The physical properties of AGN outflows and their impact on host galaxies:

The MAGNUM Survey

Growing Black Holes: Accretion and Mergers

Kathmandu
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Giovanni Cresci
INAF - Arcetri

G. Venturi, M. Mingozzi, A. Marconi, A. Marasco, G. Tozzi, C. Marconcini, L. Ulivi, F. Mannucci,, M. Perna, S. Carniani, E. Nardini, R. Maiolino et al.

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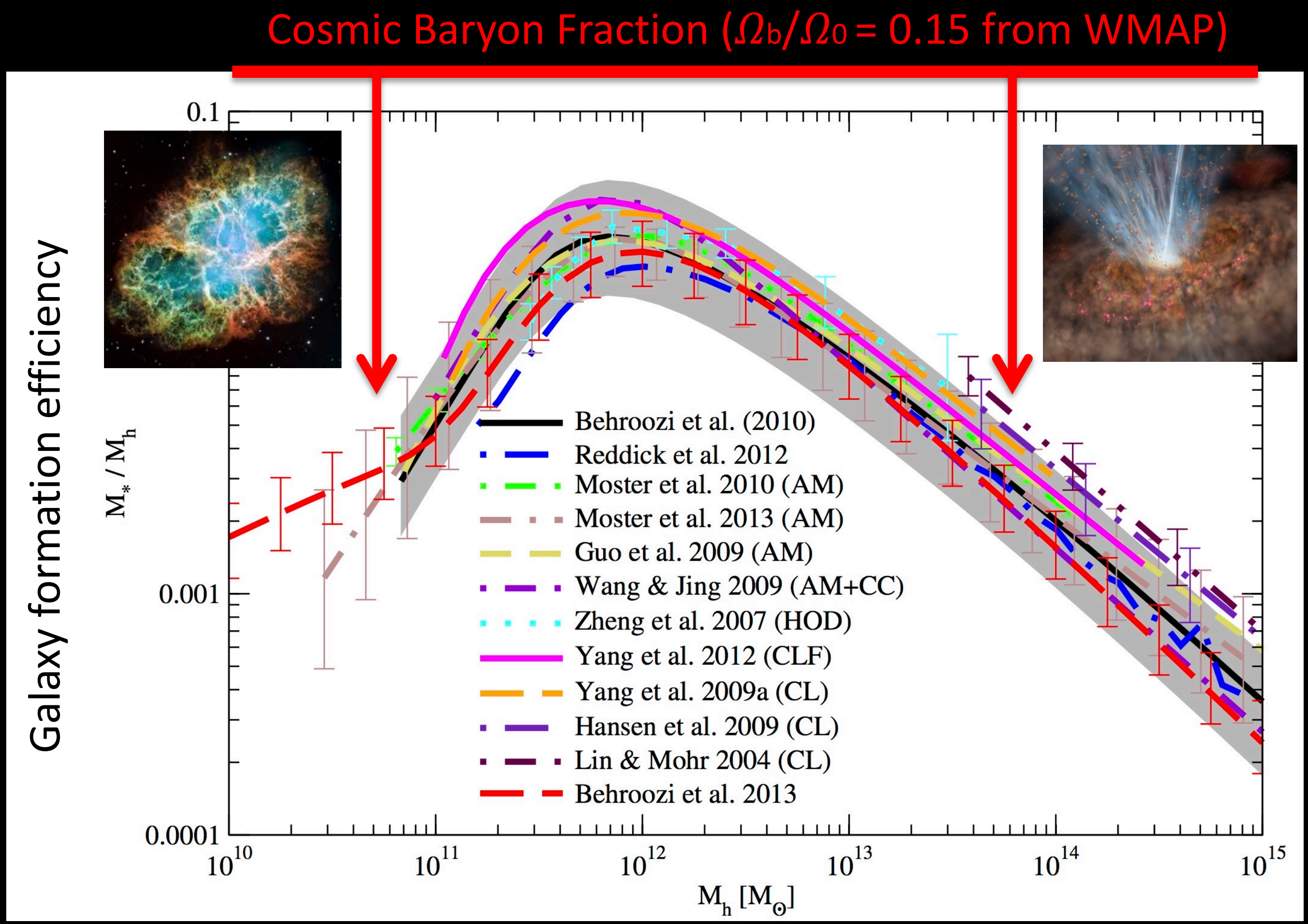
Why most baryons are not condensed into stars?

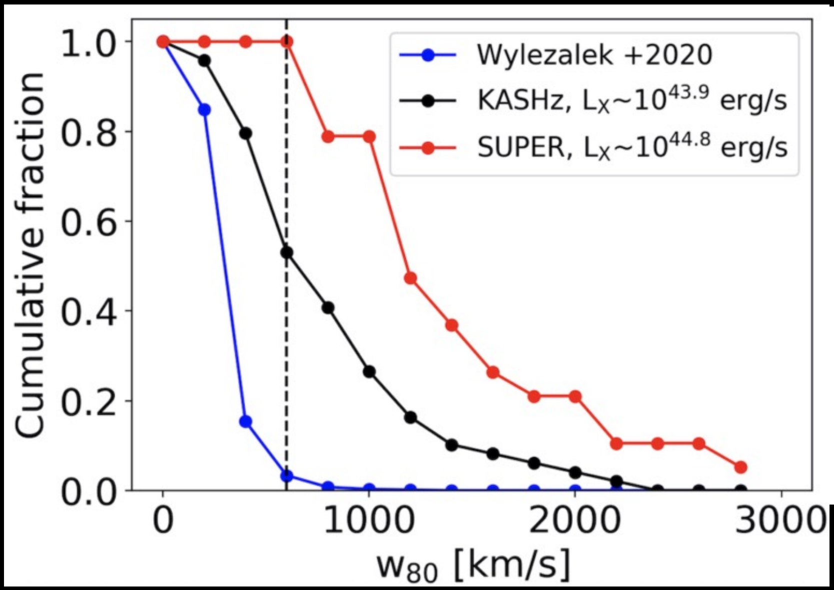


Behroozi+ 13

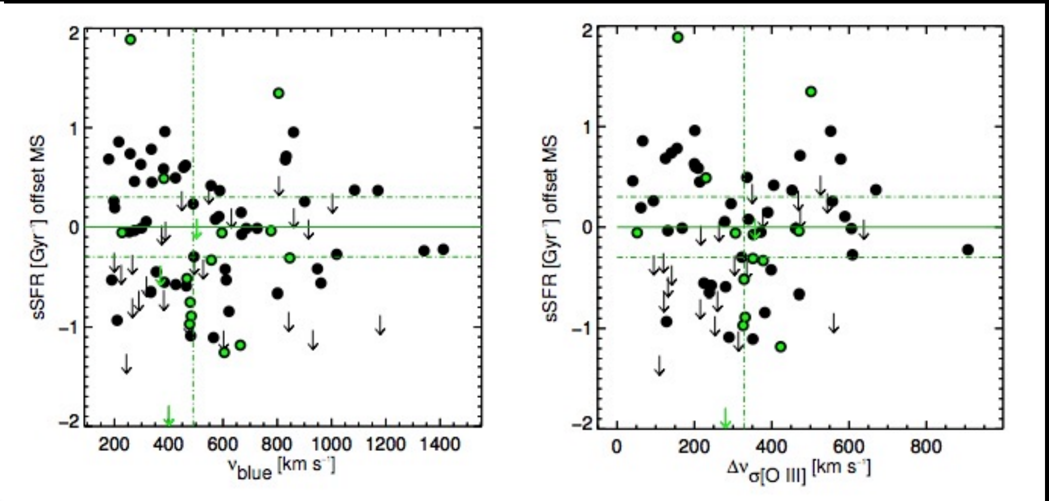
Stellar feedback can't explain reduced efficiency in massive galaxies (e.g. Hopkins+06, Croton+06, Murray+05, Menci+08 …)

Are Outflows ubiquitous?

Do we have evidences of effects on the host?



Kakkad+20 – SUPER Survey (z~2)
(see also e.g. Harrison+15, Forster-Schreiber+15,19; Leung+19)



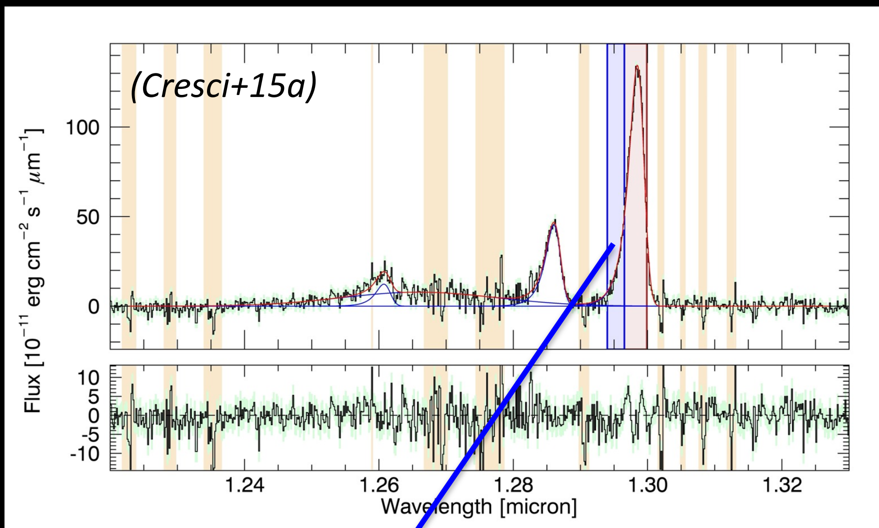
Balmaverde, GC et al. (2015): SDSS+Herschel selected QSOs (see also e.g. Leung+17, Woo+17, Woo+20, Smirnova-Pinchukova+21 …)

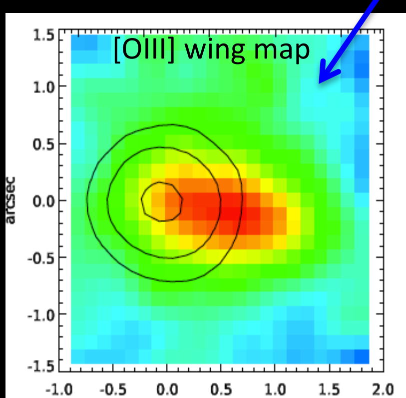
No trend between outflow velocity and SFR
(BUT: different timescales…)

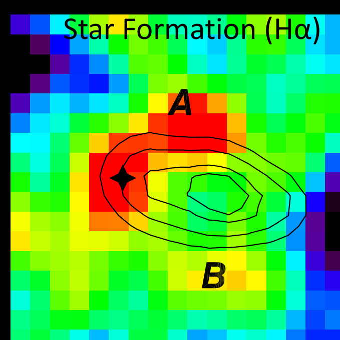
Many theoretical predictions, increasing evidences of widespread outflows, but still few observations of feedback effects on host galaxies…

Why Local?

