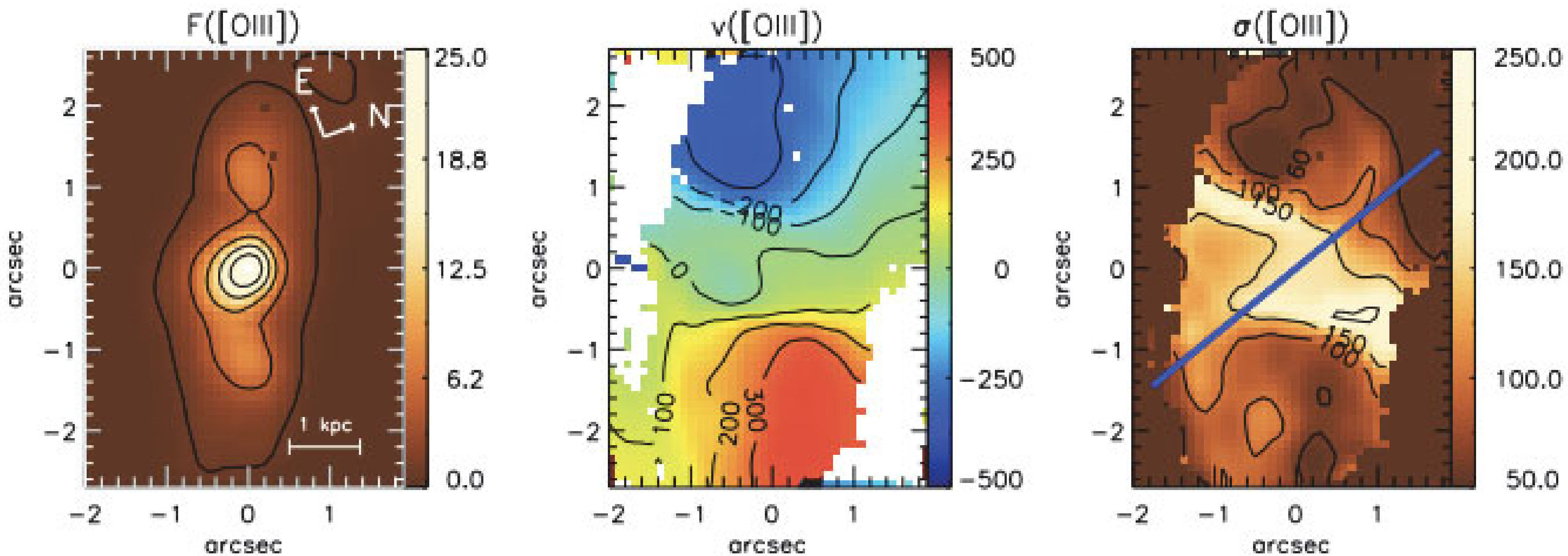


Outflow in radio galaxy 3C33
(log L[OIII]= 42.8) (GMOS, Couto+17)



- [OIII] emission observed over the whole FOV; ioniz. axis tilted relative to radio jet
- Dominant kinematics: rotation, distorted in strip ~perp. to ioniz. axis/radio jet
- Strip show high σ

Outflow in radio galaxy 3C33
(log L[OIII]= 42.8) (GMOS, Couto+17)



- High σ: lateral expansion by passage of jet? Feedback of the jet?
- Mass outflow rate: ~ 0.2 $M_\odot$ yr^{-1}; outflow power ~ 0.3% L_{bol} (jet feedback)
- Small effect in the galaxy (maybe large in intergalactic medium)

Summary and Conclusions: outflows

- Velocities: 200 – 800 km s^{-1}
- Mass outflow rates: few tenths to few $M_{\odot}$ yr^{-1}
- Power: < 0.1% - 0.3% L_{bol} in nearby AGN -> little effect on the galaxy: should be higher than 0.5% percent (Zubovas14)
- Geometry:

(1) Hollow conical/hourglass (Fisher+13: ~ 1/3 of AGN)
(2) Compact (few 100 pc)/equatorial

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

→ **Or relation with luminosity?**

Summary and Conclusions: outflows

- **Most extended emission not outflowing:** illumination of gas rotating in the galaxy disk -> possible overestimation of power of the outflow by 1-2 orders of magnitude if it is assumed that all the gas is outflowing (as many papers do!)

