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AGN Feedback and ISM properties in the nearby Universe

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Outline

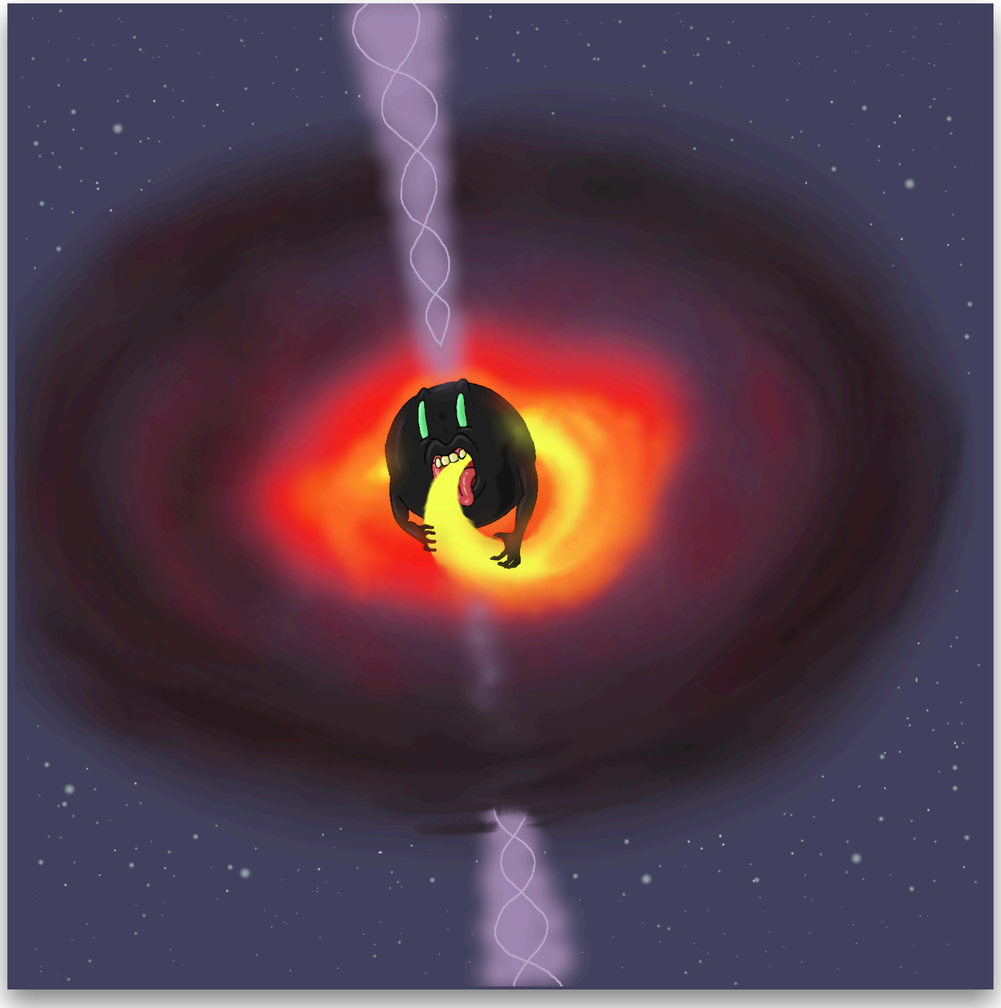
- **Introduction**

  AGN Feeding and Feedback

- **Results**

  Disks and outflows in local Universe

- **Conclusions**



Credit L. Capuano

AGN Feeding and Feedback

AGN feedback is necessary to explain **Galaxy Formation and Evolution.**

Observational evidence of strong link between SMBH and host galaxies **M – σ relation.**

FEEDING

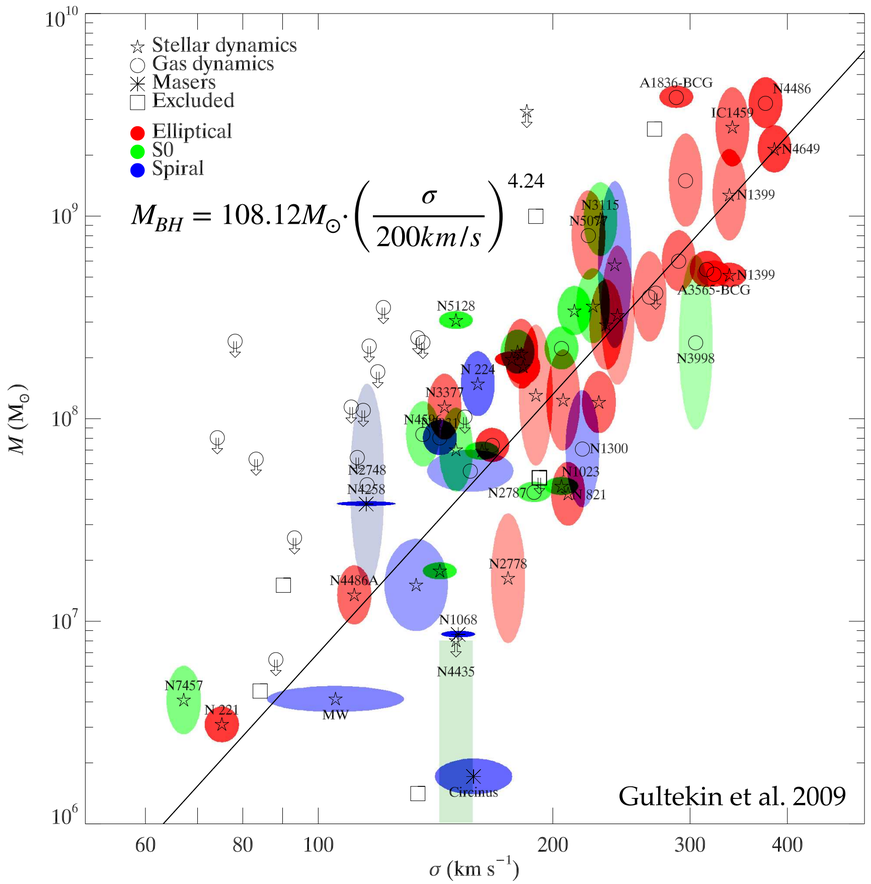
Star Formation process: conversion of gas into stars

AGN phase: gas accretion onto the central SMBH

$$L_{AGN} = \epsilon \dot{M}_{acc} c^2$$

FEEDBACK

Injection of **energy and momentum** into the ISM/CGM: winds, shocks, jets by AGN and SNe