QSO feedback finally revealed at high-z…







Negative and positive feedback in a z~1.5 QSO

… but at high-z very difficult to measure outflow physical quantities and provide interpretation even at high spatial resolution

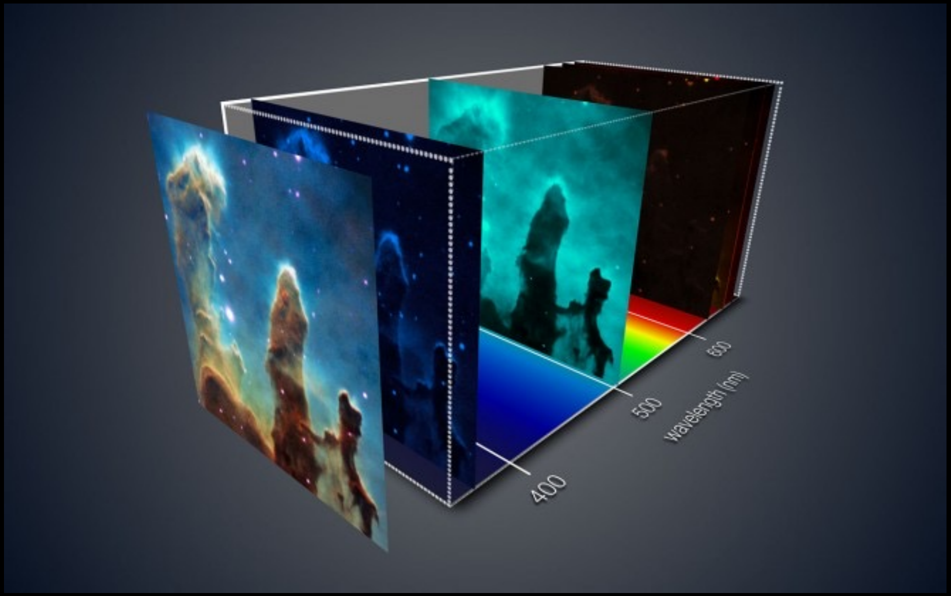
↓

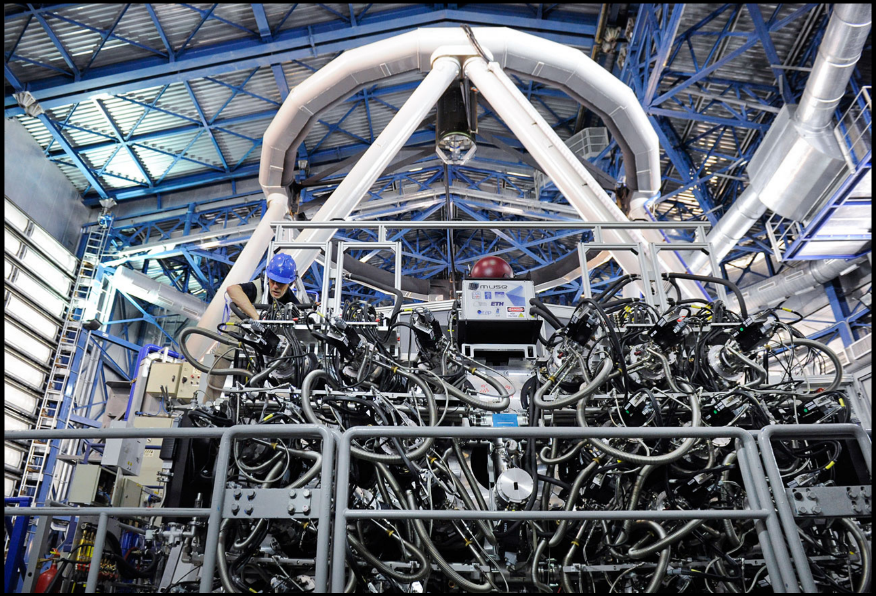
A IFU view of the nearest AGNs would provide much larger intrinsic spatial resolution to study SF and AGN activity, ionization conditions, inflows, outflows etc.

The MUSE instrument at VLT

Integral field spectrometer in the optical range:

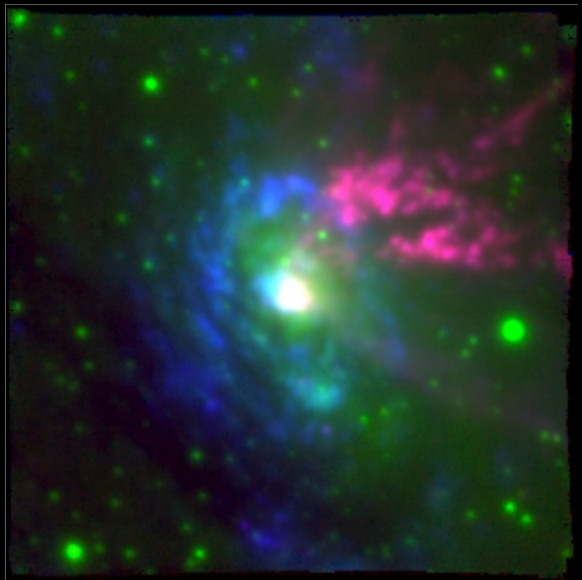
- fov 1x1 arcmin^2, advanced slicer design feeding 24 identical spectrographs
- $4650 < \lambda < 9300$ A @ $1500 < R < 3500$
- 90,000 0.2”×0.2” spaxels
- image quality limited by atmosphere (but GALACSI seeing enhancer now offered)
- High stability (no moving parts) and high throughput (0.35 end-to-end)
- 400 Mpixels (!!) in total

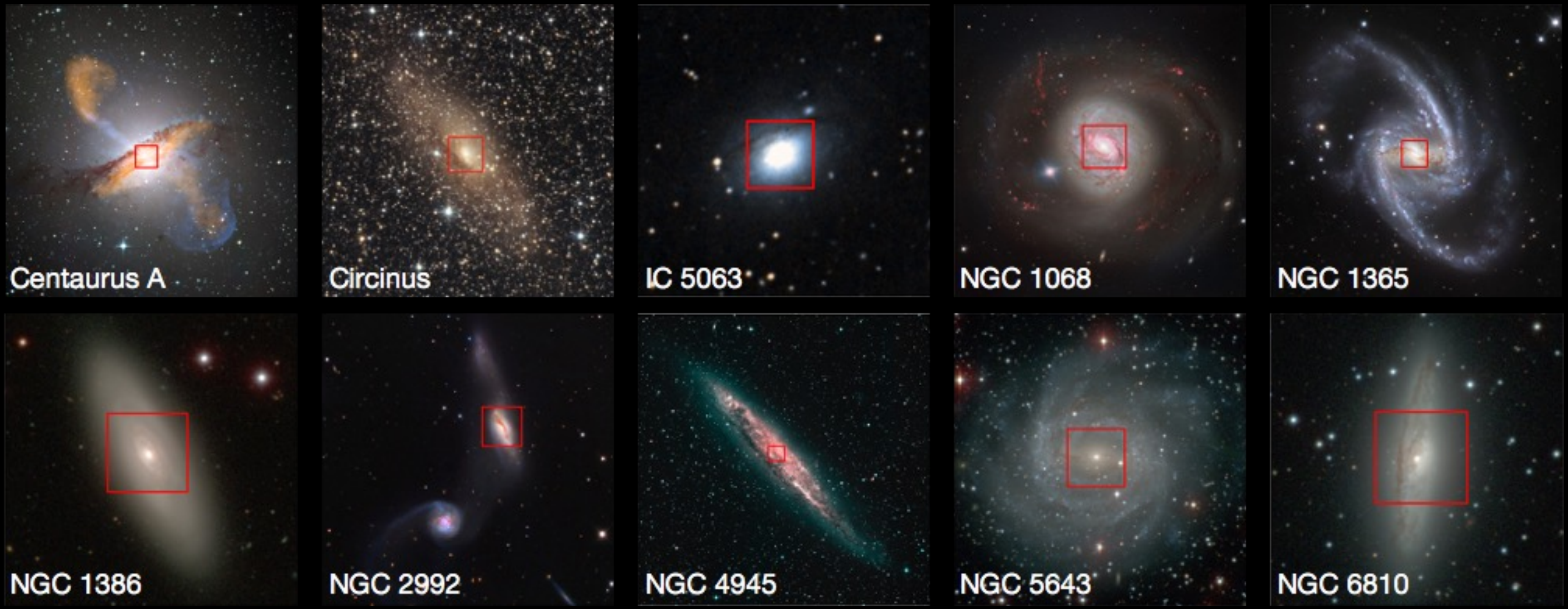




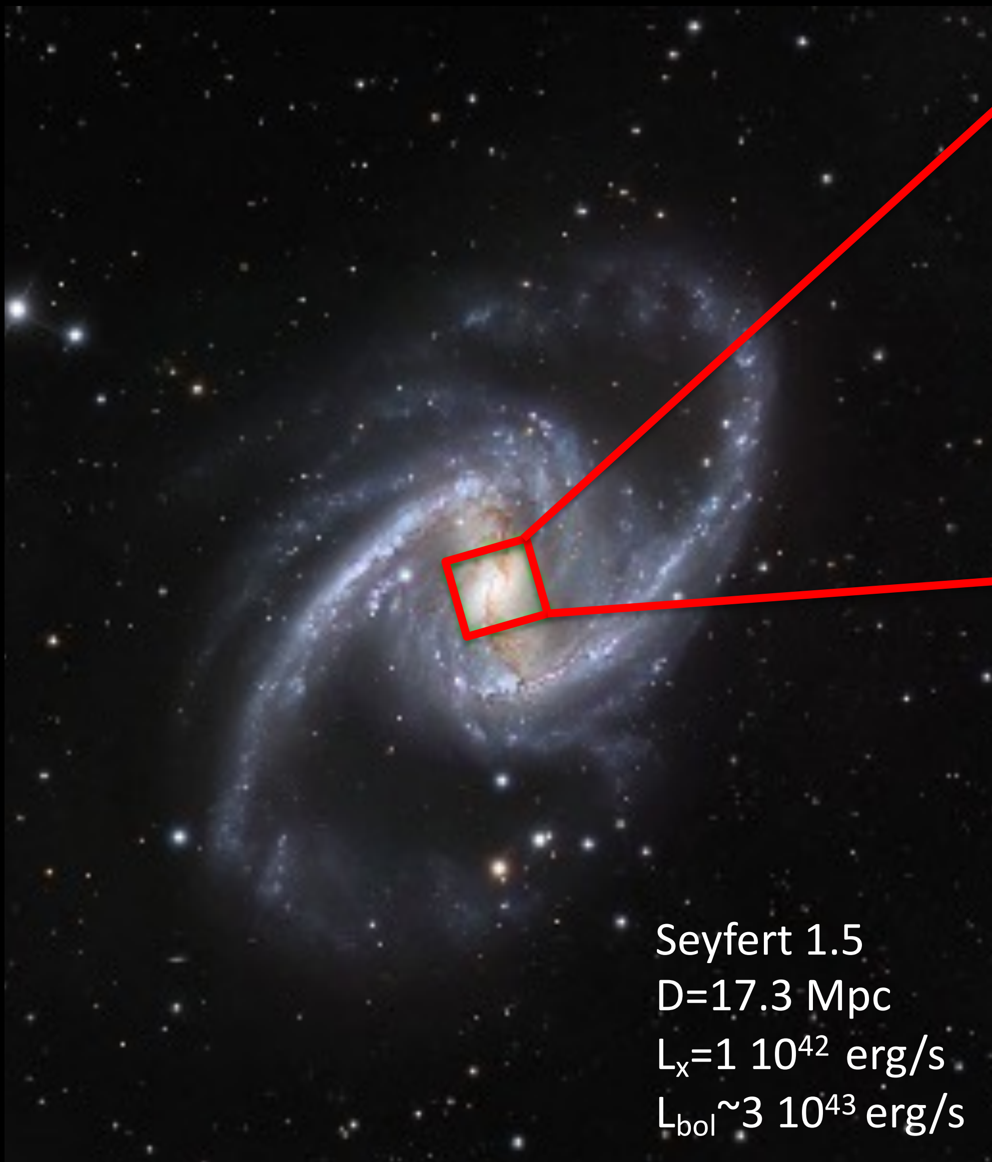
MAGNUM: Measuring Active Galactic Nuclei Under MUSE Microscope