- **Future: IFU observations of more distant and luminous sources are necessary to test the scenario: sensitivity and angular resolution: GMT!**

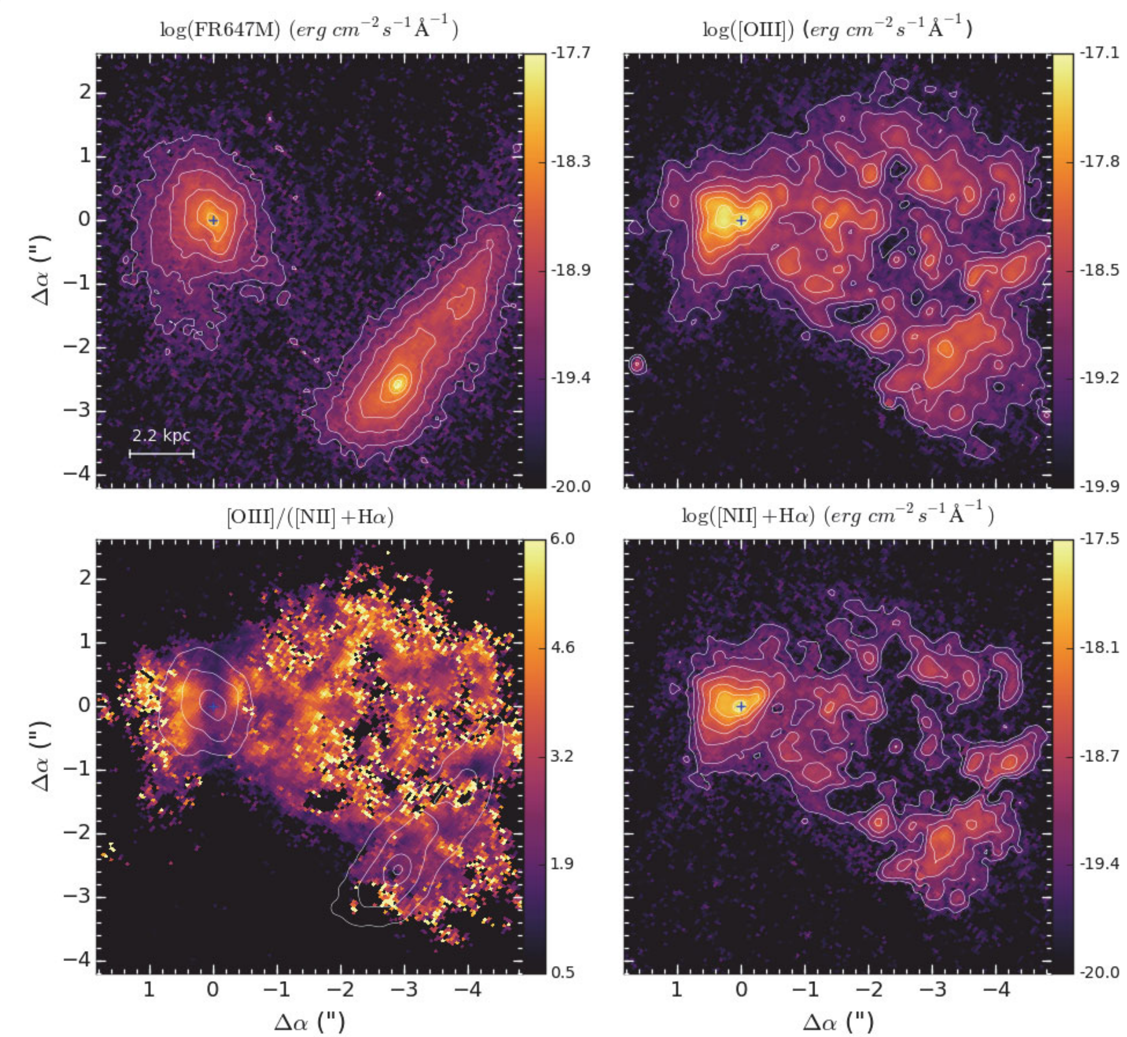
Quest for more luminous outflows

Storchi-Bergmann+17: Narrow-band HST-ACS images of 9 QSOs 2 0.1<z<0.5, with log L[OIII]>42.8