Motivation: AGN Feeding and Feedback cycle

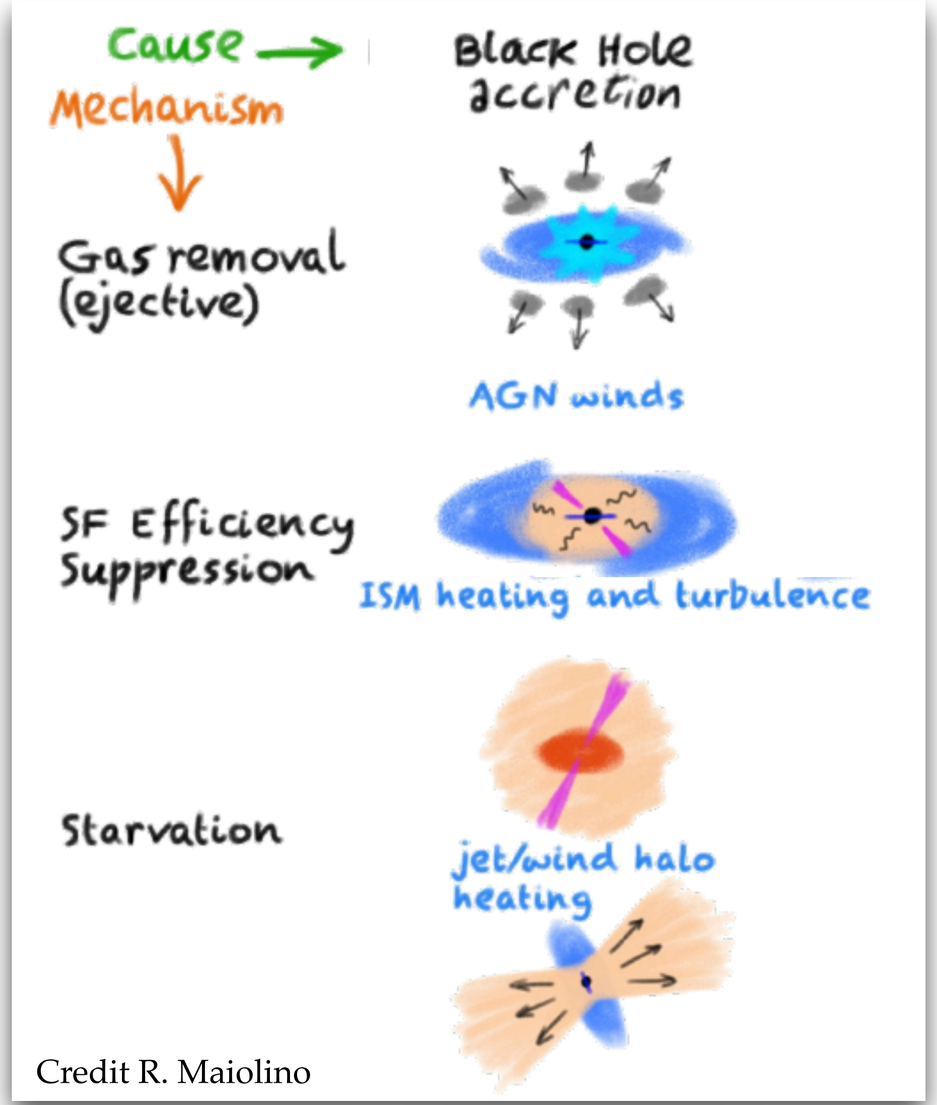
Radio Jets / AGN winds can drive **multiphase outflows**

Neutral atomic, ionised and cold molecular gas phases

The gas of the ISM can be removed, heated up or disrupted influencing the **star formation**

Global Effects:
Integrated properties ⟶ scaling relations

Local Effects:
Locally modified properties

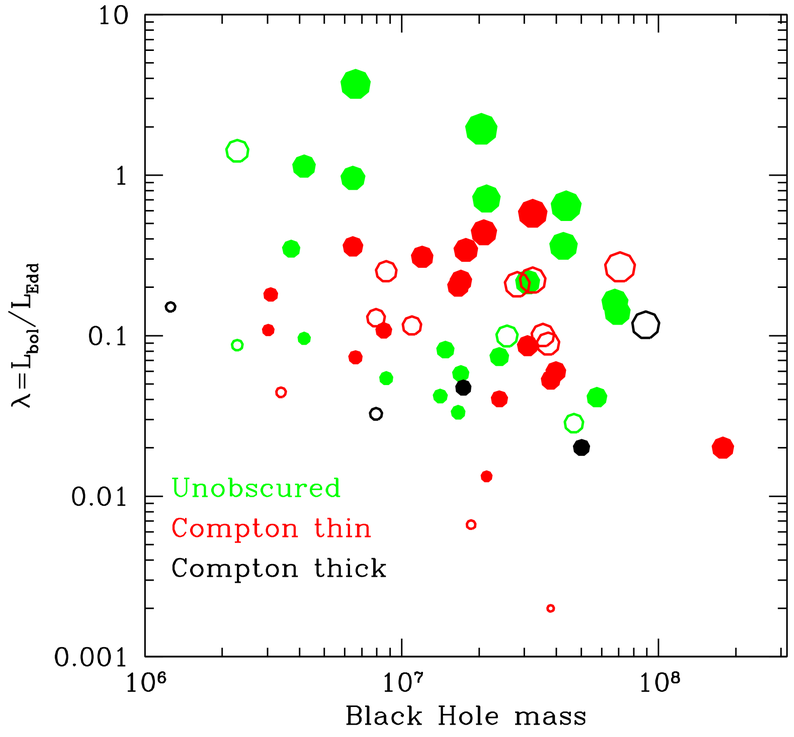


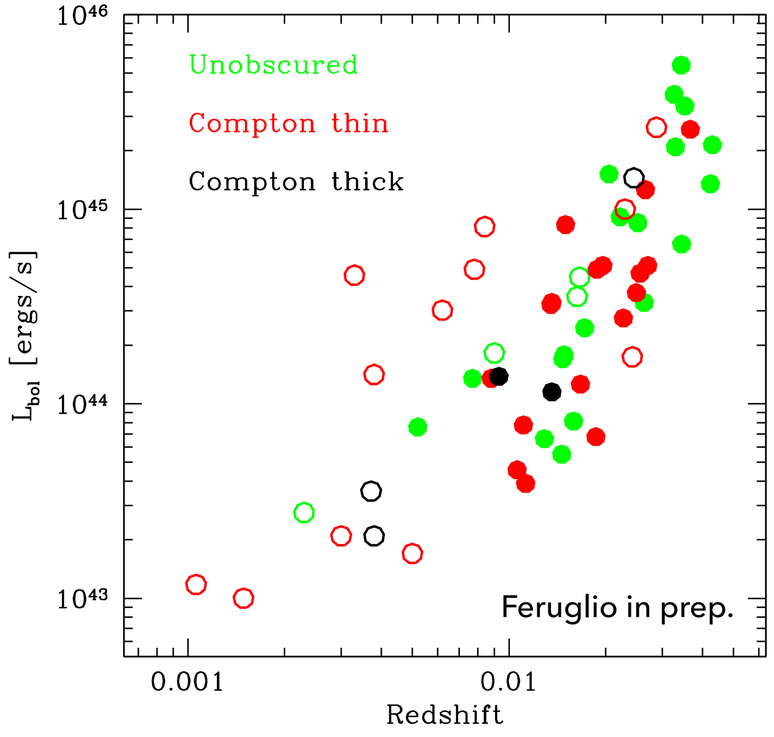
Credit R. Maiolino

IBISCO - The IBIS -AGN CO survey

- 47 AGN hard-Xray selected AGN from the INTEGRAL-IBIS catalog (Malizia et al. 2017)
- Unbiased against nuclear obscuration
- $L_{bol} > 10^{43}$erg/s
- $z < 0.05$
- Accurate BH masses (MASER or reverberation mapping), M* and SFR
- Accurate measure of nuclear properties from INTEGRAL, NuSTAR, XMM spectra

