

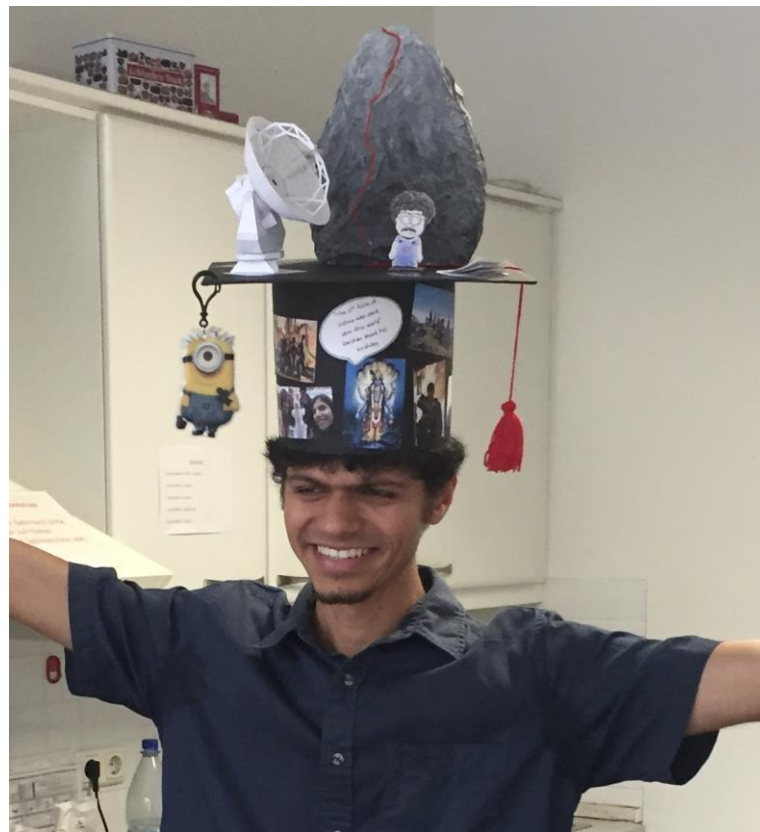


AGN feedback: a multi-scale and multi-phase challenge

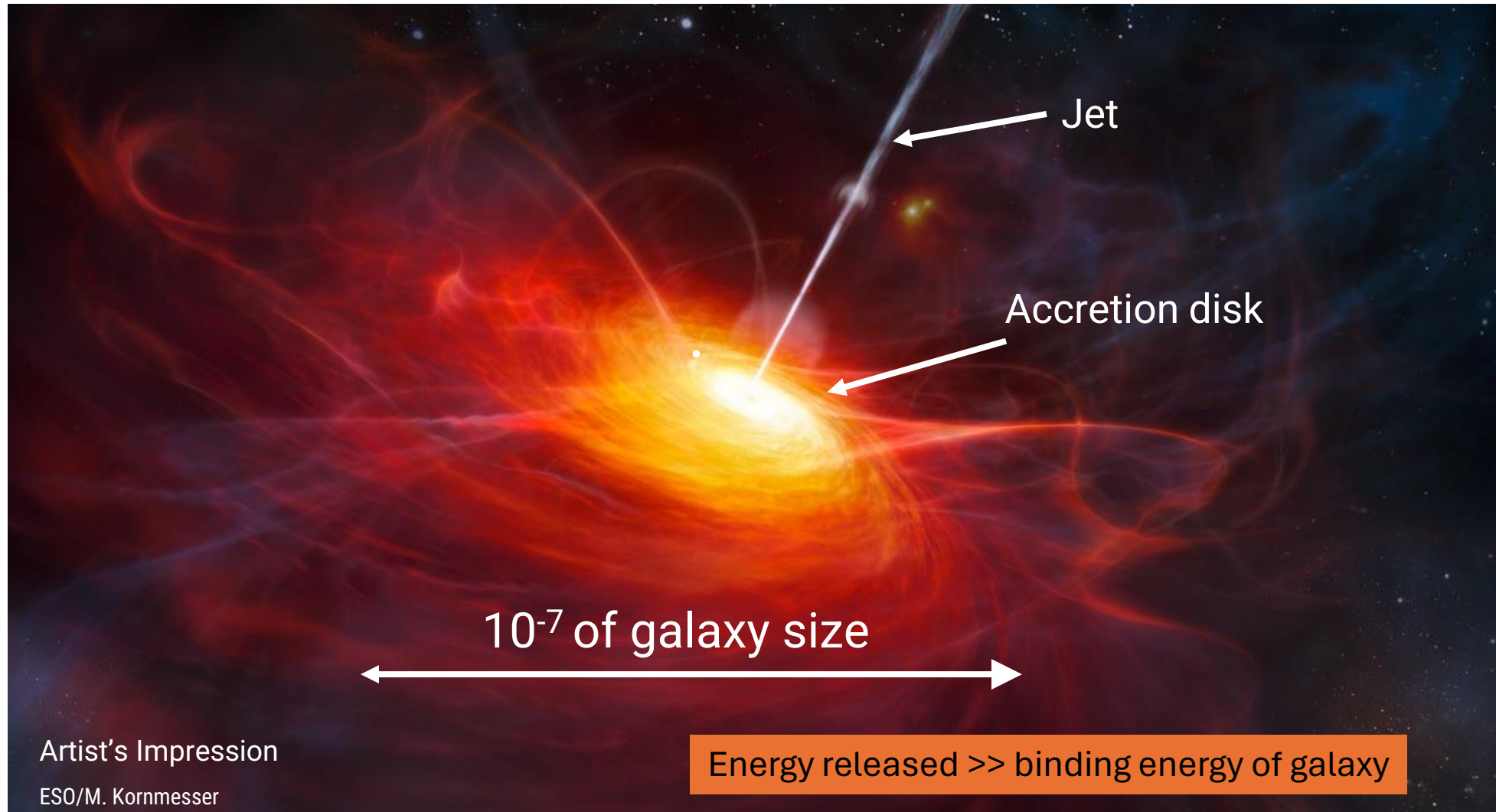
Vincenzo Mainieri (ESO)