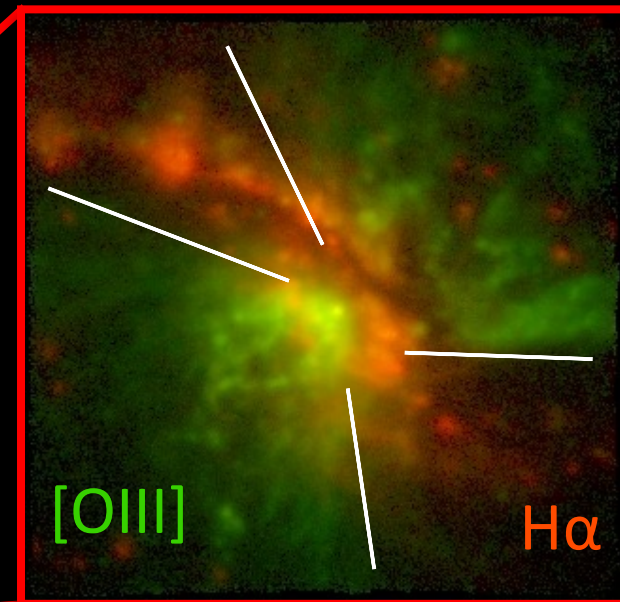
- Targeting Nearby AGNs (D < 50 Mpc) observable from ESO with MUSE
- Seeing limited (~1”):
  15 pc (@4Mpc)
  115 pc (@30Mpc)
- so far 10 objects analyzed (900,000 spectra!!)
- Multi-wavelength data available: *Chandra, XMM-Newton, Alma, Galex, HST, Spitzer, Herschel,Radio…*

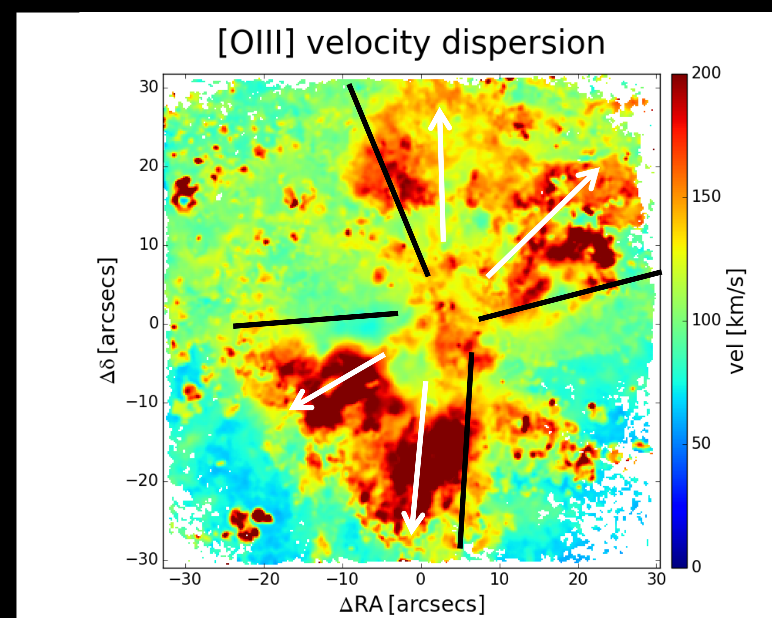




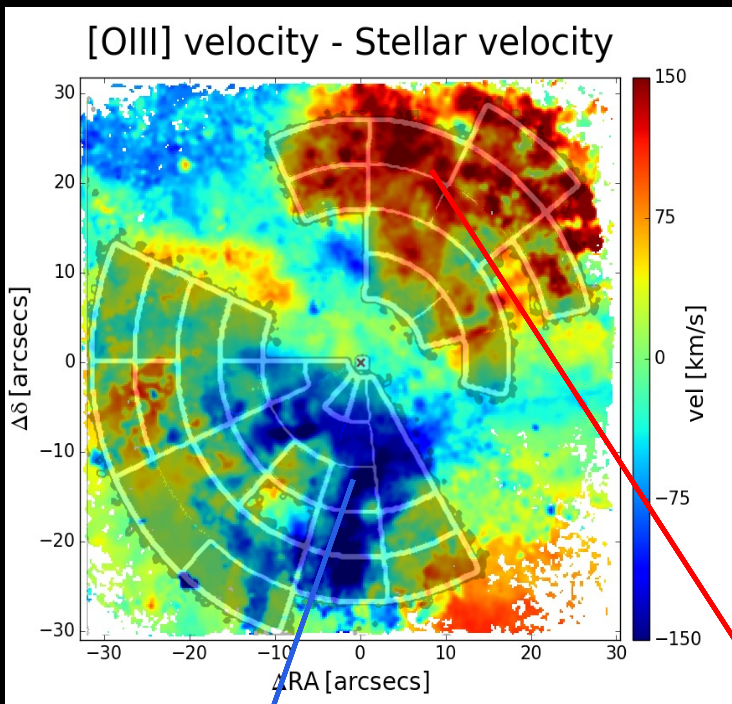
NGC 1365: an AGN in the Great Barred Galaxy







NGC 1365: mapping the mass outflow rate

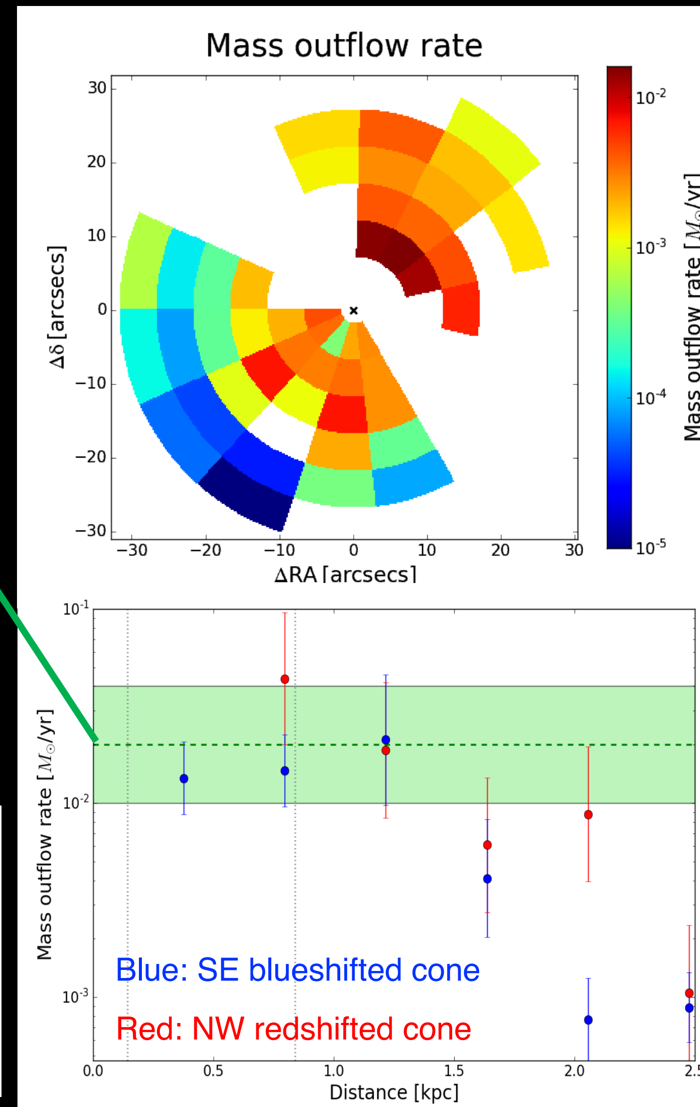


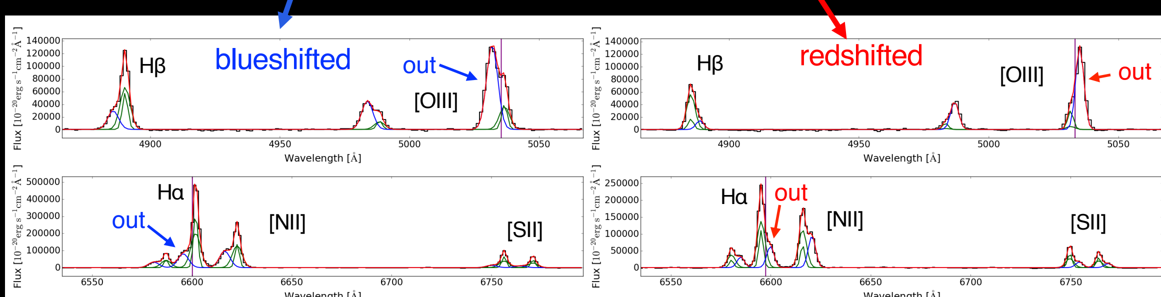
Mass outflow rate of nuclear X-ray wind

($v \sim 3000$ km/s)

from Fe XXV and Fe XXVI absorption lines

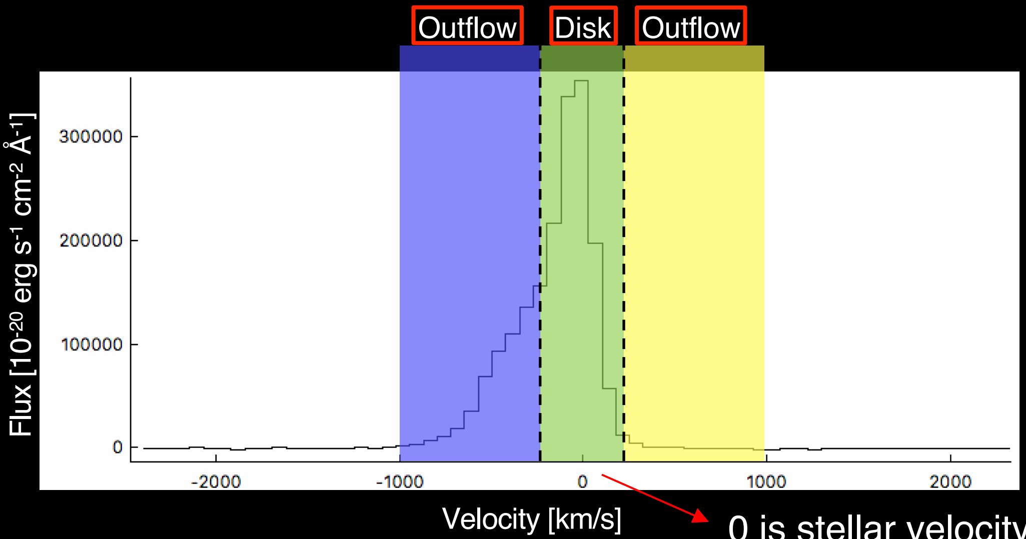
$\dot{M} \sim 0.04\ M_{\odot}/\mathrm{yr}$