Uboscured +Compton thin +Compton thick



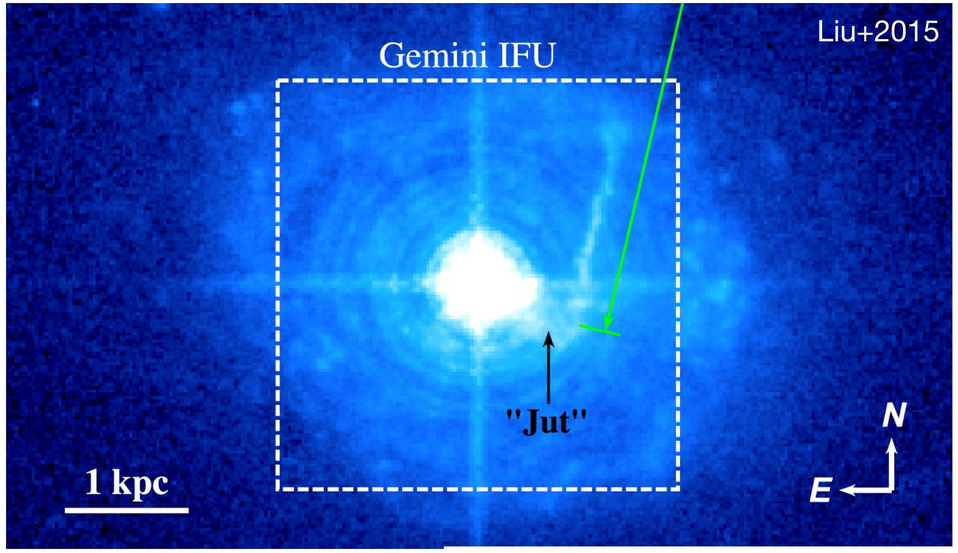


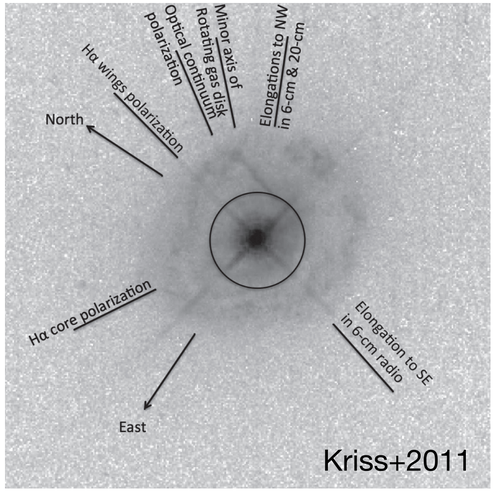
Subset of 15 objects with available IRAM30m, ALMA, MUSE and VLA radio data

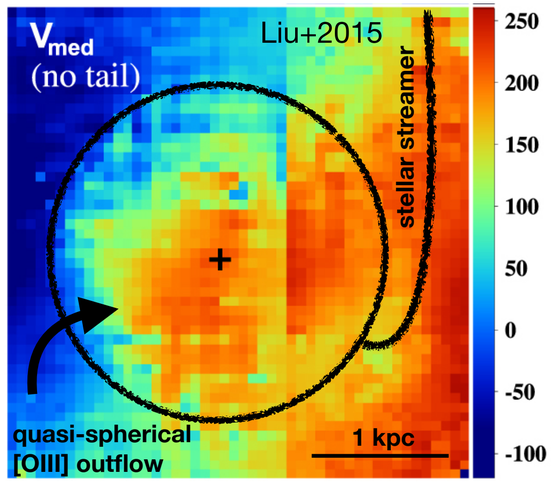
Mrk509 and outflow

Local type 1.5 Seyfert at z = 0.034 with a $L_{bol} \sim 10^{45}\, erg/s$ (Duras+2020)

- **Bulge** in Optical imaging (Ho & Kim2004)
- **Ionised gas disk & starburst ring** (Kriss+2011) with active SF, , $SFR = 5\, M_{\odot}/yr$ (Gruppioni+2016) and $M_{*} = 3 \times 10^{10} M_{\odot}$
- Ongoing minor merger with a gas rich dwarf (Fischer+2015, tidal tail)
- **[OIII] quasi spherical wind** (Liu+2015) with v = 290 km/s and $\dot{M}_{out} = 5 M_{\odot}/yr$ within ~2 kpc
- **UFOs** on the nuclear region with v~0.150.2c and outflow rate $\dot{M}_{UFO} = 0.005 - 0.05\ M_{\odot}/yr$ (Tombesi+2011,2012)
- Ionised wind in absorption in UV (Kriss+2011, 200 pc)