Scale: better than 500 pc/0.1"

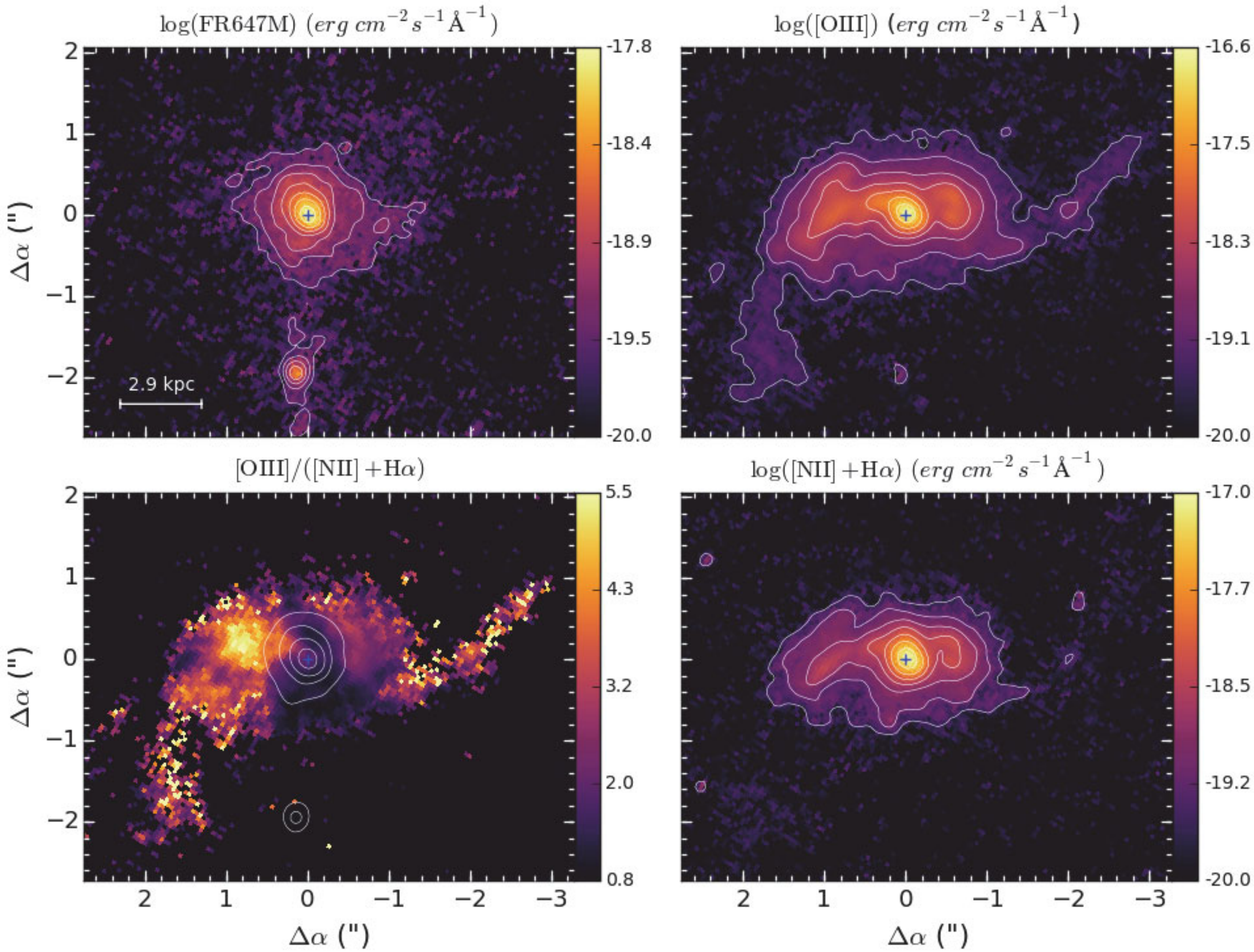
Sample selection: from SDSS QSO 2 catalog of Reyes+08