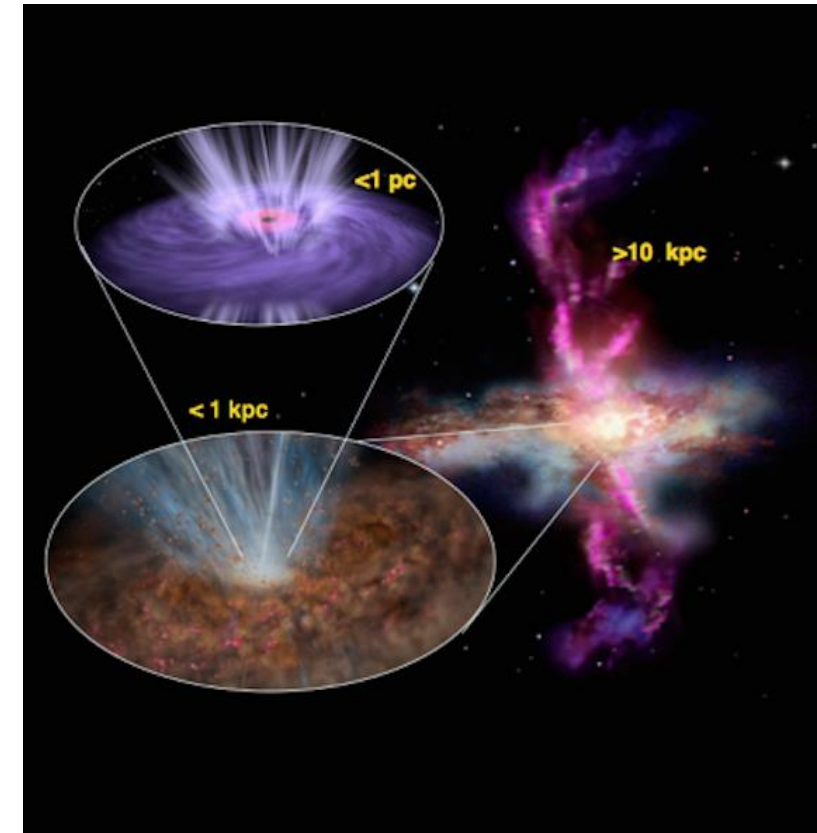
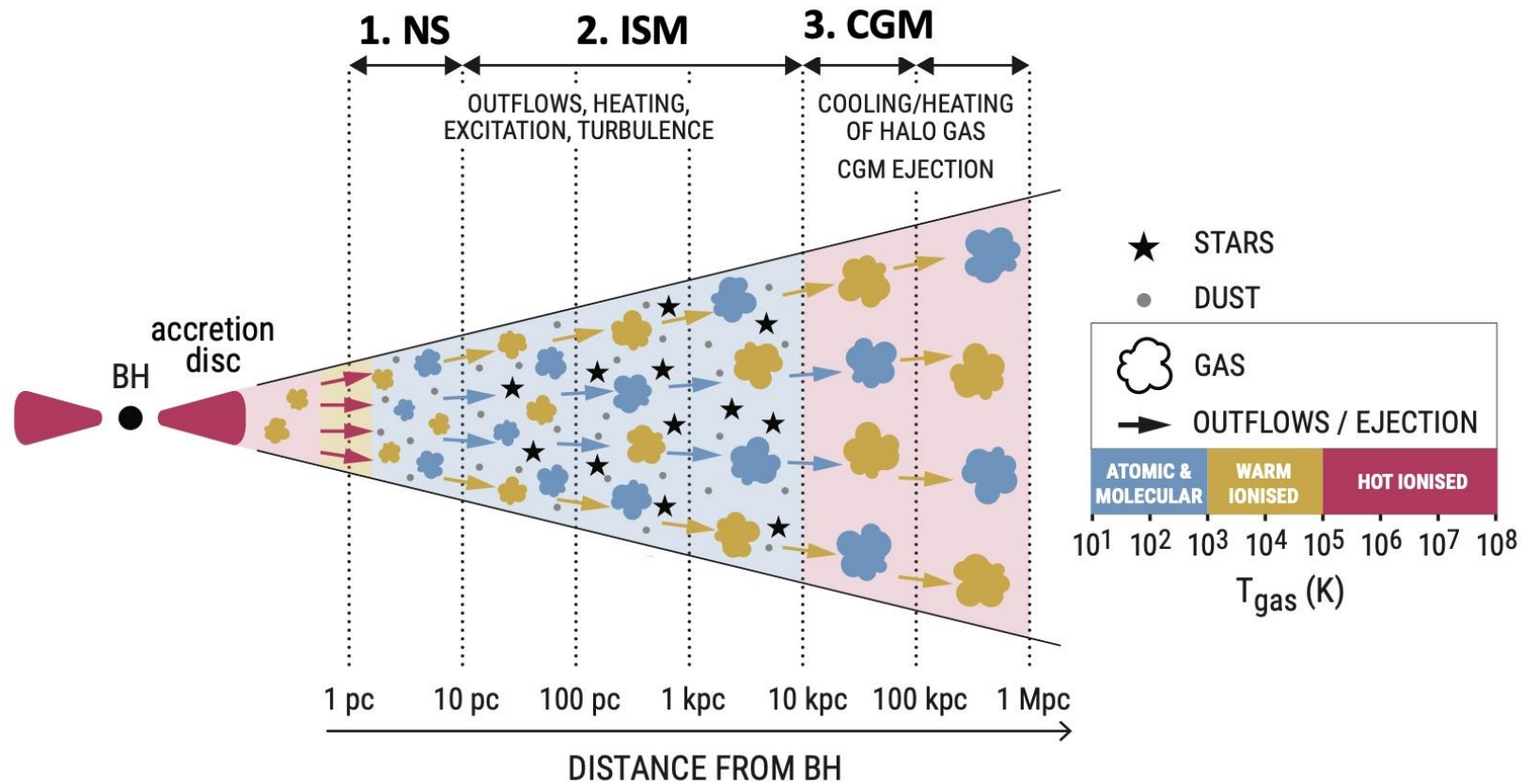
20+ years working with Paolo from the sub-mJy radio sky to AGN-feedback



AGN as a main actor in galaxy evolution?