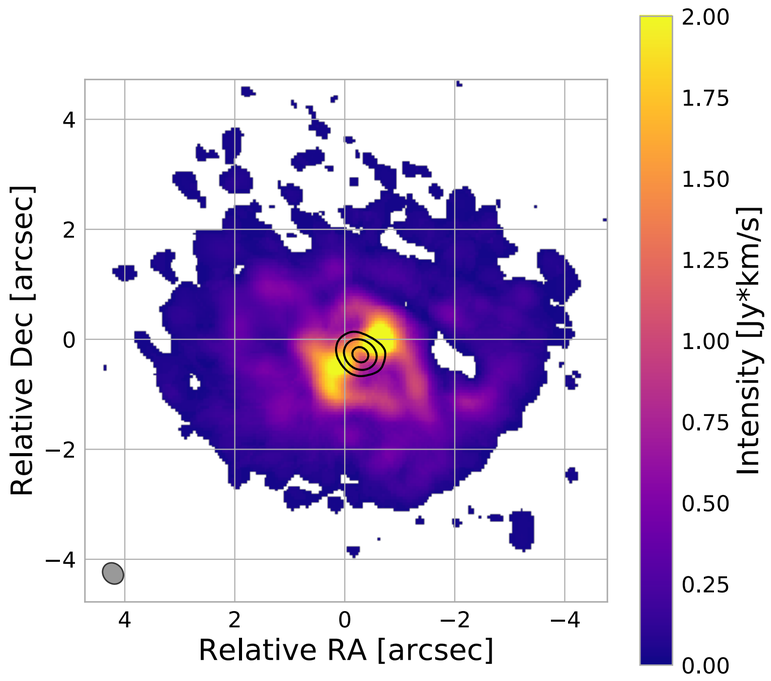
Mrk509 observed with ALMA

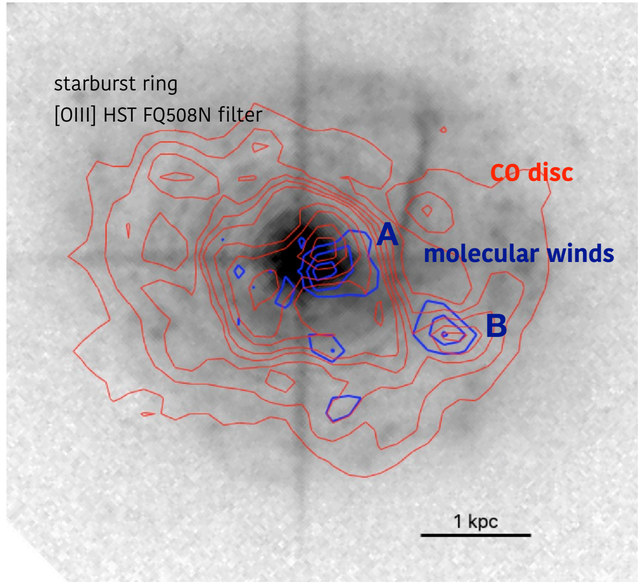
ALMA observation of CO(2-1) at 270 pc resolution

- CO disk with $M(H_2) = 1.7 \times 10^9 M_\odot$ ($\mu_{gas} = 5\,\%$) and size 5.2 kpc coincident with starburst ring

- Dynamical Model (3DBAROLO, Di Teodoro & Fraternali 2015) : i = 44 deg and $M_{dyn} = (2.0 \pm 1.1) \times 10^{10} M_\odot$

- Inclined warped disk + kinematical perturbation at 200 pc and 1.4 kpc from nucleus





- Molecular winds with velocity of 200-250 km/s

  $\dot{M}_{out} = 6.4 - 17\ M_\odot/yr$ optically thin/thick case

- Inner molecular wind overlaps with ionised wind and similar velocity: cooling sequence in AGN-driven wind (momentum conserving wind/radiation pressure on dust)

- Outer wind overlaps with starburst ring, energy consistent with SNa driven wind, not related to tidal tail

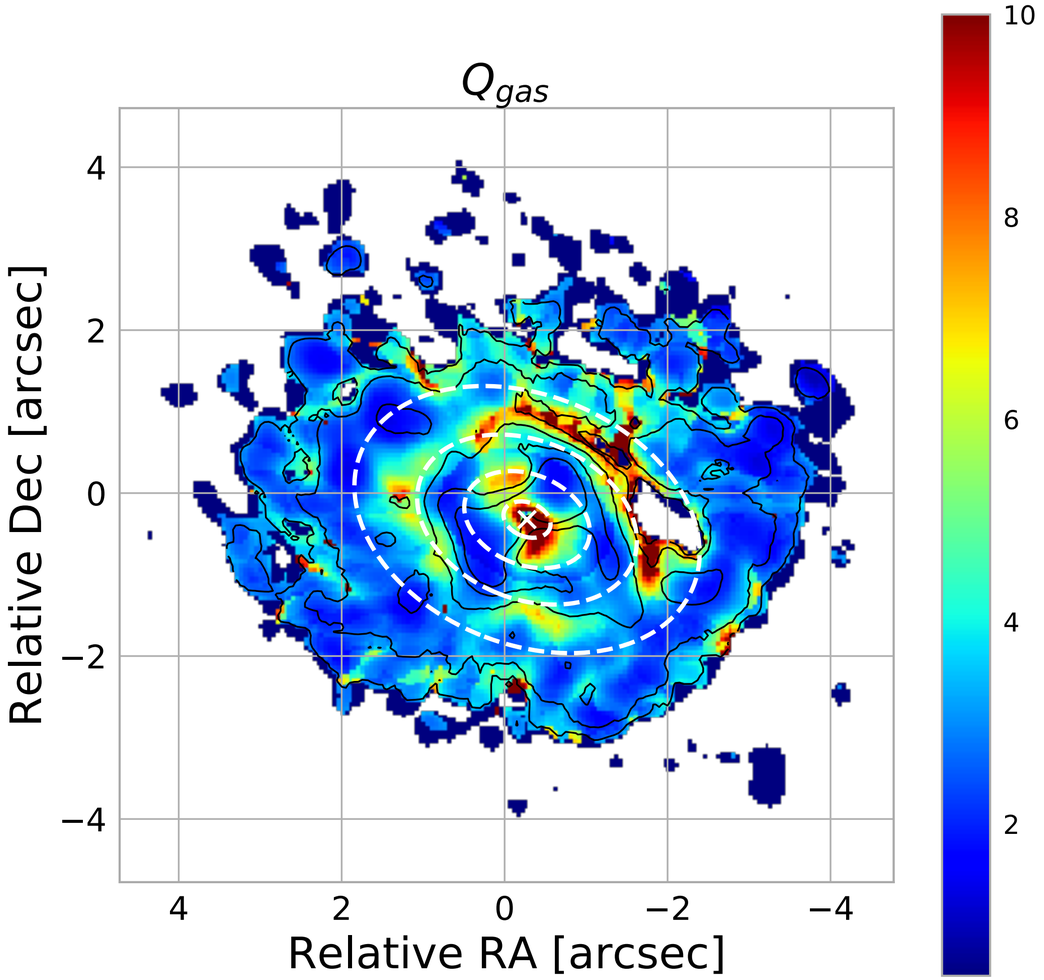
Disk stability vs outflow

Toomre parameter $Q_{gas} = \frac{a v_{rot} \sigma_{disp}}{\pi R G \Sigma_{gas}}$

($Q_{gas} > Q_{crit} = 1 - 3$, disk stable)

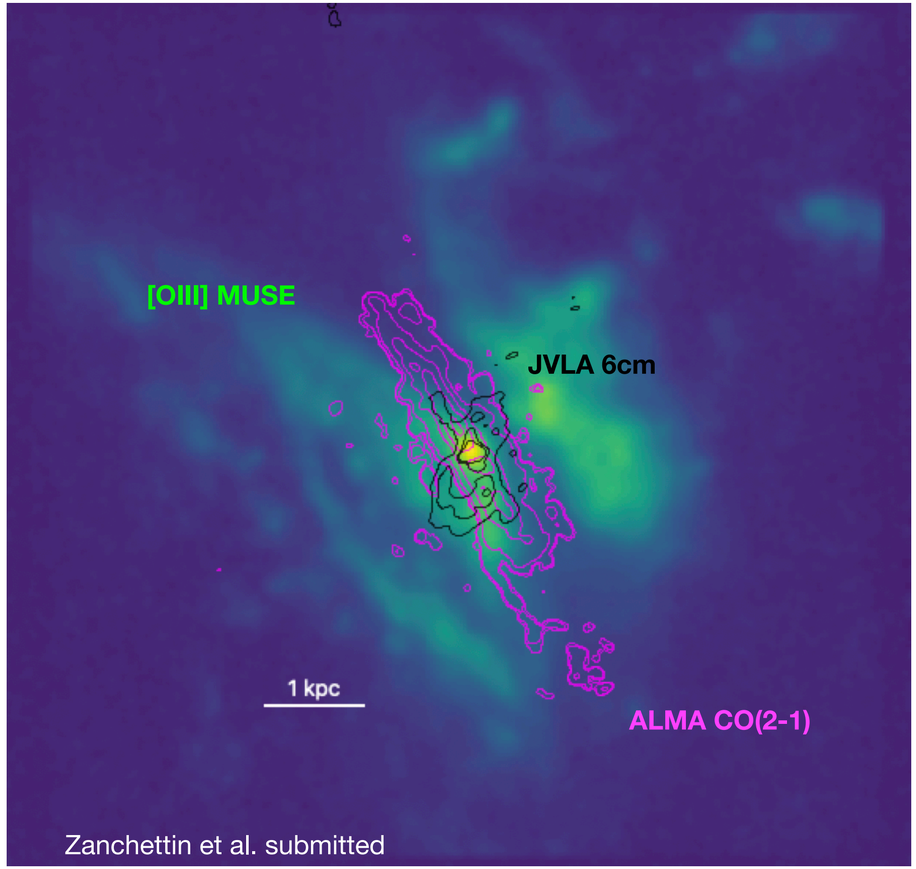
In Mrk 509 (Q_{star} not included in this analysis):