Ionization cones at 0.1<z<0.5 (HST-ACS, Storchi-Bergmann+17)



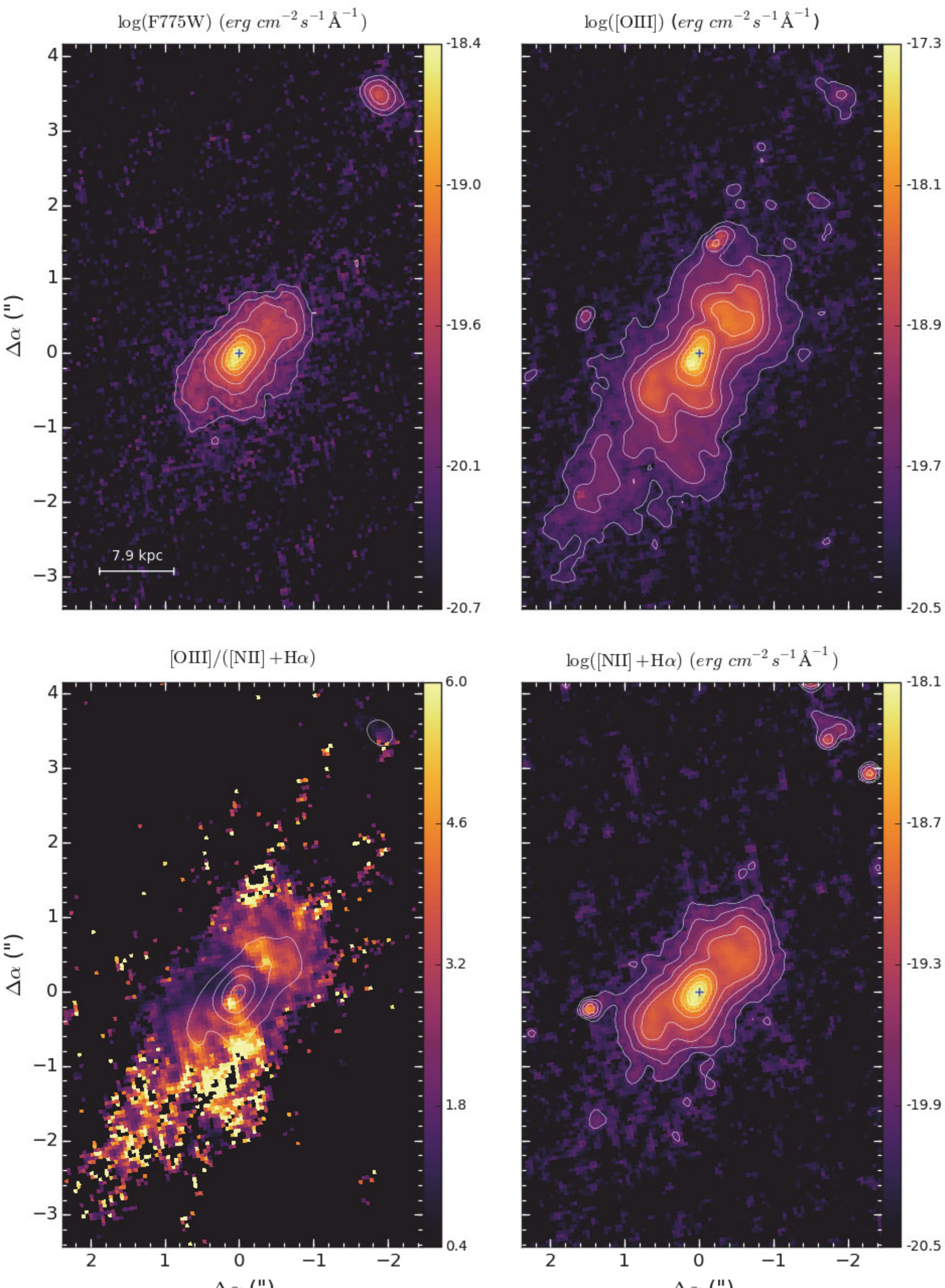
Ionized gas extent: ~ 7 kpc

Ionization cones at 0.1<z<0.5 (Storchi-Bergmann+17)