AGN feedback is a multi-scale and multi-phase problem



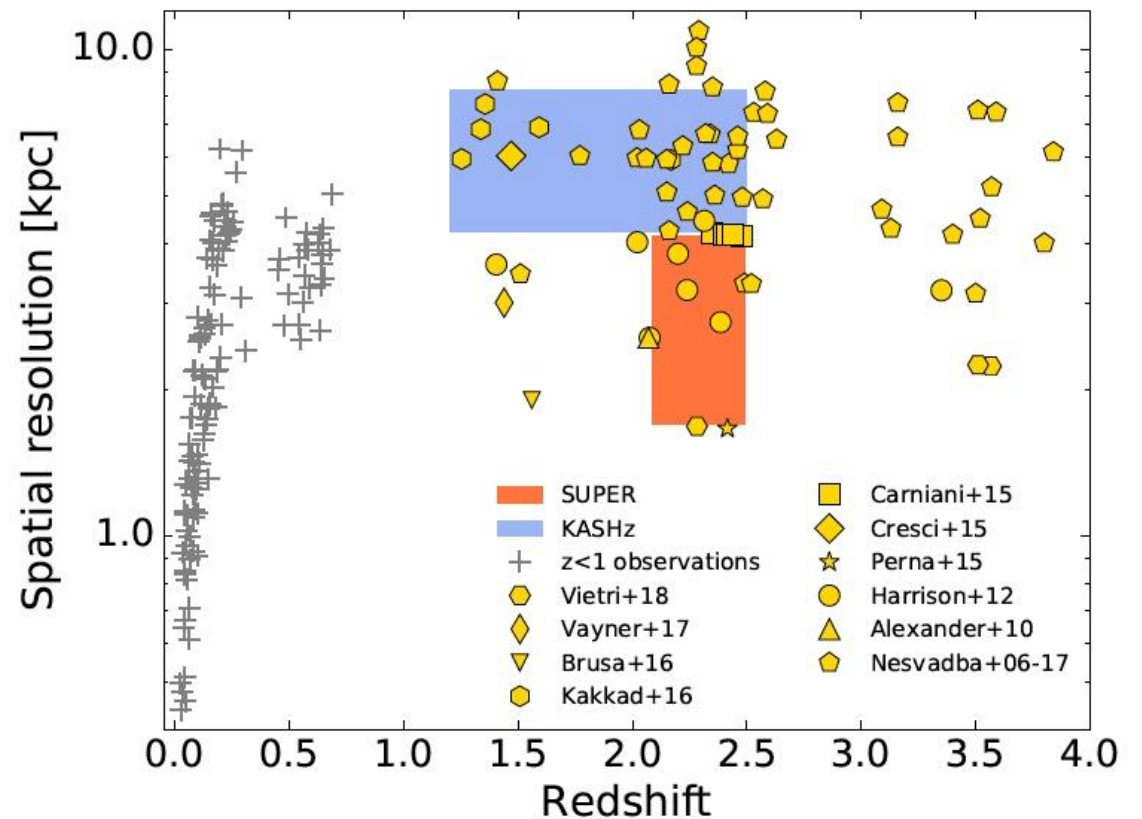
Harrison & Ramos Almeida 2024