- Disc stable at nucleus and outflow region : $Q_{gas} = 3.5 - 5$ and $\sigma_{disp} = 30 - 40$ km/s
- Marginally stable disc at starburst ring : $Q_{gas} \sim 3$ and $\sigma_{disp} \sim 20$ km/s
- Stable disk at location of molecular winds, in agreement with suppression of SF in that region (Liu+2015)



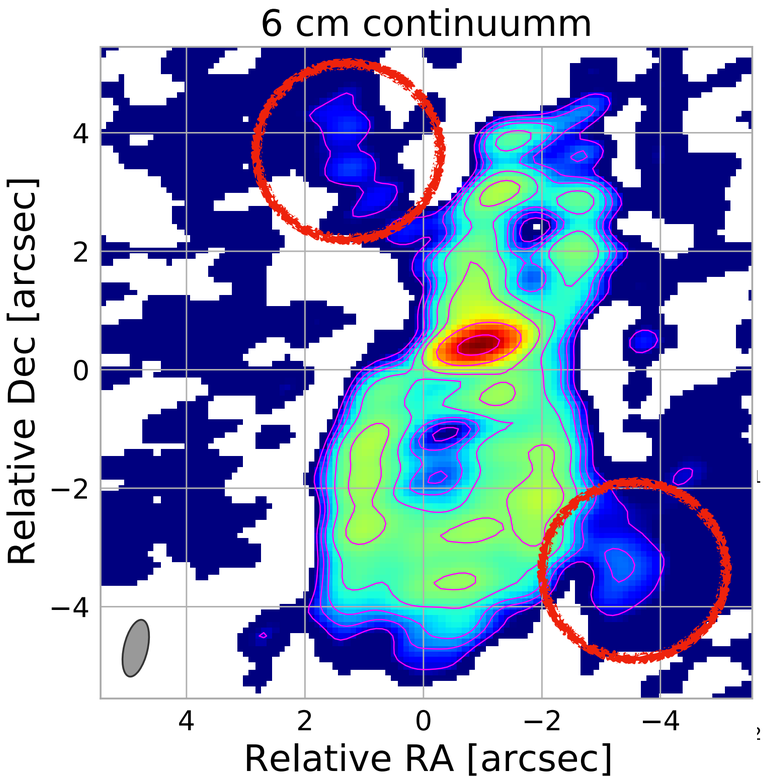
NGC2992 multiphase disk and outflow

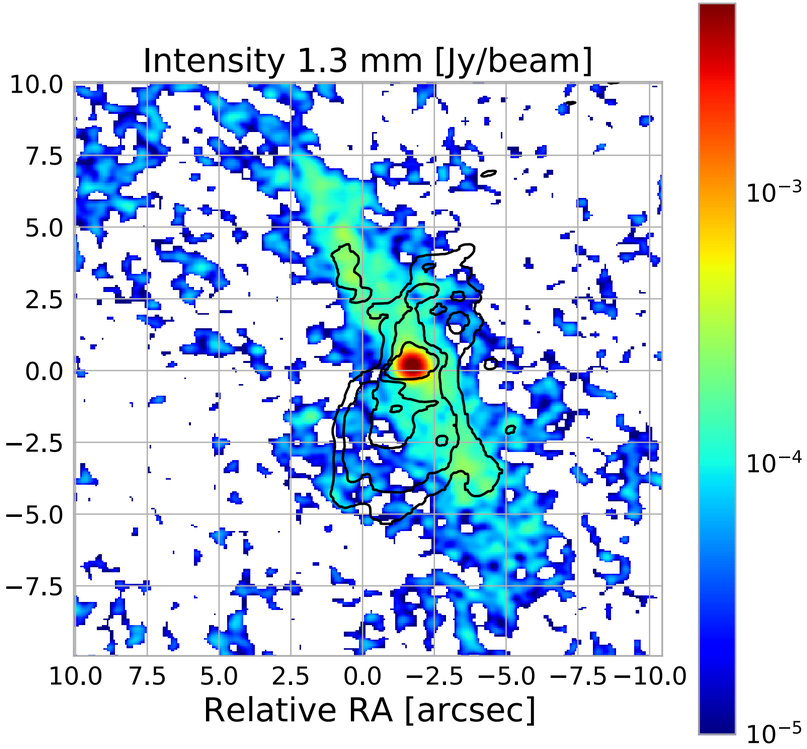
Swift, XMM-Newton and NuSTAR X-ray data: highly variable nuclear continuum and UFOs components (Marinucci et al. 2018, Middei et al. 2022)



- JVLA 6cm observations **: 8-shaped** structure of about 8 arcsec (~1 kpc) along PA = −26 deg
- ALMA continuum maps at 1.3 mm: **cold dust component** in the inclined disc (~1.5 kpc) and within radio emission
- ALMA CO(2-1) data at ~100pc resolution: **molecular gas disk and outflow**
- MUSE data : **warm ionised gas disk and ionised wind (NRL)** Mingozzi et al. 2019

Radio emission





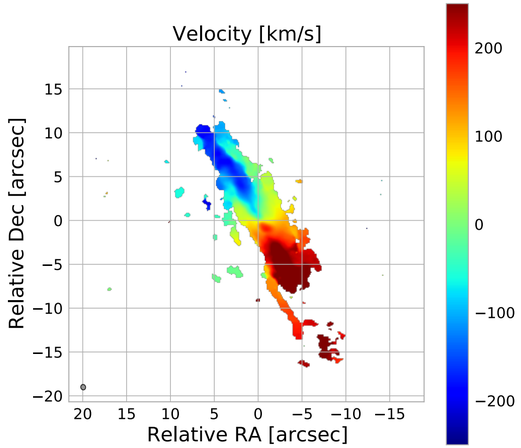
- $\Sigma_{\mathrm{SFR},1} = 0.4\mathrm{M}_\odot/\mathrm{yr}/\mathrm{kpc}^2$ and $\Sigma_{SFR,2} = 0.5 M_\odot/yr/kpc^2$
- $\Sigma_{\mathrm{H2},1} = 168\mathrm{M}_\odot/\mathrm{pc}^2$ and $\Sigma_{H2,2} = 175 M_\odot/pc^2$