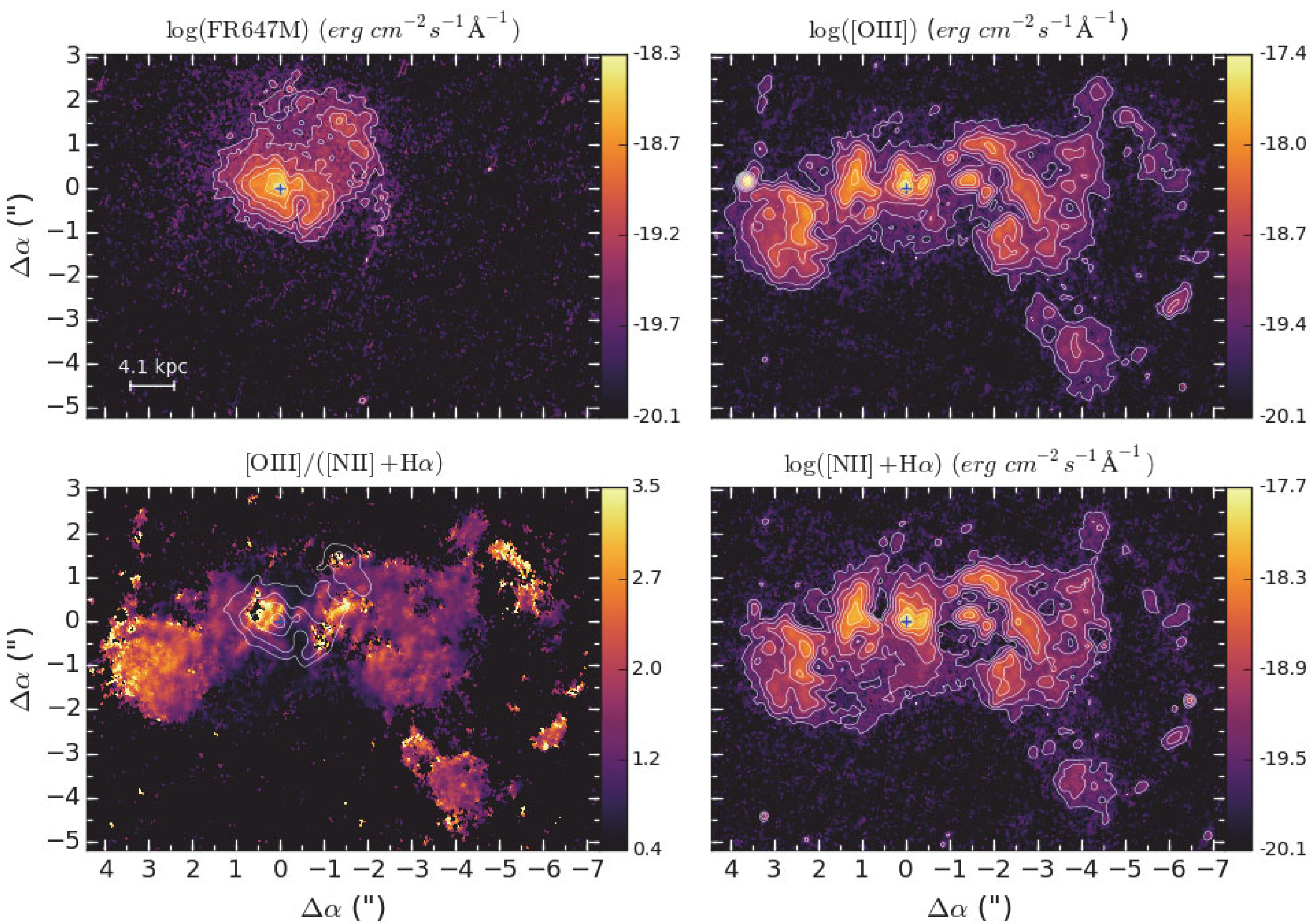
Ionized gas extent: ~ 7 kpc

Ionization cones