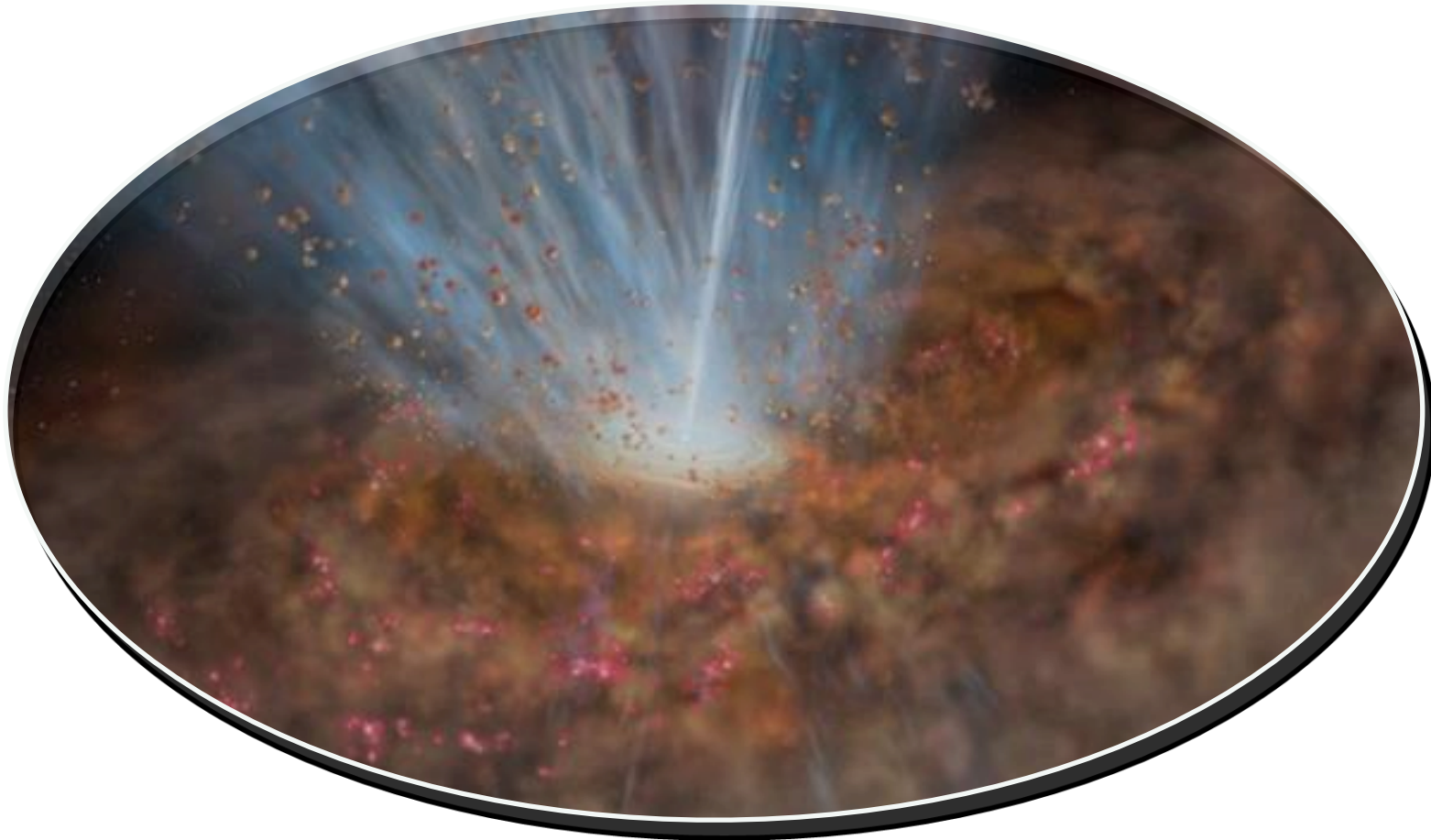


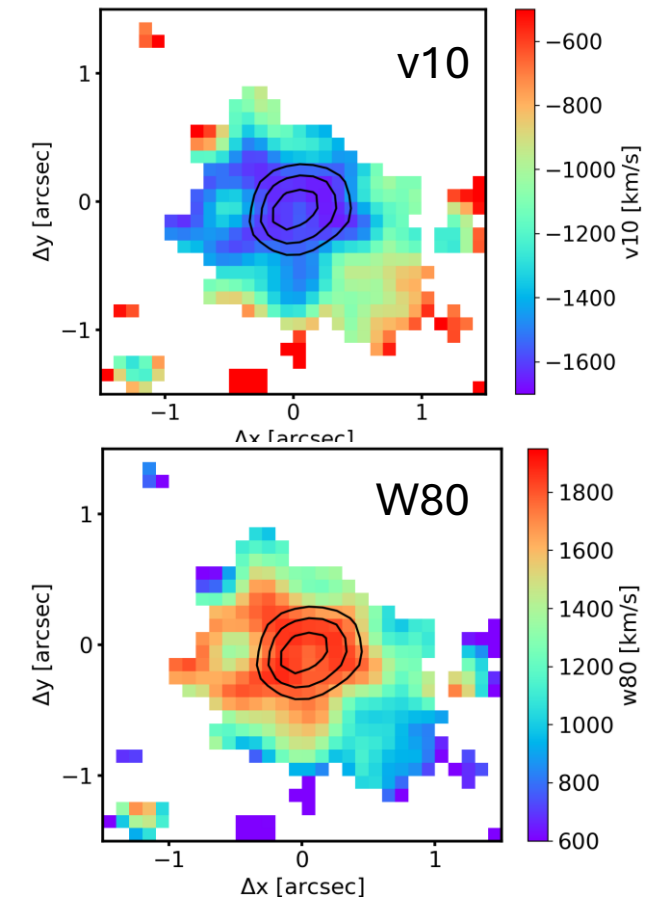
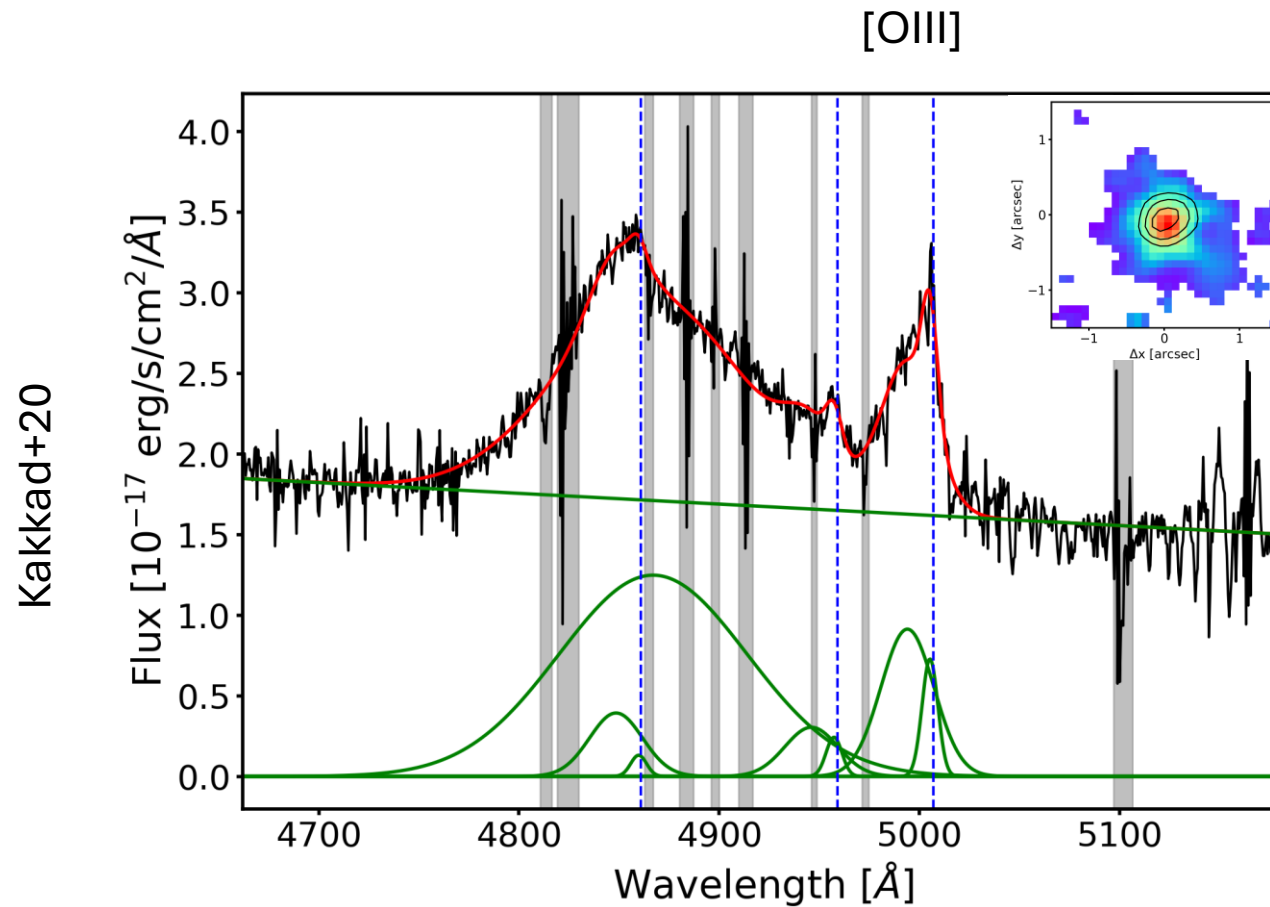
PI: V. Mainieri