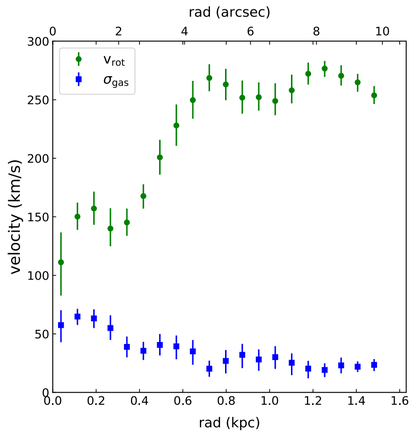
- VLA 6cm emission : 8-shaped emission due to expanding plasma bubble into the ISM + radio emission due to SF
- ALMA 1.3mm emission : dust disc almost edge-on $M_{dust} = (4.04 \pm 0.03) \times 10^6 \mathrm{M}_\odot$ ($\mathrm{T}_{\mathrm{dust}} = 30\mathrm{K}$ and $\beta = 1.5$)

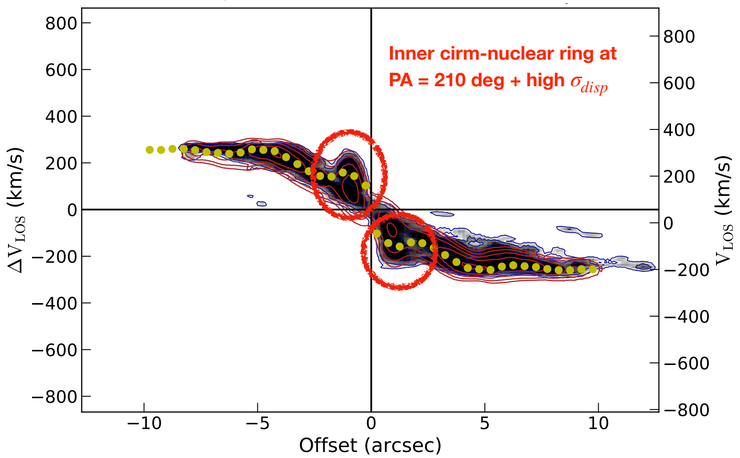
NCG2992: multiphase discs

Zanchettin et al. submitted

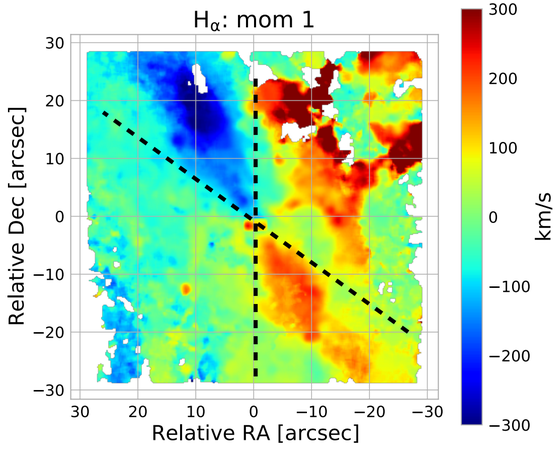
MOLECULAR (ALMA 12m)

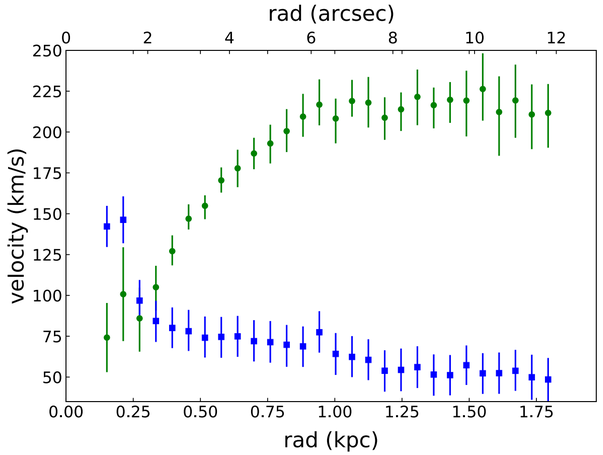






IONISED (MUSE/VLT)



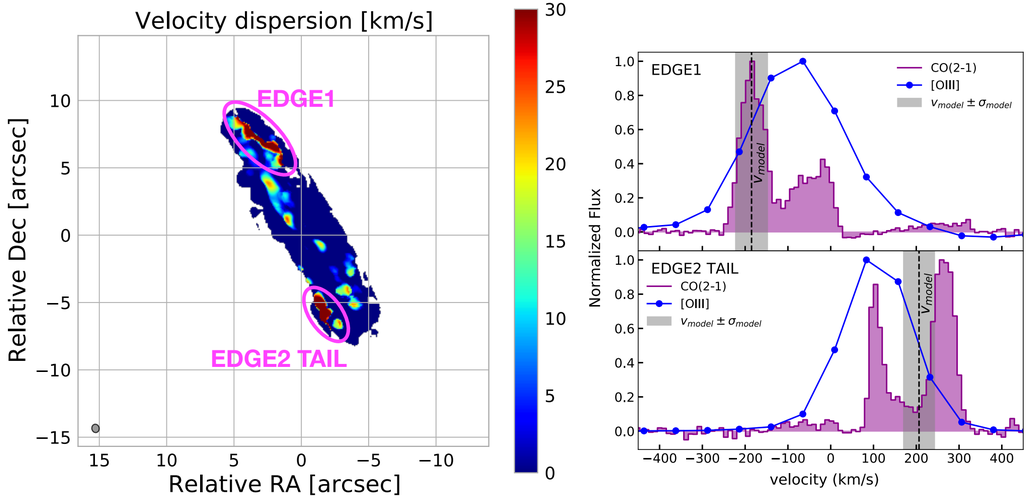


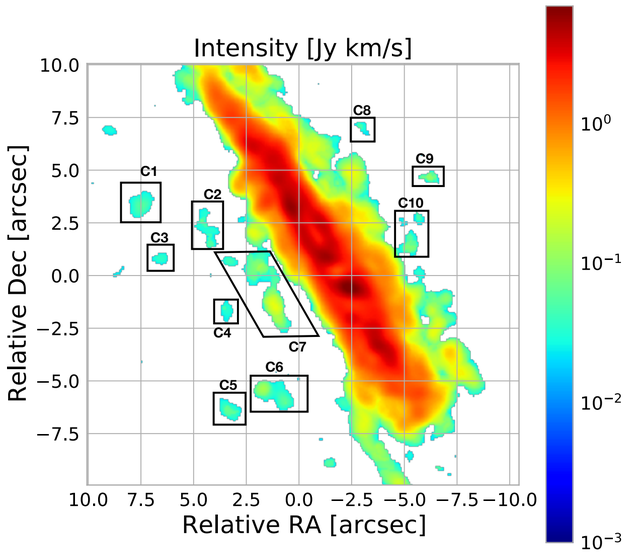
- **Molecular and ionised disc with same inclination**
- **Disc model of CO and H_α kinematics (3DBAROLO) : similar**
  $v_{rot} \sim 220\,\mathrm{km/s}$ **at** $r = 1\,\mathrm{kpc}$
  $\sigma_{disp,mol} \sim 30 - 60\,\mathrm{km/s}$
  $\sigma_{disp,ion} \sim 60 - 100\,\mathrm{km/s}$
- **Molecular circum-nuclear ring**