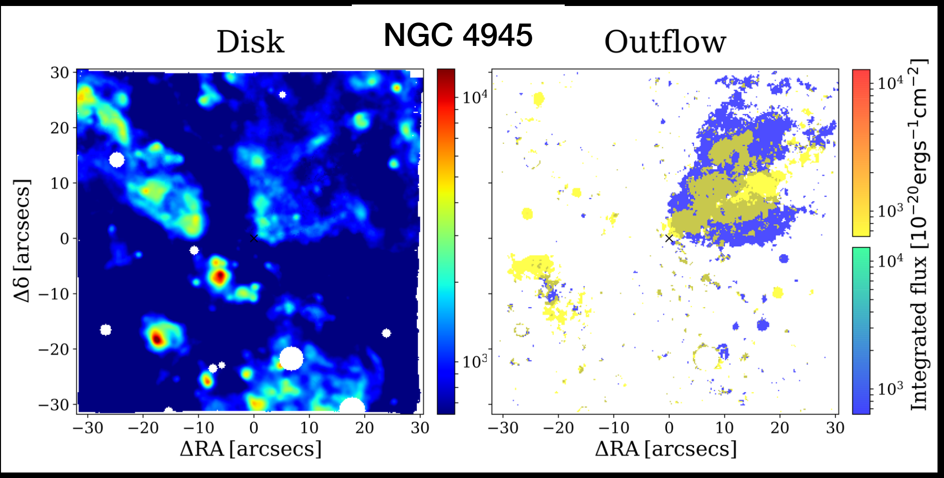
Venturi, GC et al. 2018

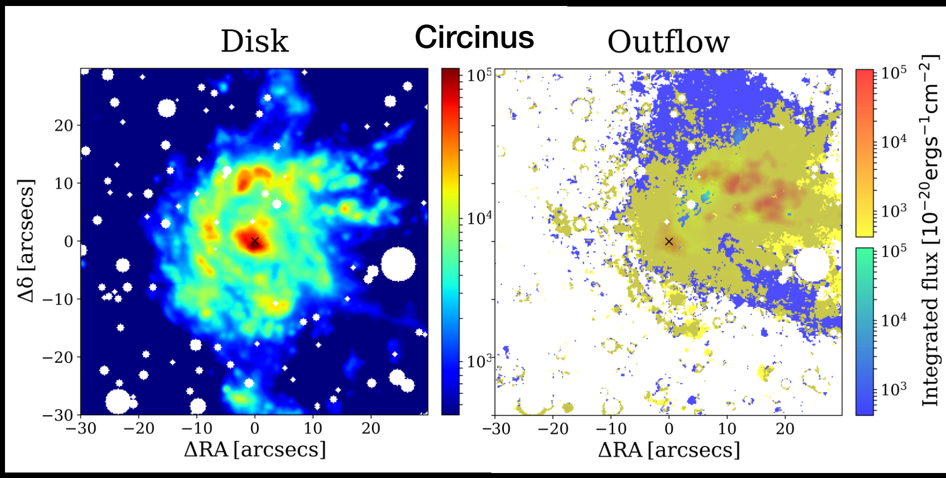
Velocity resolved ISM conditions



0 is stellar velocity measured in each spaxel

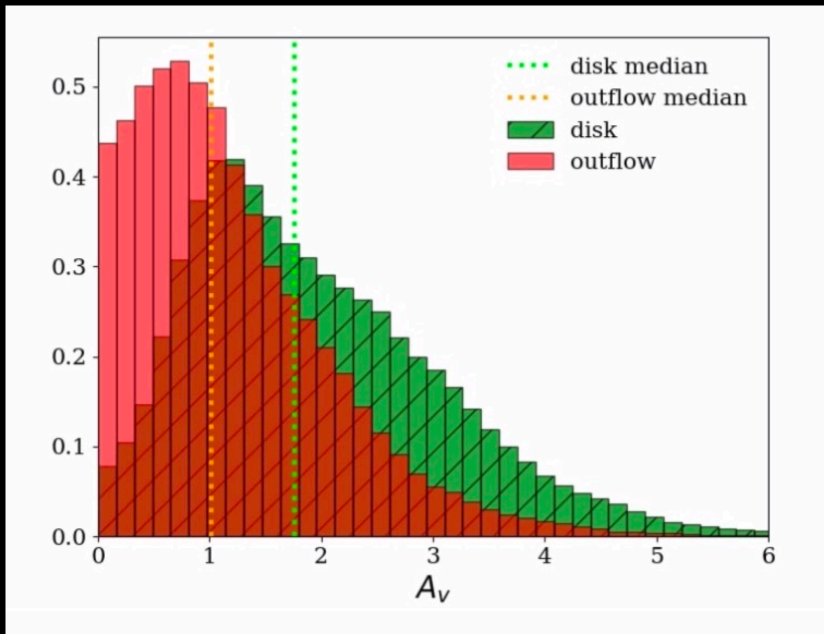
Emission line profiles divided in **velocity bins** to **separate outflows from disk**

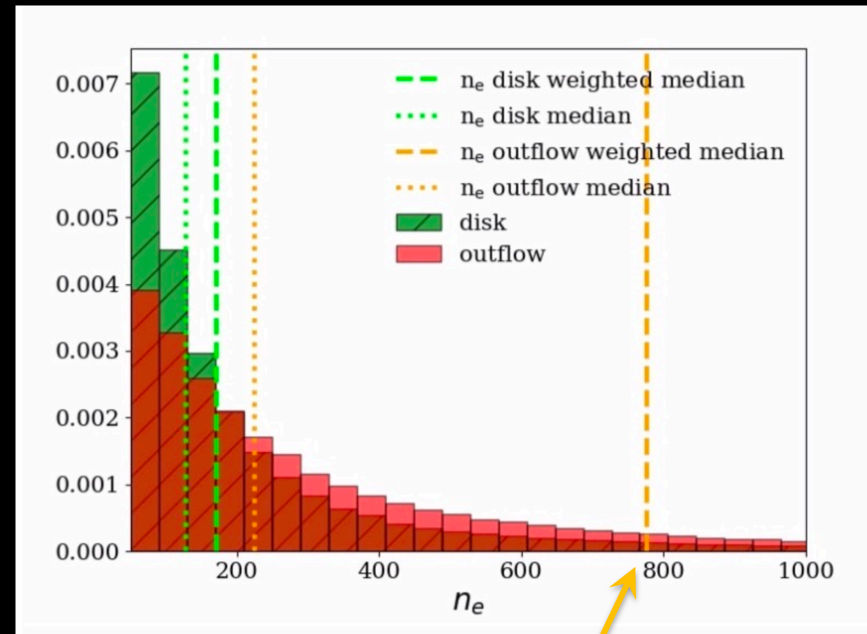


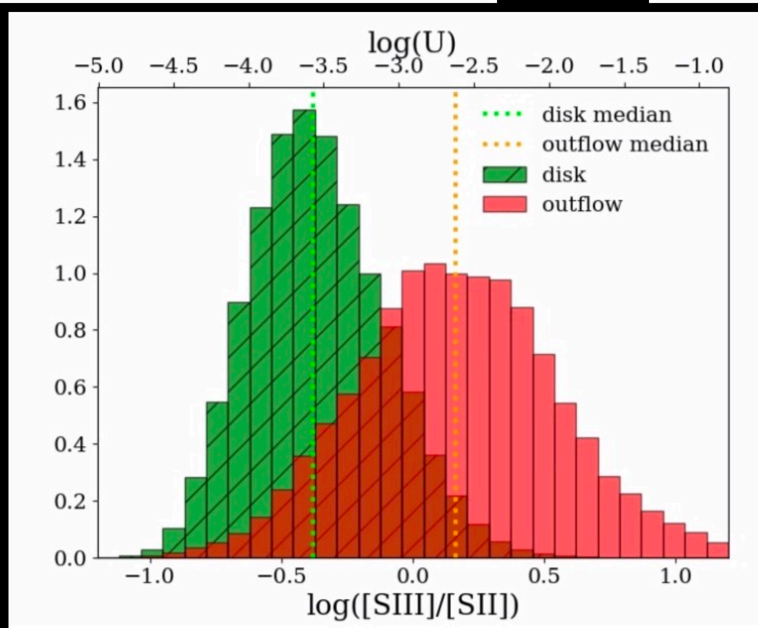


Mingozzi, GC et al. 2018

Velocity resolved ISM conditions: disks vs outflows



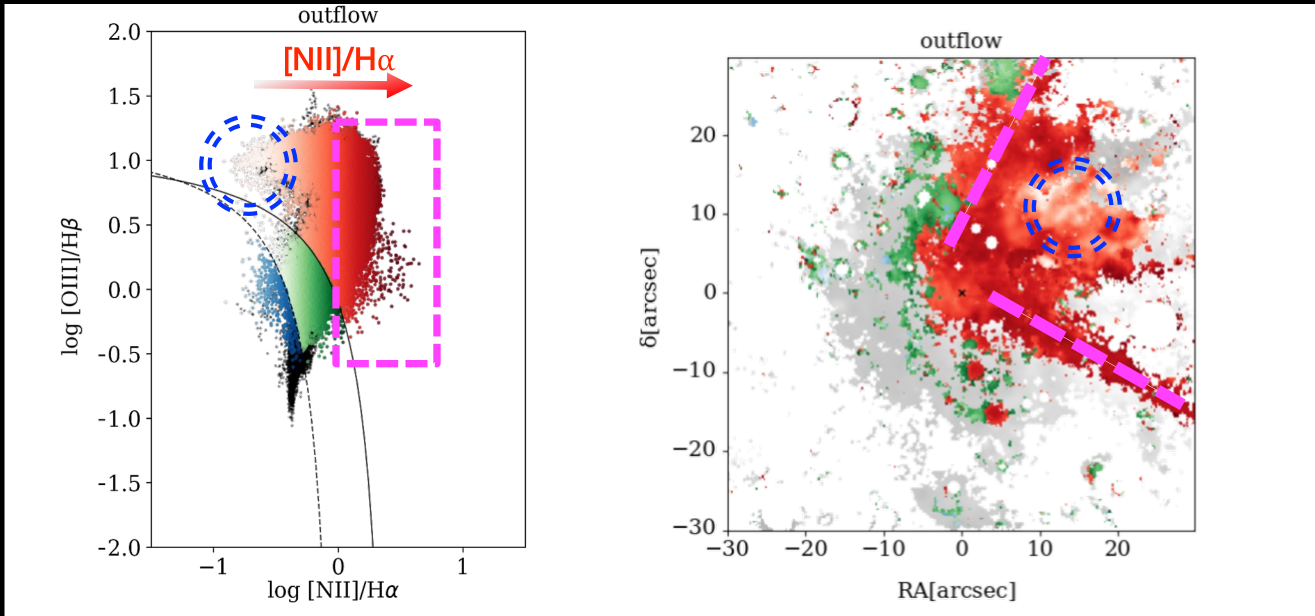




Luminosity weighted value compatible with high-z estimates (e.g. Perna+17, Baron & Netzer19, …)