Co-Is: Fiore, Marconi, Balmaverde, Bongiorno, Brusa, Carniani, Cicone, Circosta, Civano, Comastri, Cresci, Feruglio, Georgakakis, Harrison, Husemann, Kakkad, Lamastra, Lamperti, Lanzuisi, Liu, Mannucci, Menci, Menzel, Merloni, Netzer, **Padovani**, Perna, Piconcelli, Popesso, Puglisi, Salvato, Scholtz, Schramm, Schulze, Silverman, Vietri, Vignali, Zamorani, Zappacosta

- 280 hours @ VLT/SINFONI (IFS) with AO
- PSF FWHM $\approx 0.2''$ - $0.3''$
 ≈ 2 kpc spatial resolution
- **Blind survey**, ~ 40 AGN at $z=[2.12-2.49]$
- Ionized outflows $\rightarrow$ **[OIII] λ 5007** (H)
- Star formation $\rightarrow$ **H α** (K)
- COSMOS, CDF-S, XMM-XXL, Stripe82X

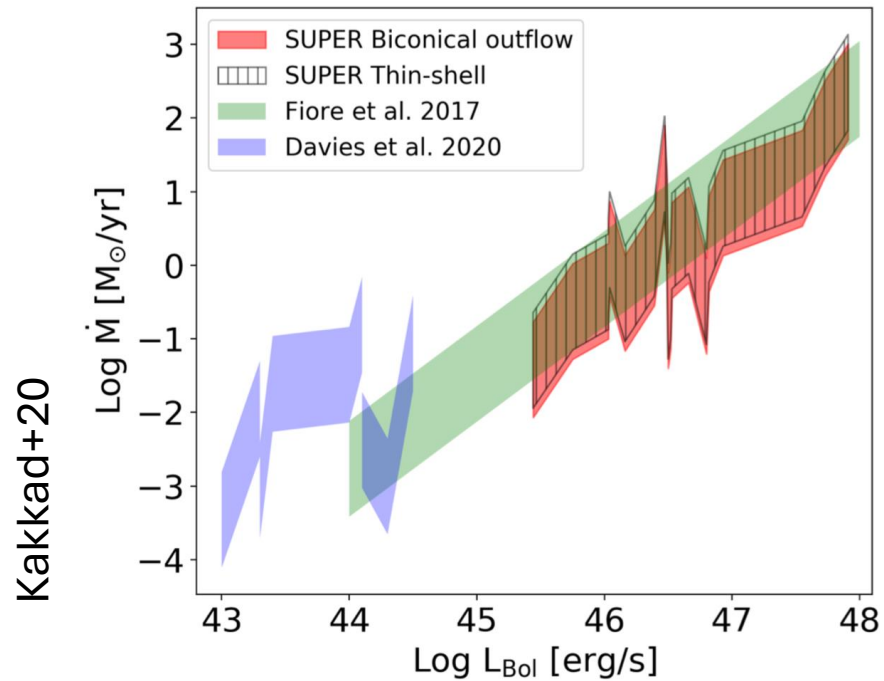




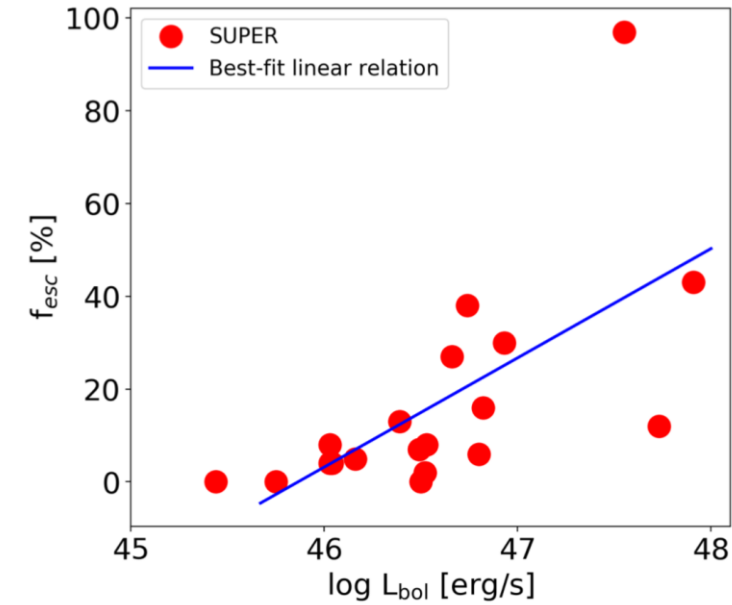




Galactic scale outflow demographic

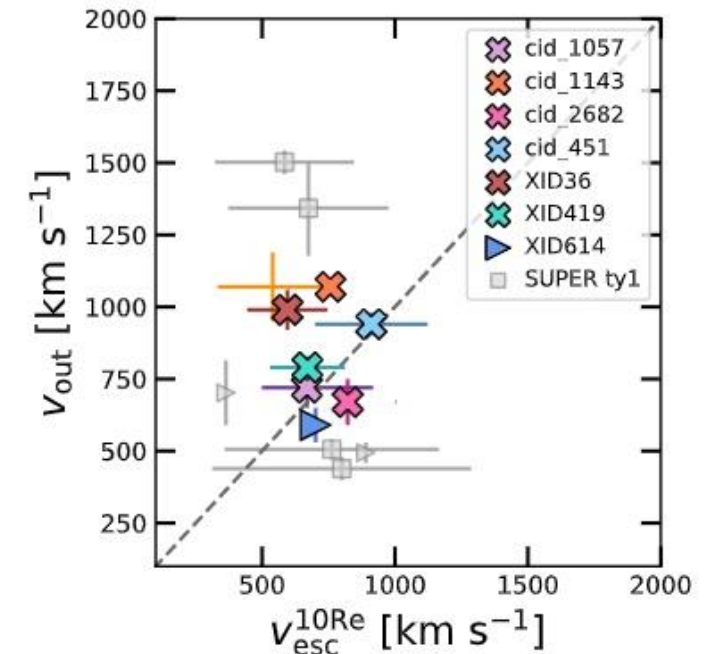
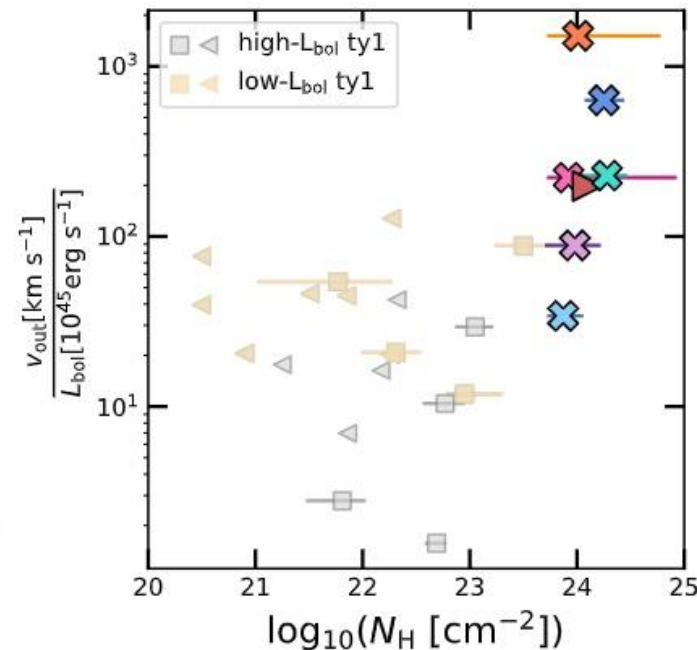
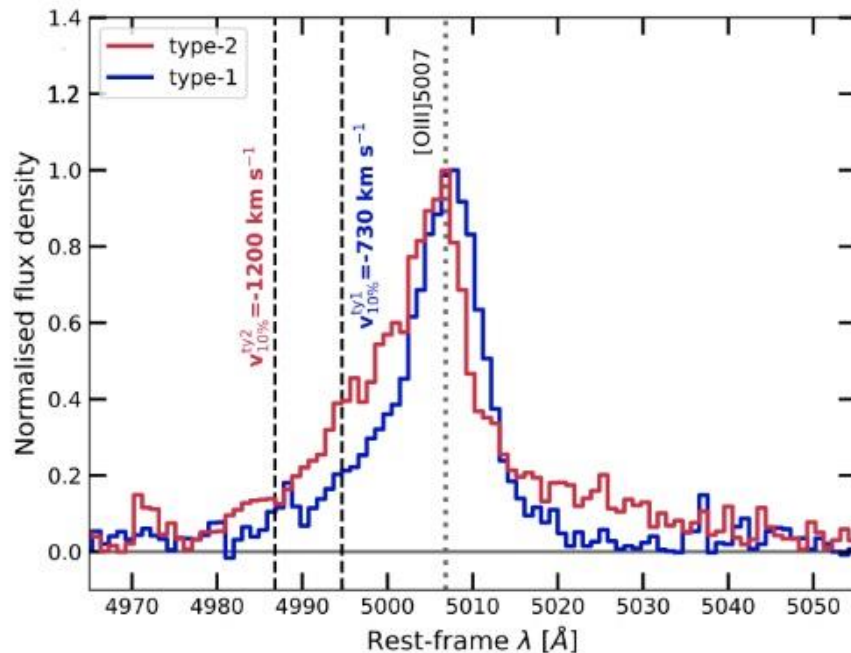


- $\dot{M}_{\text{out}}$ increases with L_{bol}
- $\dot{M}_{\text{out}}$ uncertainties mostly related to the assumption on n_e