NCG2992 : molecular perturbations

Perturbations to disc-like kinematics

- EDGE1 molecular gas in outflow with velocity similar to the ionised phase $M(H_2) = 2.7 \times 10^7 M_\odot$
- EDGE2 complex kinematics due to the tail that connects NGC2992 to NGC2993



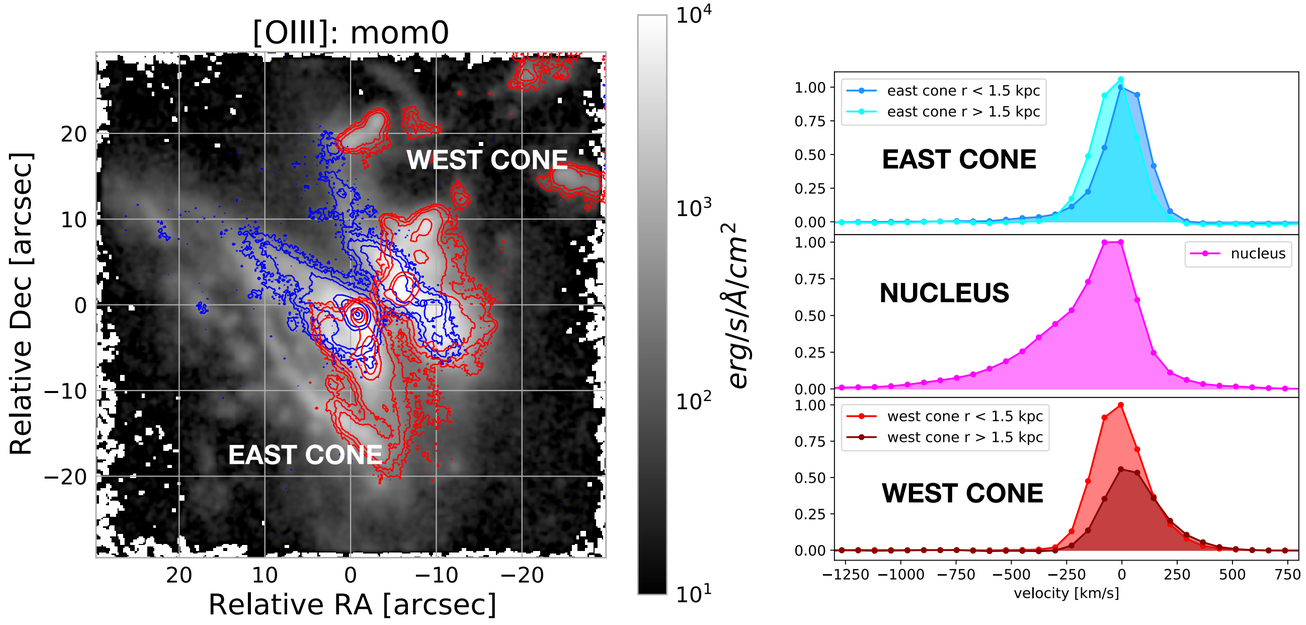


Clumps of molecular gas detected outside the disc:

- Velocity up to 200 km/s
- Located from 0.6 kpc up to 1.5 kpc from the AGN
- $M_{total}(H_2) = 1.6 \times 10^7 M_\odot$

Zanchettin submitted

NCG2992 : ionised outflow from nuclear up to kp scales



Complex [OIII] kinematics traced through :

- Blue wing : v[-1000, -200]km/s
- Red wing : v[200, 1000]km/s

[OIII] traces high velocity gas outflowing at nucleus where no molecular outflow is detected

	$L_{[OIII]}$ [10^{42}erg/s] (a)	A_V (b)	n_e [cm^{-3}] (c)	M_{of} [10^6M$_\odot$] (d)	r_{of} [kpc] (e)	v_{of} [km/s] (f)	$\dot{M}_{of}$ [M$_\odot$/yr] (g)	$\dot{E}_{kin}$ [10^{40}eg/s] (h)
Nucleus (N)	22.5±3	3.9	3495	0.26±0.04	0.3	-895±5	2.2±0.3	56±8
West Cone 1 (W1)	6.5±1	1.4	228	11±2	1.5	217±5	5.1±0.7	8±1
West Cone 2 (W2)	1.1±0.2	-	58	7±1	6.7	217±5	0.7±0.1	1.1±0.2
East Cone 1 (E1)	2.1±0.3	1.5	146	5.6±0.8	1.5	-375±5	4.3±0.6	19±3
East Cone 2 (E2)	0.5±0.1	-	21	10±2	5.6	-227±5	1.3±0.3	2.1±0.5