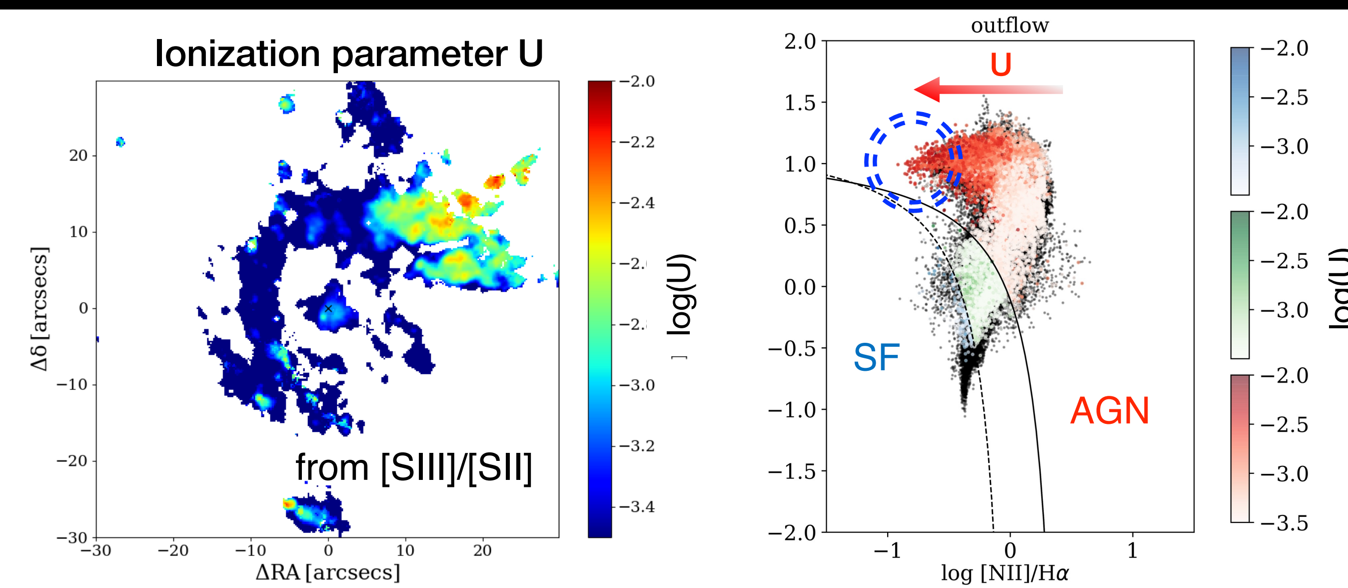
Mingozzi, GC et al. 2018

Velocity resolved BPT diagrams (Circinus)



The highest **[N II]/Hα** ratios correspond to the **edges of the outflow and highest velocity dispersions:**

Shock excitation

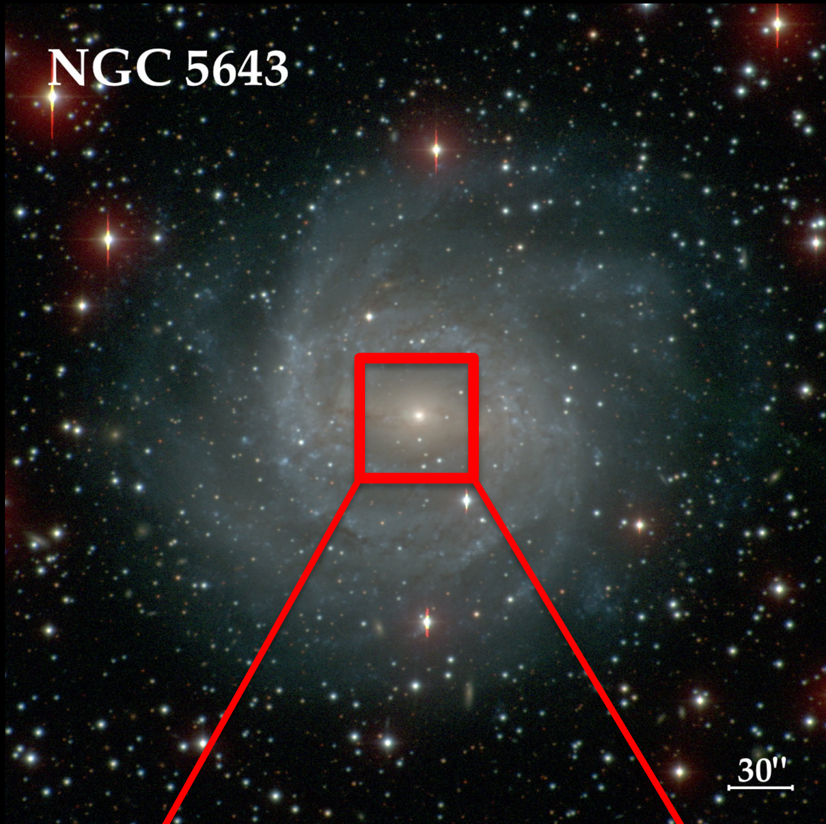


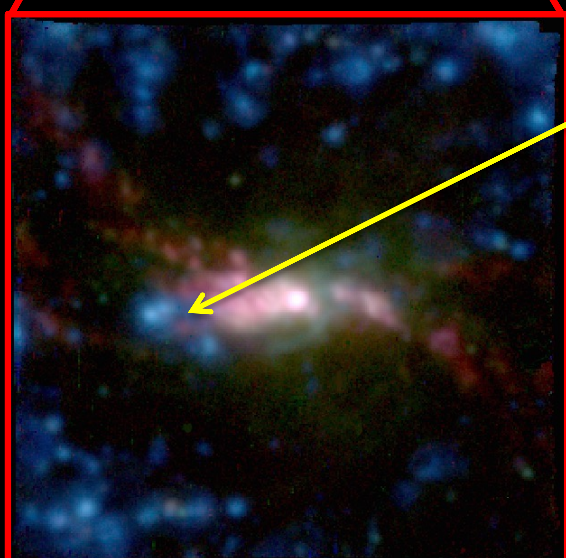
The **lowest [N II]/Hα** ratios correspond to the **highest ionization parameters U in the center of the outflow:**