Most of the ionized gas is not able to escape from the galaxy

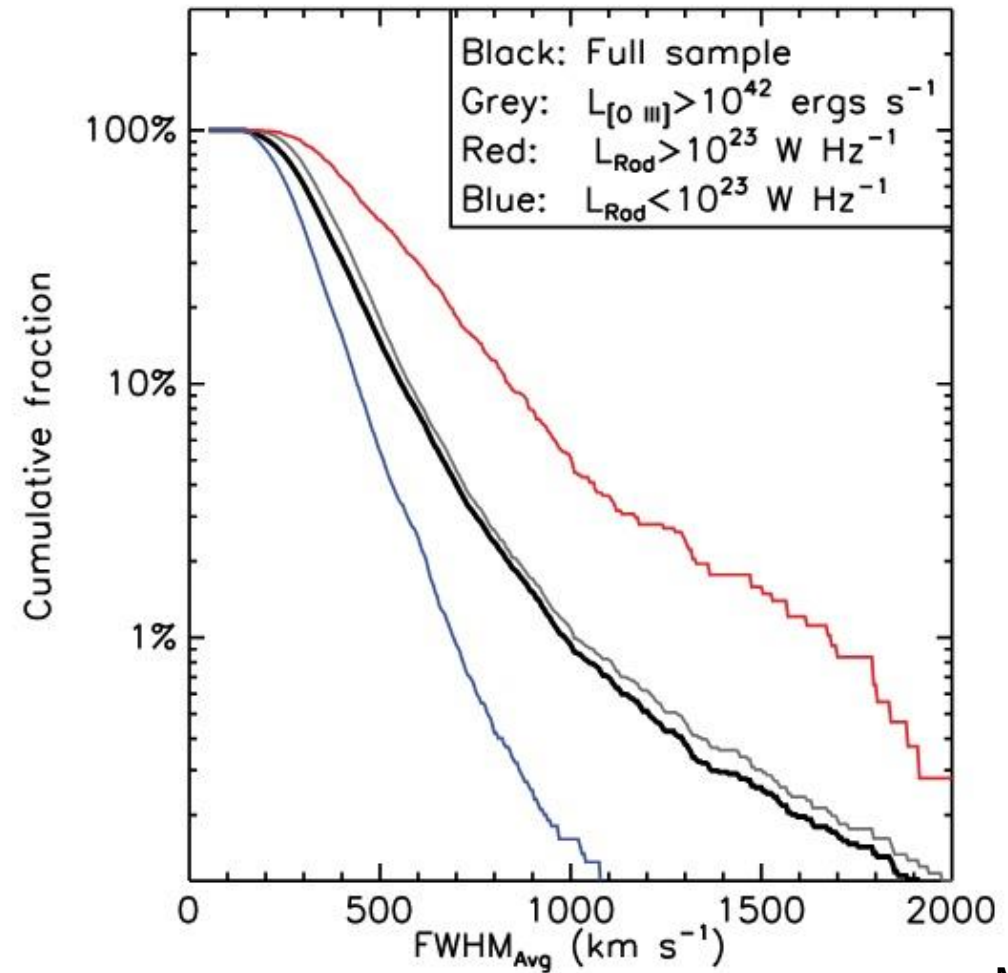
- Fast ionized outflows more prevalent in Type-2 than Type-1: radiation pressure on dust as driving mechanism
- Outflow velocities comparable with v_{esc} : gas relocated at least to 30-50 kpc from the centre



Extreme gas kinematics: statistical approach

- Higher prevalence of [OIII] outflows in AGN with moderate radio luminosities (compact rather than extended jets)

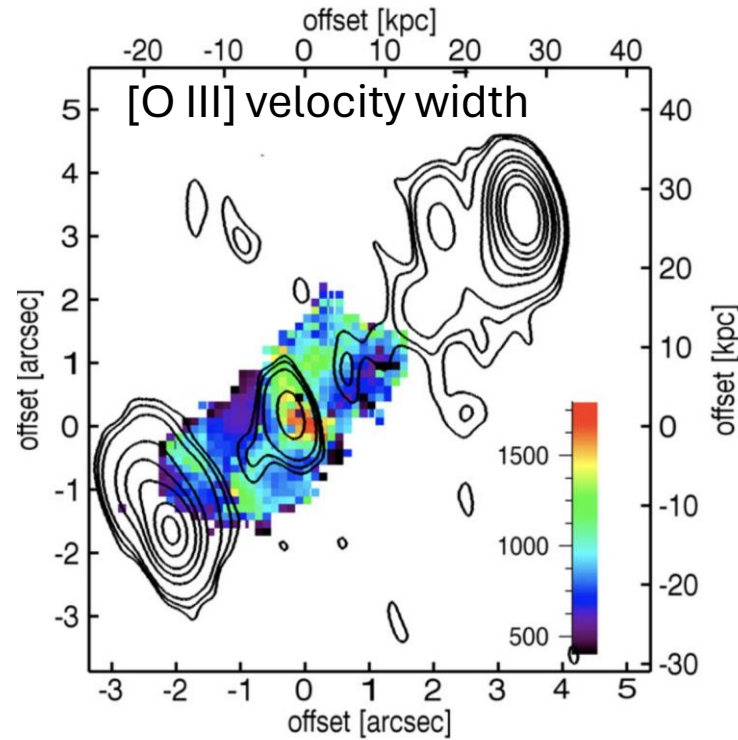
Also see, e.g., Zakamska & Greene 2014;
Bischetti+17; Molyneux+19; Kukreti+23



Mullaney+13

Extreme gas kinematics: individual studies

Nesvadba+08; $z \sim 2$ powerful radio galaxy (and quasar)