at $0.1<z<0.5$



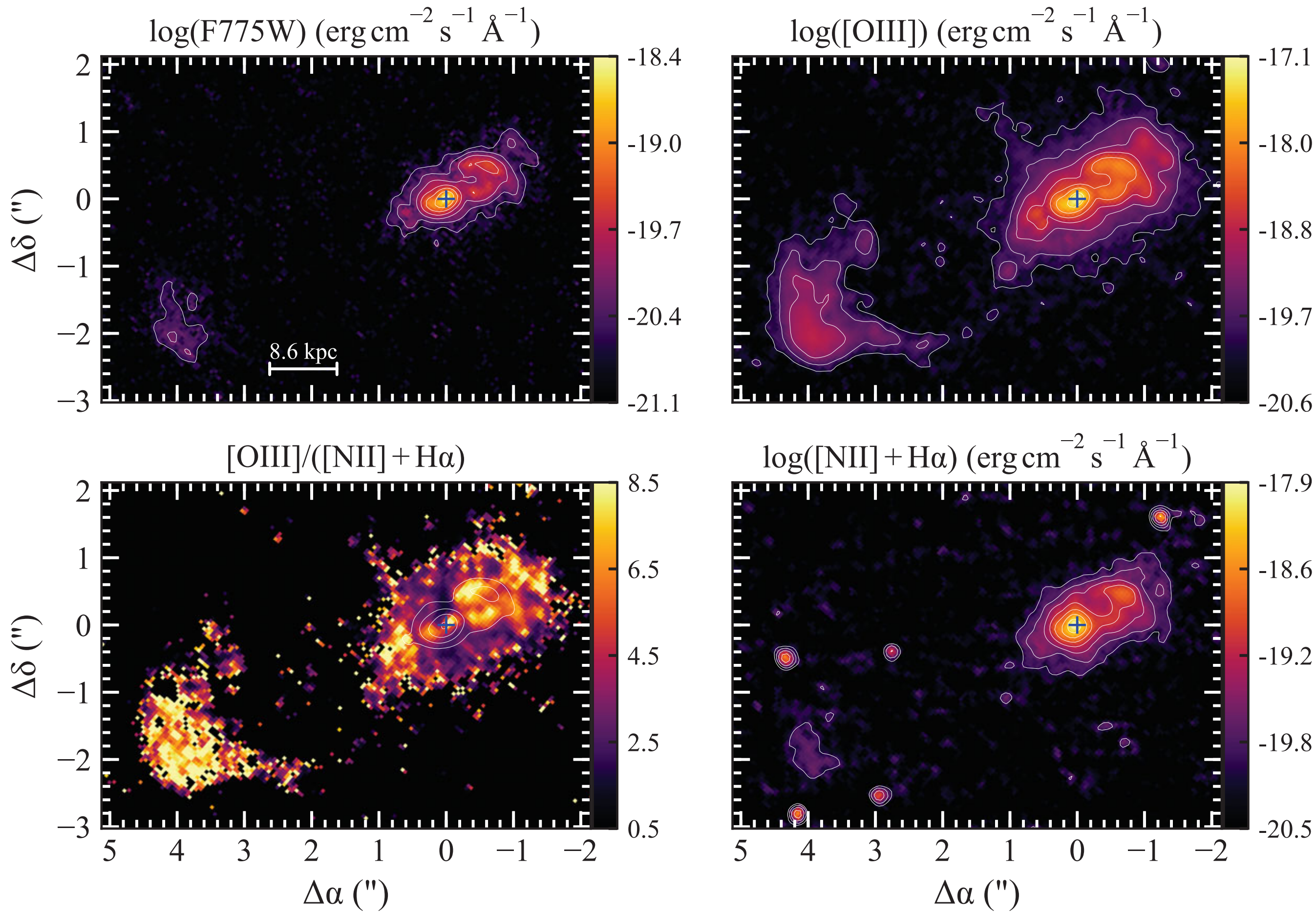
Ionized gas extent:
19 kpc!