Matter bounded Clouds

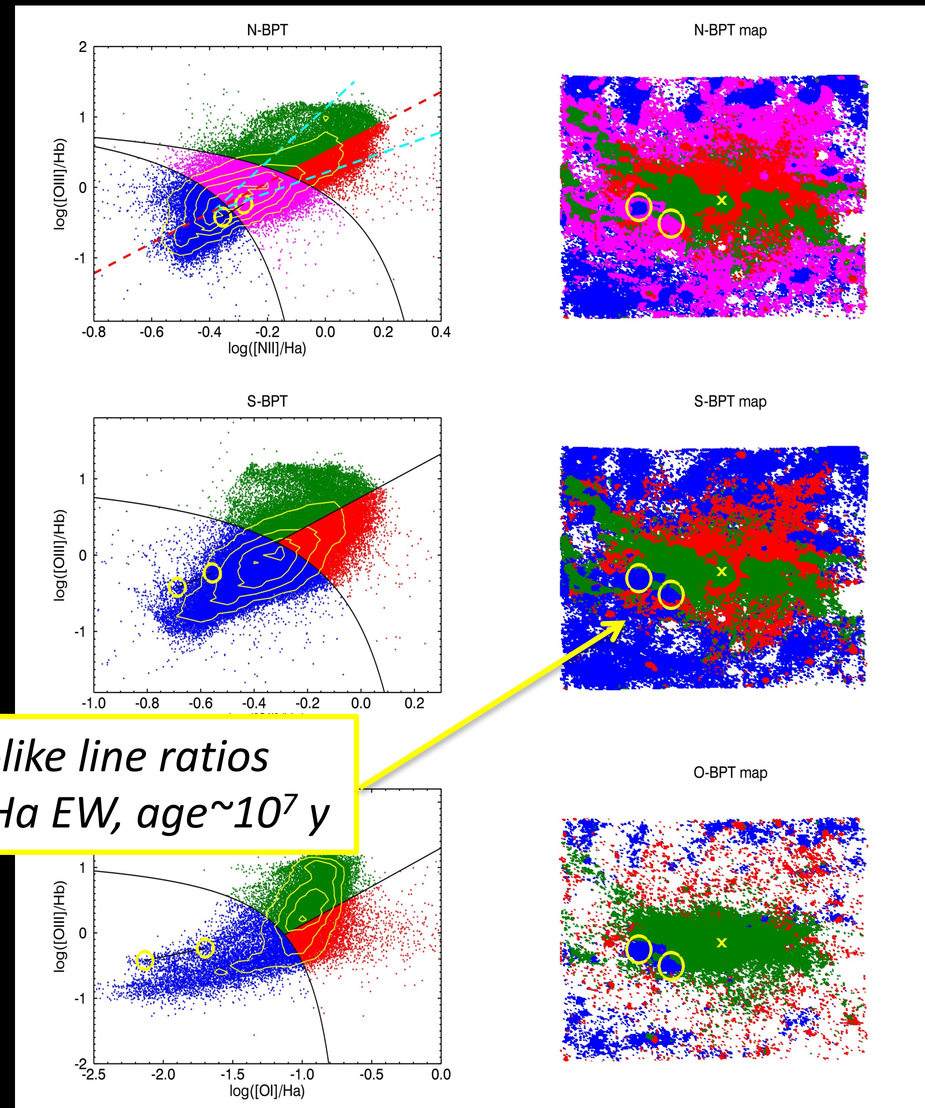
Mingozzi, GC et al. 2018

Impact of outflows: positive feedback





SF-like line ratios
High Ha EW, age~10^7 y

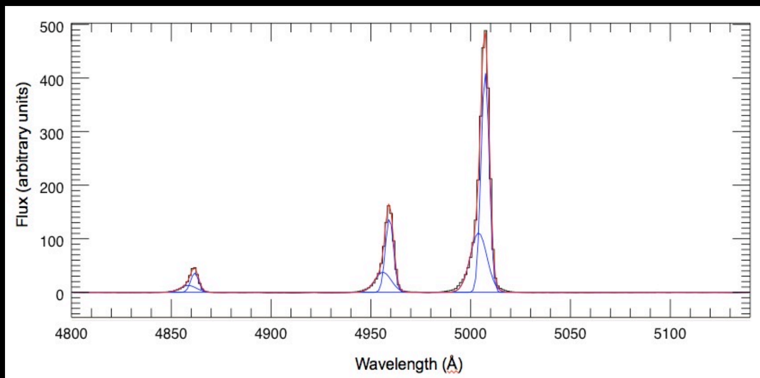


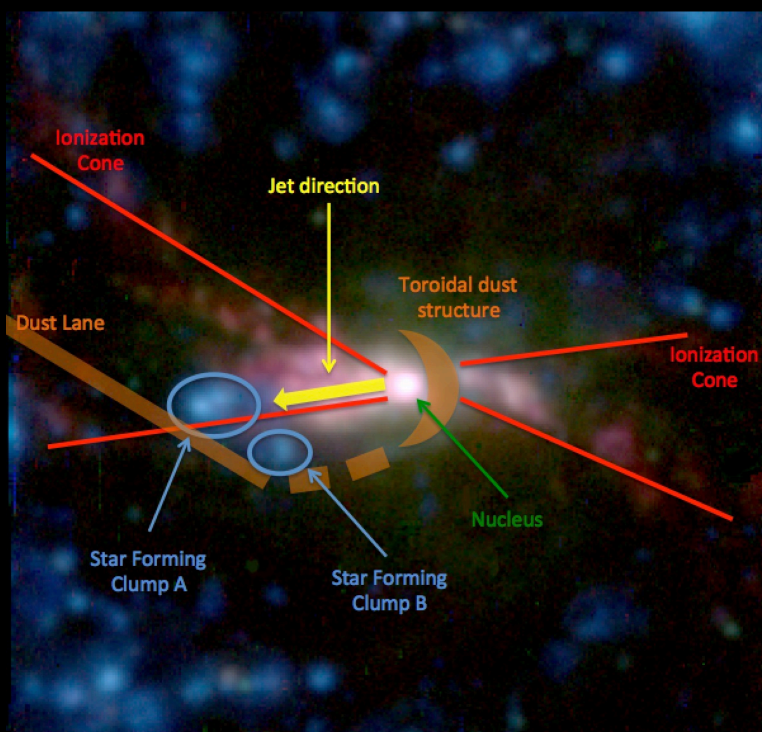
GC et al. 2015b

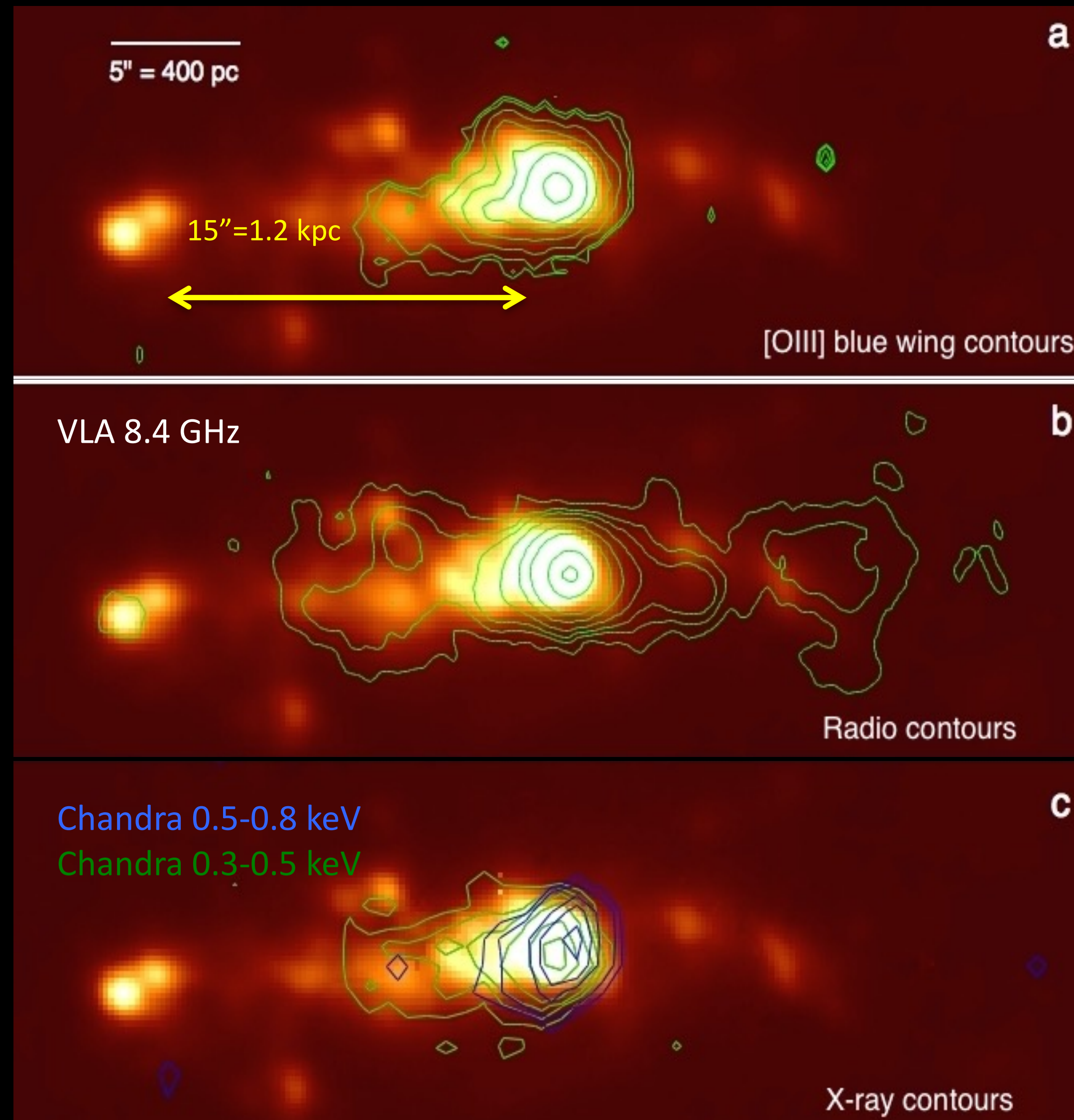
Seyfert 2, D=17.3 Mpc

L_X=1 10^{40} erg/s; L_{bol}~7 10^{42} erg/s

Impact of outflows: positive feedback

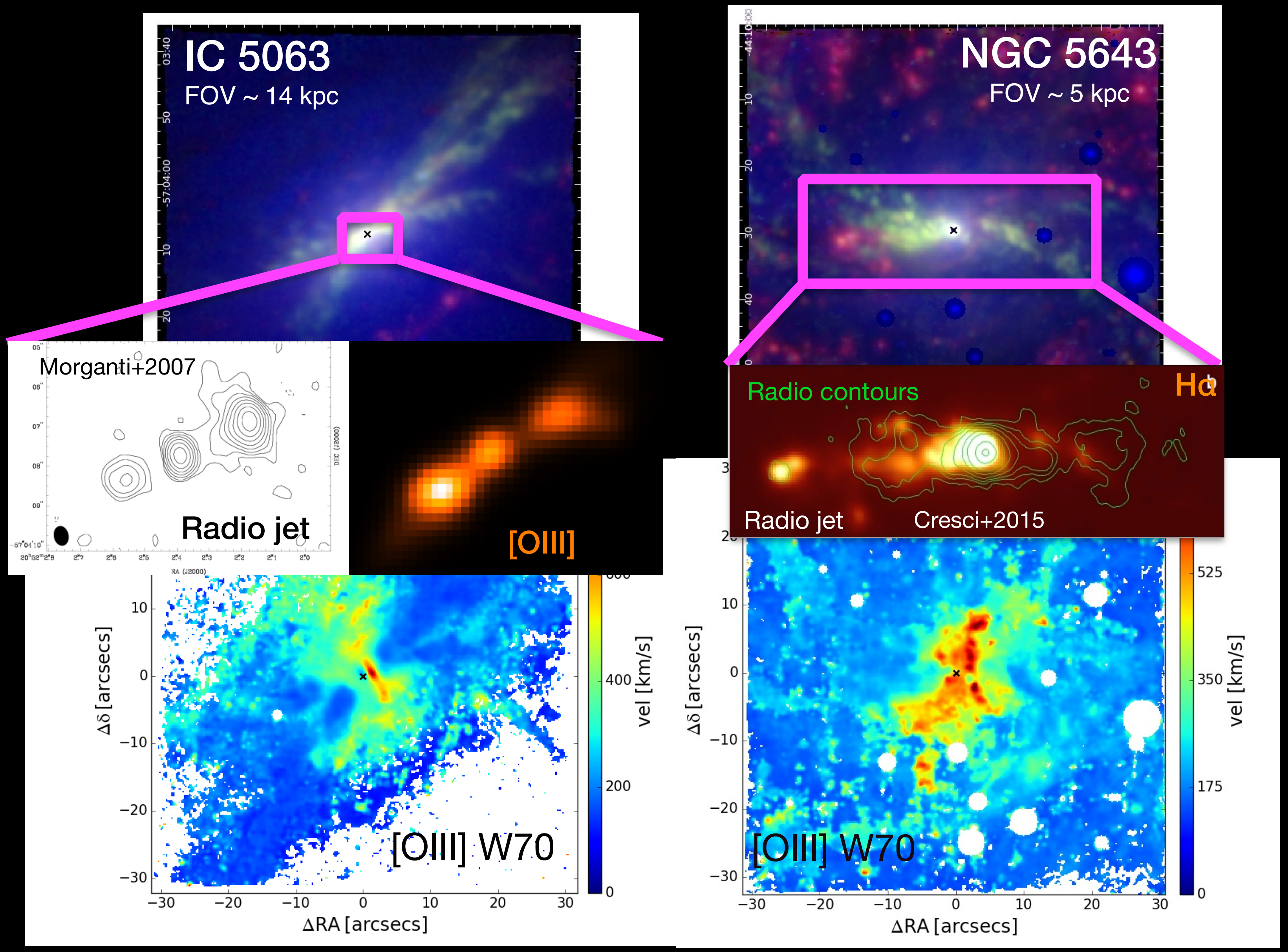






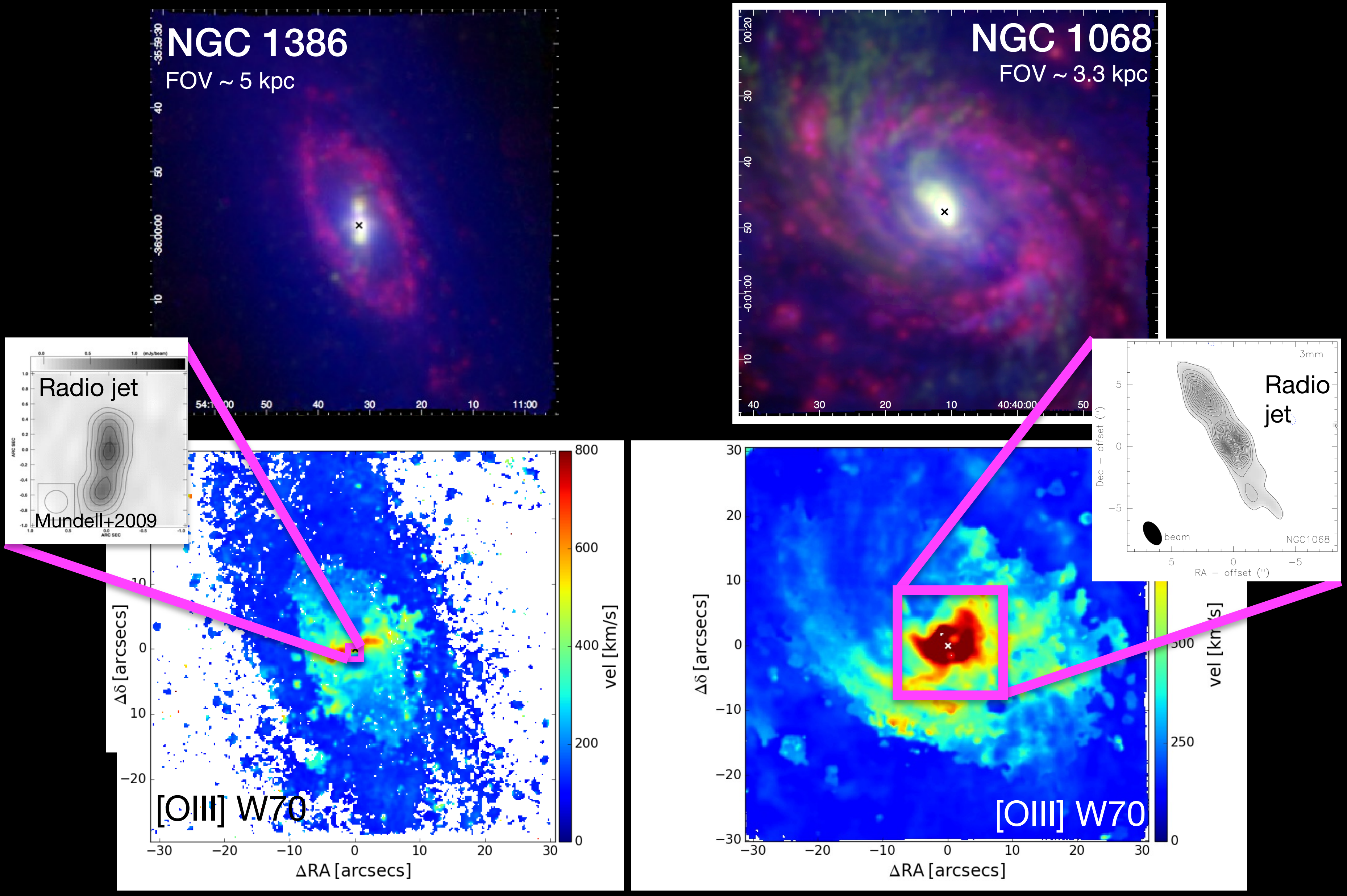
GC et al. 2015b

Impact of outflows: jet induced turbulence in the disks



outflows/turbulence perpendicular to AGN cones and radio jet!