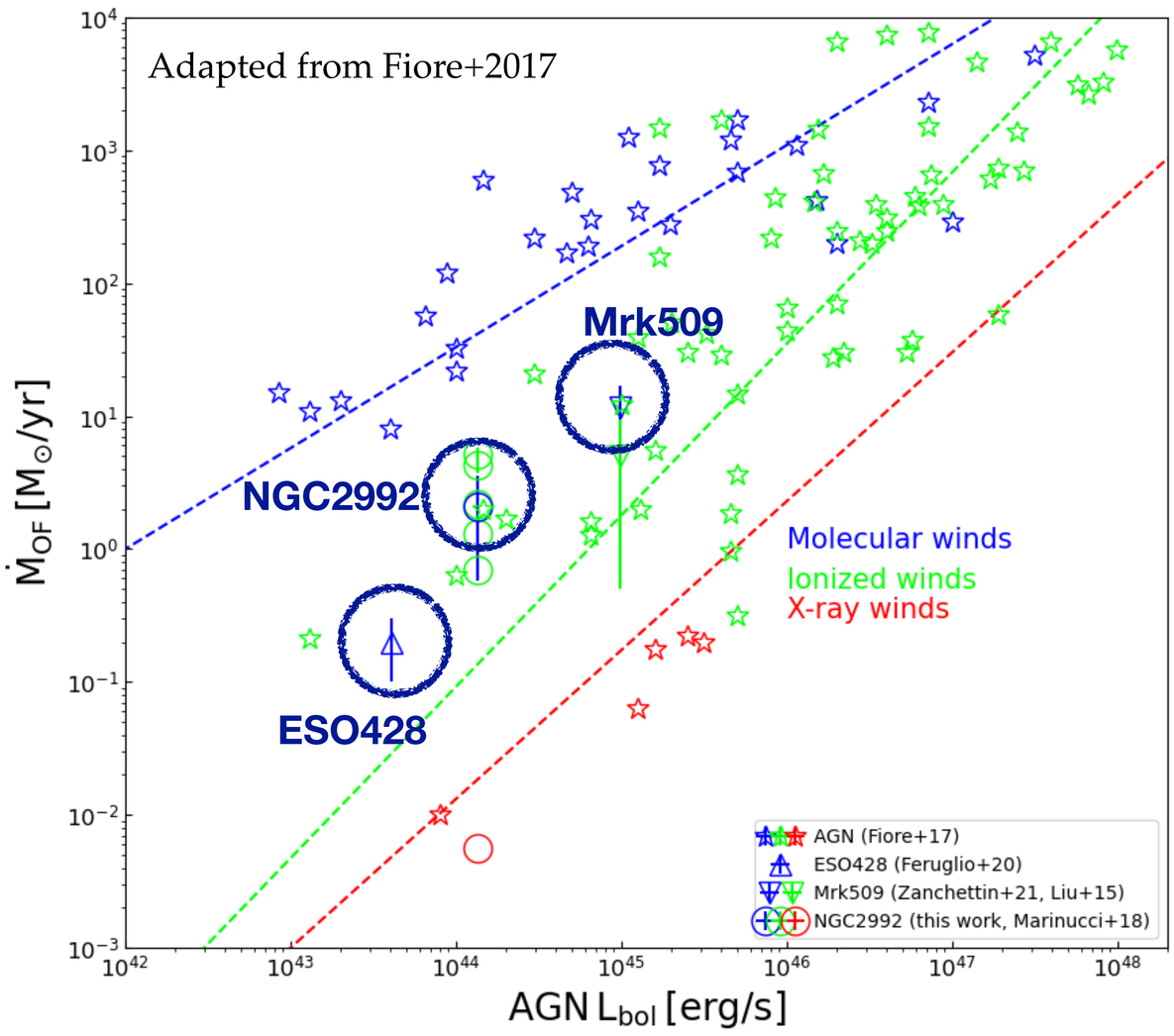
Zanchettin et al. submitted

AGN wind scaling relations

- **ESO428, NGC2992, Mrk509 :**

  molecular outflow rate significantly below the best-fit correlation for molecular winds

- Importante of a **multi-wavelength** analysis of the IBISCO sample with ALMA sub-mm and MUSE/VLT optical



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Conclusions

- Mrk509 : Multiphase momentum-conserving AGN driven outflow and analysis of the CO disc stability with ALMA data
- NGC2992 : Multiphase disc and winds, molecular gas detected in outflow within the ionised cones with ALMA, MUSE/VLT and radio data
- Indication that the molecular outflow rate is significantly below the best-fit correlation for molecular winds

Gas density

Ionised mass : $M_{ionised} = 0.8\ 10^{8} \frac{L_{[OIII]}}{10^{44}} \frac{n_e}{500}^{-1} \sim 3 \times 10^{6} M_{\odot}$ (Carniani+2015)

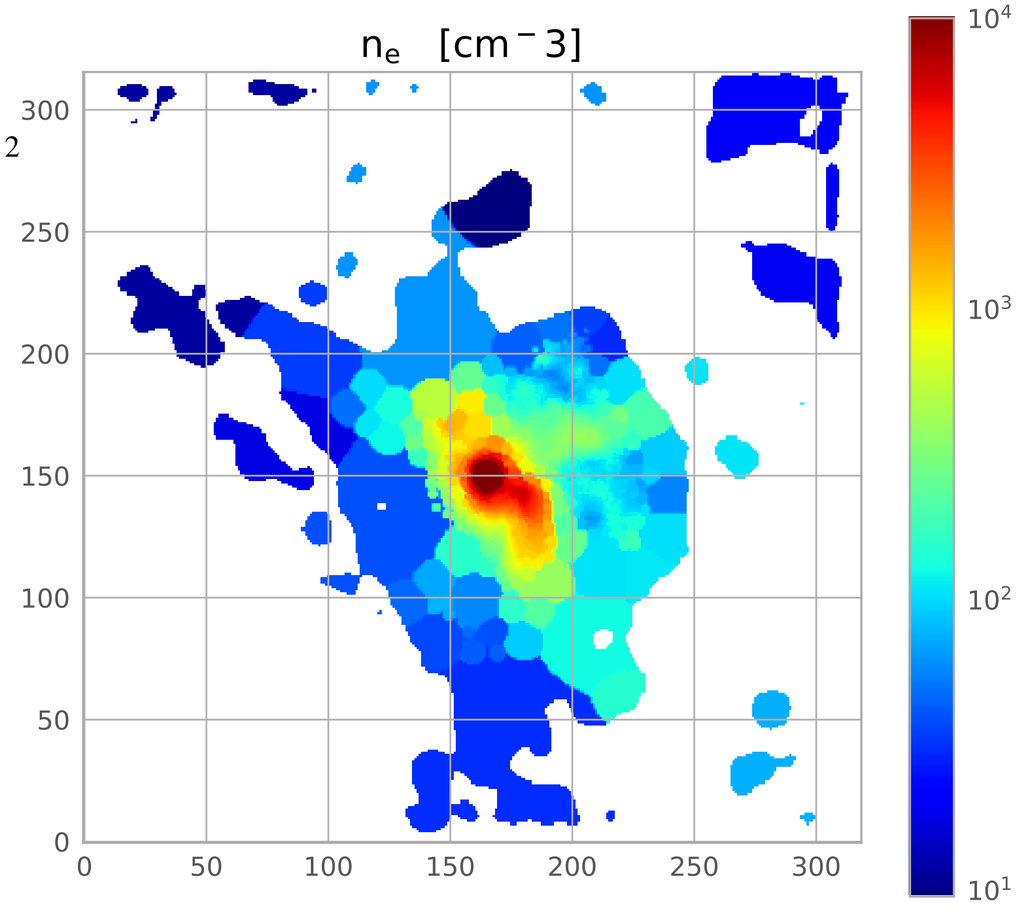
- Ionisation parameter

$$logU = a_1 + a_2 log\left(\frac{[OIII]}{H_\beta}\right) + a_3 log\left(\frac{[OIII]}{H_\beta}\right)^2 + a_4 log\left(\frac{[NII]}{H_\alpha}\right) + a_5 log\left(\frac{[NII]}{H_\alpha}\right)^2$$

- Electron density $n_e = 3.2 \frac{L_{bol}}{10^{45} erg/s} \left(\frac{r}{1kpc}\right)^{-2} \frac{1}{U} cm^{-3}$ where

$L_{bol} = 10^{44.13} erg/s$ (Baron and Netzer 2019)

- Voronoi tessellation with minimum $S/N = 10$



Variation of n_e within the cones, n_e exceeding 10^3 in inner regions

[SII] doublet cannot be used as proxy