Ionization cones at 0.1<z<0.5 (Storchi-Bergmann+17)



Ionized gas extent: 22 kpc!

Ionization cones at 0.1<z<0.5 (Storchi-Bergmann+17)

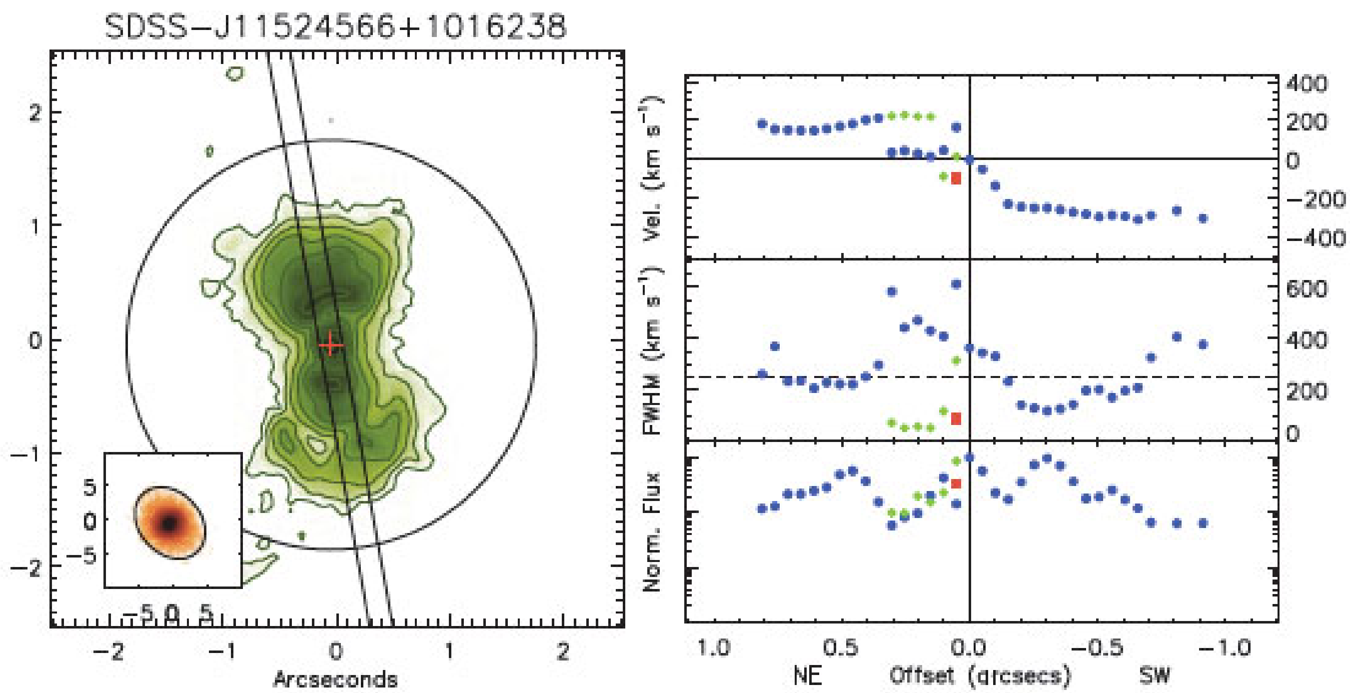


Ionized gas extent: 30 kpc!