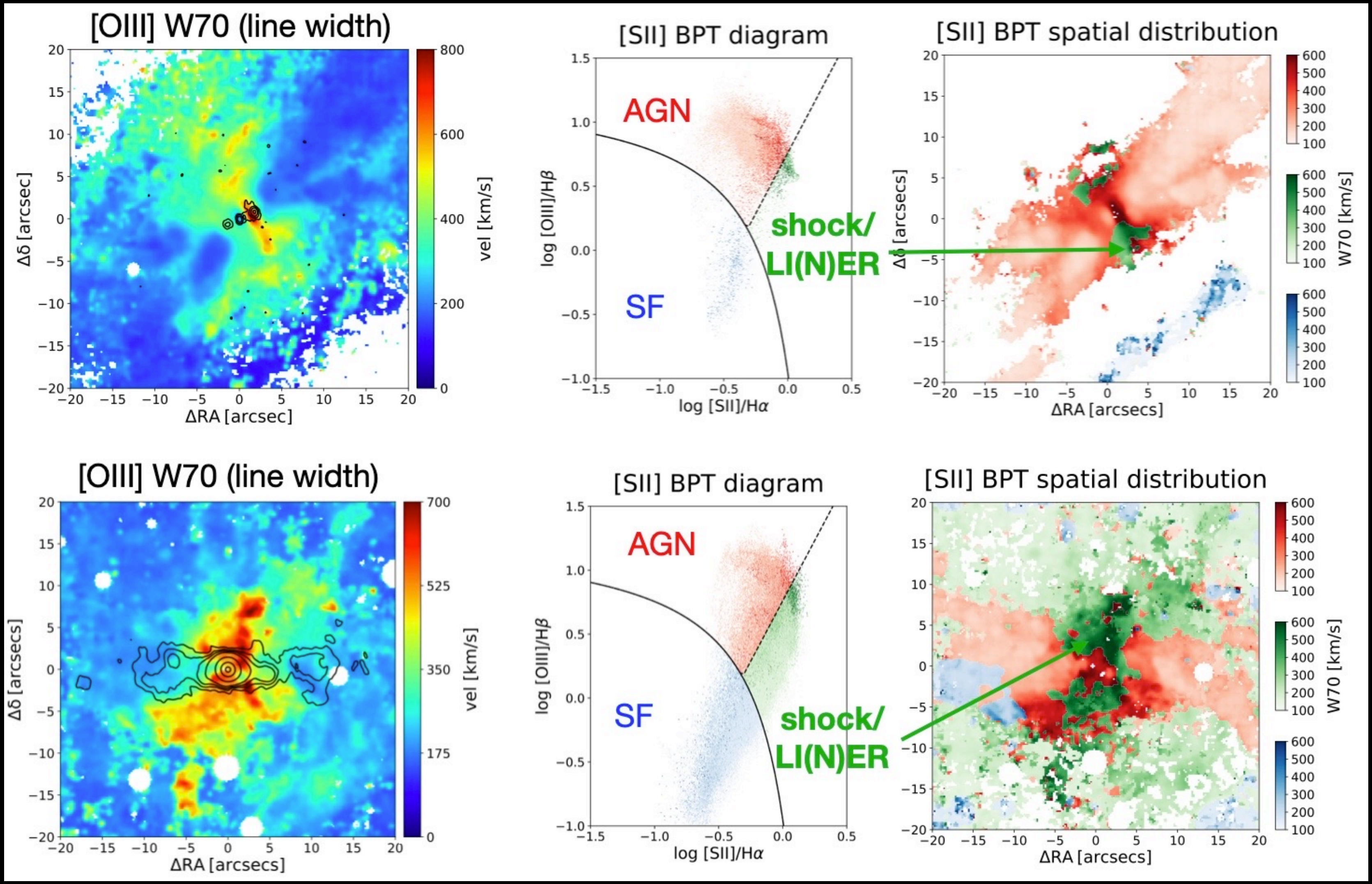
Impact of outflows: jet induced turbulence in the disks



Venturi, GC et al. 2021

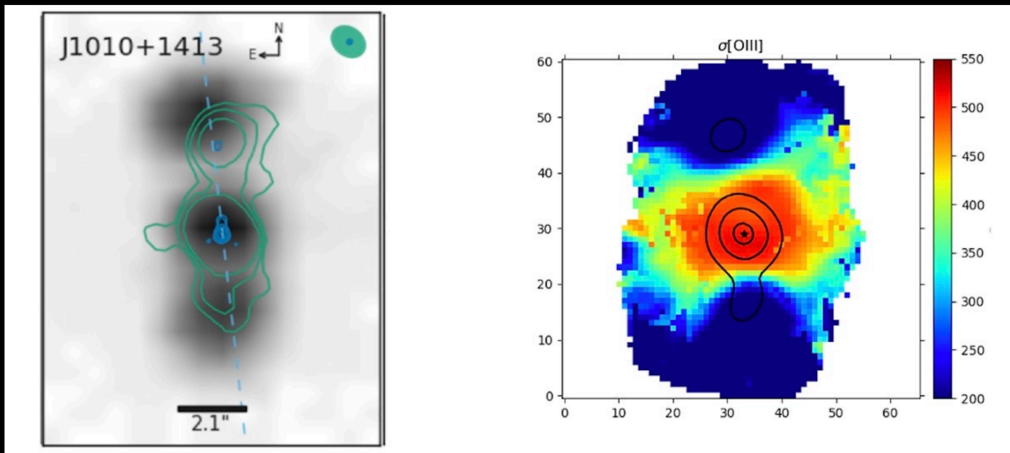
Impact of outflows: jet induced turbulence in the disks

High line width regions show shock-like ionisation



Venturi, GC et al. 2021

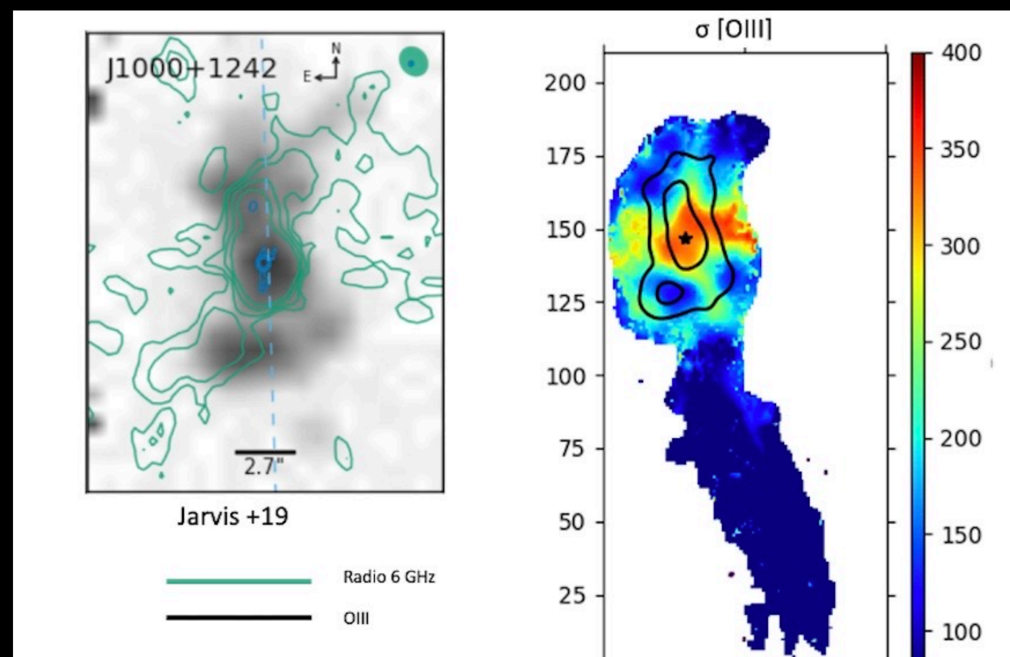
Impact of outflows: jet induced turbulence in the disks



Jarvis +19

MUSE data of a sample of **luminous (L_{AGN} ~10^{46} erg s^{-1}) QSO at z ~ 0.2**:

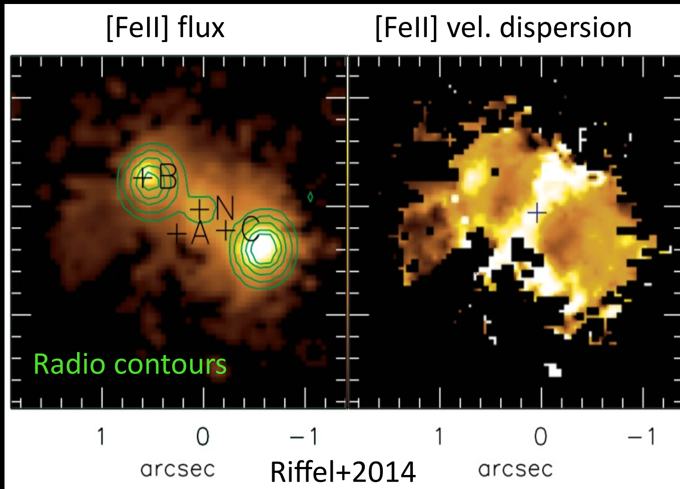
Same effect always observed when a low luminosity jet is present!



Jarvis +19

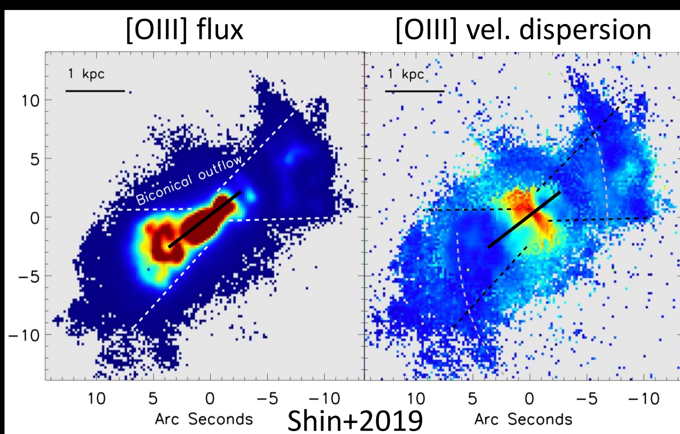
Ulivi et al. in prep.

Jet induced turbulence in the disks

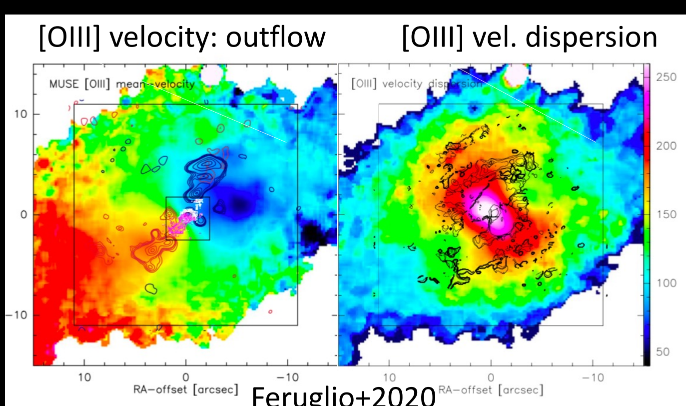


Enhanced velocity dispersion perpendicular to radio jets and ionisation cones **observed** (but not recognized) **in other galaxies hosting compact low-power jets!**

(see Couto+13, Riffel+14,15, Schnorr-Müller+14, Lena+15, Diniz+15, Freitas+18, Finlez+18, Shimizu+19, Durré&Mould19, Shin+19, López-Cobá+20, Feruglio+20, Girdhar+22)



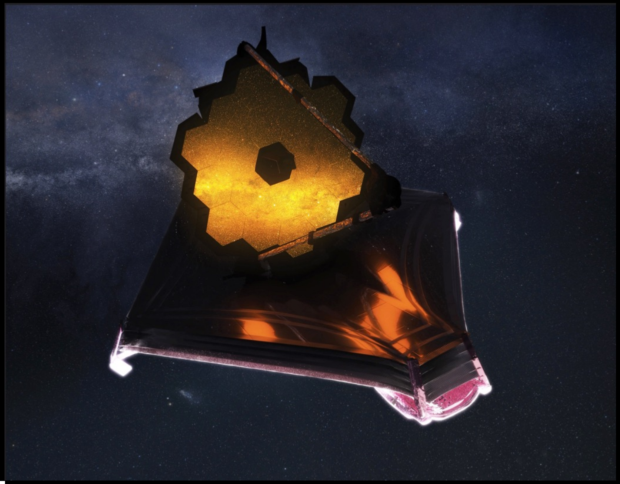
The jets in all these galaxies show evidence of being at **low inclinations** (≲40°) w.r.t. galaxy disc —> strong **jet-disc interaction!**

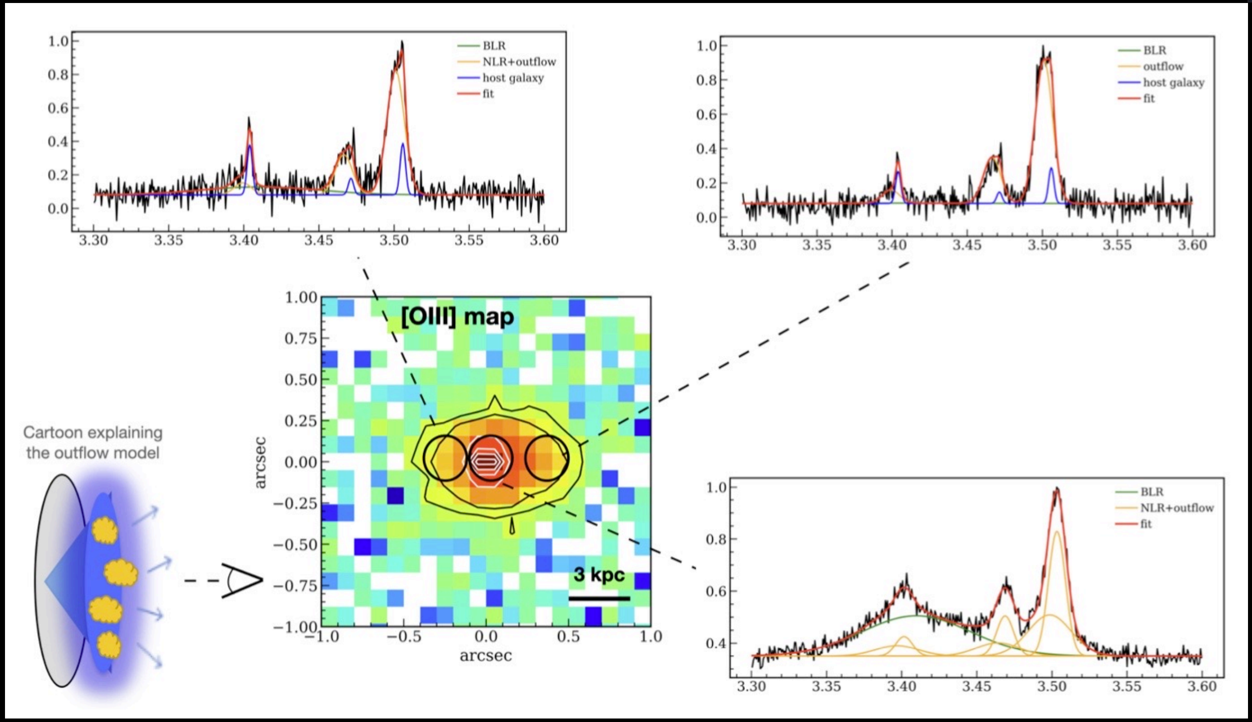


Evidence of turbulence induced Feedback?

The future: JWST!

- High spatial resolution and unprecedented sensitivity
- Possibility to expand AGN outflow studies beyond z~3
- IR coverage allows the study of warm molecular H_2 transition, dust in outflows etc.





Broad [OIII] map in a simulated NIRSpec IFS observation of a z~6 QSO (courtesy S. Carniani)

- Significant number of ERS and Cycle 1 proposal devoted to AGN outflows studies
- NIRSpec GTO GA-IFS survey will observe ~20 AGN at z>3

The future: not only JWST and ELTs

ERIS

Enhanced Resolution Imager and Spectrograph

is the new generation upgrade for both NACO and SINFONI,
and will be a fundamental AO capability for the VLT: imaging and IFU in the near-IR at the diffraction limit of the VLT,
with much higher Strehl and sky coverage

First light: 2022

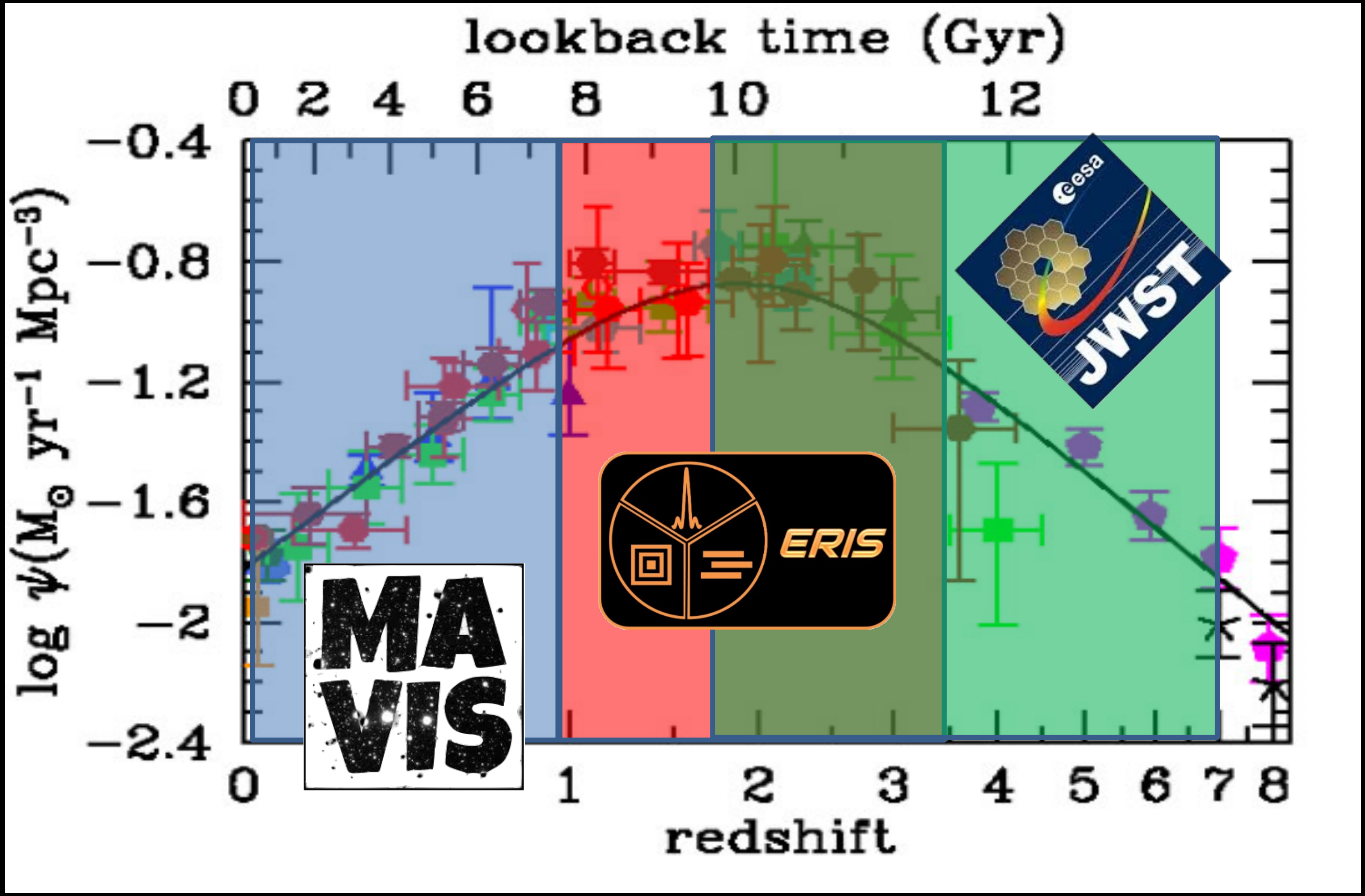
MAVIS

MCAO-Assisted Visible Imager & Spectrograph

is a forthcoming instrument for the VLT AOF (Adaptive Optics Facility).
It will provide near-diffraction limit imaging and IFU in the optical over a large (~30''x30'') fov using Multi-Conjugate AO:
an HST with IFU capabilities from the ground!

Currently in Phase B
First light ~2025

The future: not only JWST and ELTs!



- Forthcoming IFU system AO-fed in the NIR and Optical will open new complementary windows in our understanding of AGN physics and their interplay with the host galaxy
- from the peak epoch of SF and BH accretion to present

Conclusions

- MUSE data of nearby AGNs provide huge amount of information on the physics of the nuclear regions of galaxies:
- detailed study of outflow structure, kinematic and excitation
- relation between AGN and SF, positive feedback and jet induced turbulence

- A lot of work in progress:
  - detailed 3D kinematical modeling to infer outflow parameters
  - multi-cloud photoionization modeling for the physical properties of ionized gas
  - ALMA follow-up of UFO hosts and MAGNUM galaxies (MAGNUM FEAR, PI S. Carniani, G. Venturi): comparison between the properties of ionized and molecular outflows

- Bright future ahead: new AO facilities and JWST finally online!