Kinematics? Fischer+17

- Similar, but lower z sample: 11 most luminous targets on Reyes+08 under z=0.12, with log L[OIII]>42.3
- STIS spectra along ionization axis
- Preliminary results: outflow kinematics much more compact than [OIII] emission

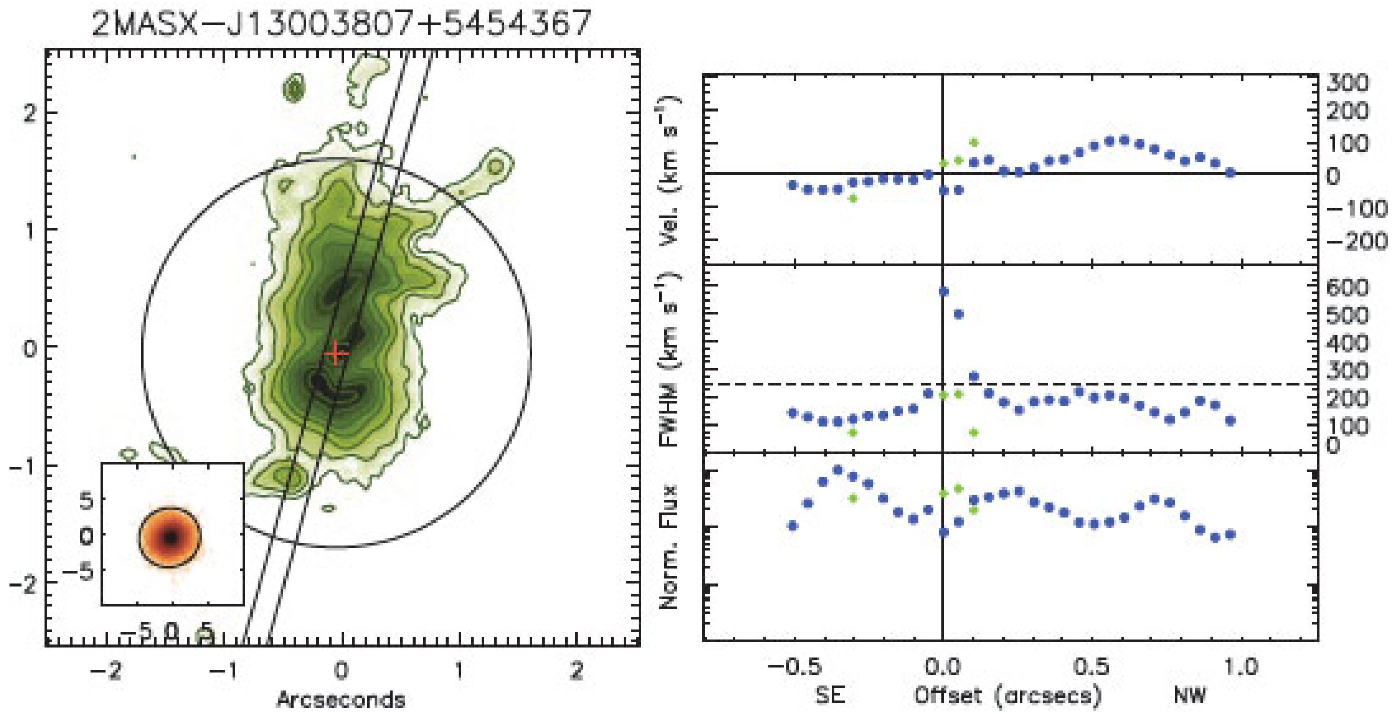
Fischer+17: ACS + STIS



Disturbed (outflow) kinematics within 0.4": 520 pc (total [OIII]= 2.1 kpc)

Kinematics dominated by rotation

Fischer+17: ACS + STIS



Disturbed (outflow) kinematics within 0.2": 320 pc (total [OIII]= 4 kpc)

Kinematics dominated by rotation