High velocities (and shocks/ionization) alignment with jets

Jet Power

Powerful jets

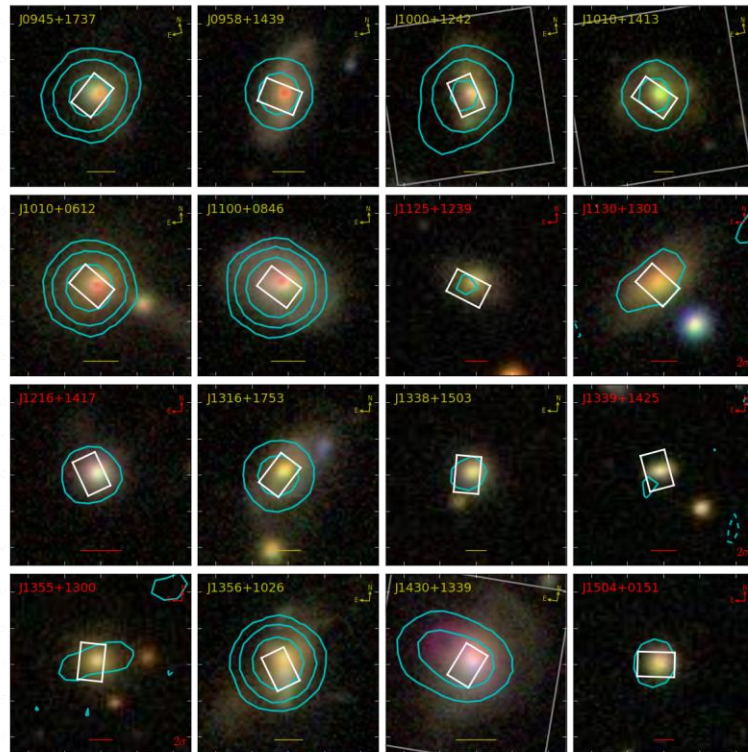
$\sim 10^{44} \text{ erg s}^{-1}$

Low power jets

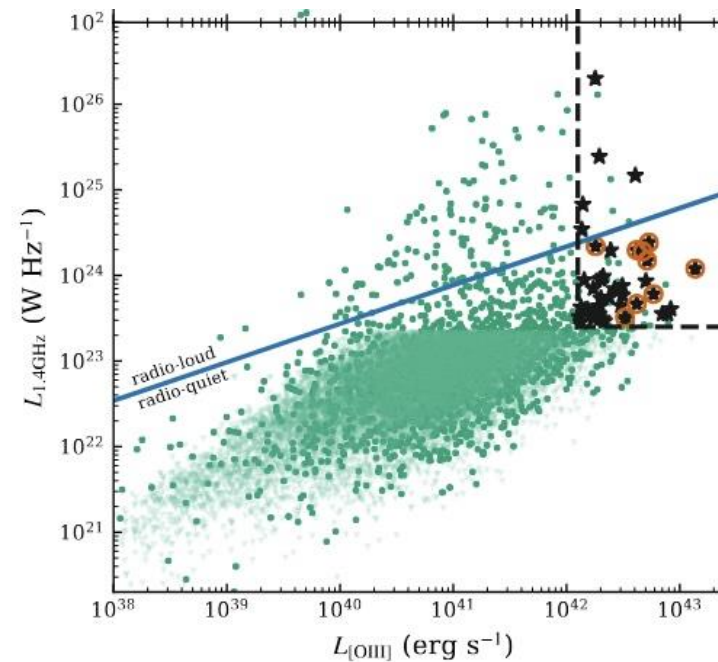
Radiative Power

High resolution JVLA observations of "radio-quiet" quasars

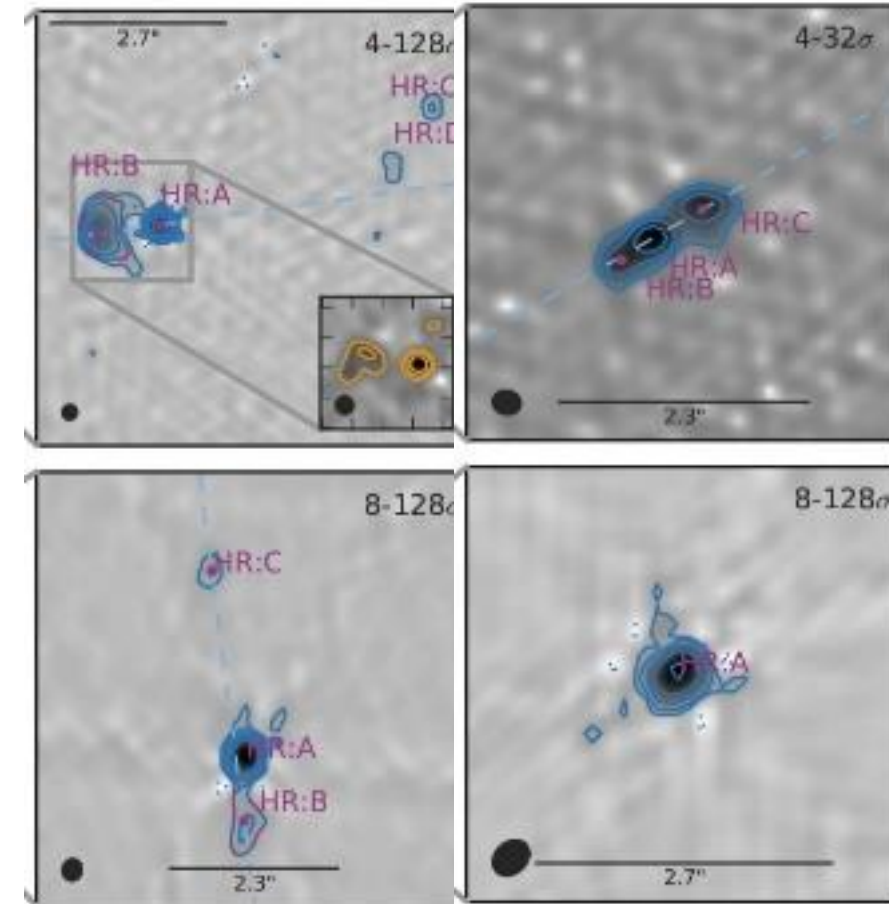
FIRST (FWHM $\sim 5''$)

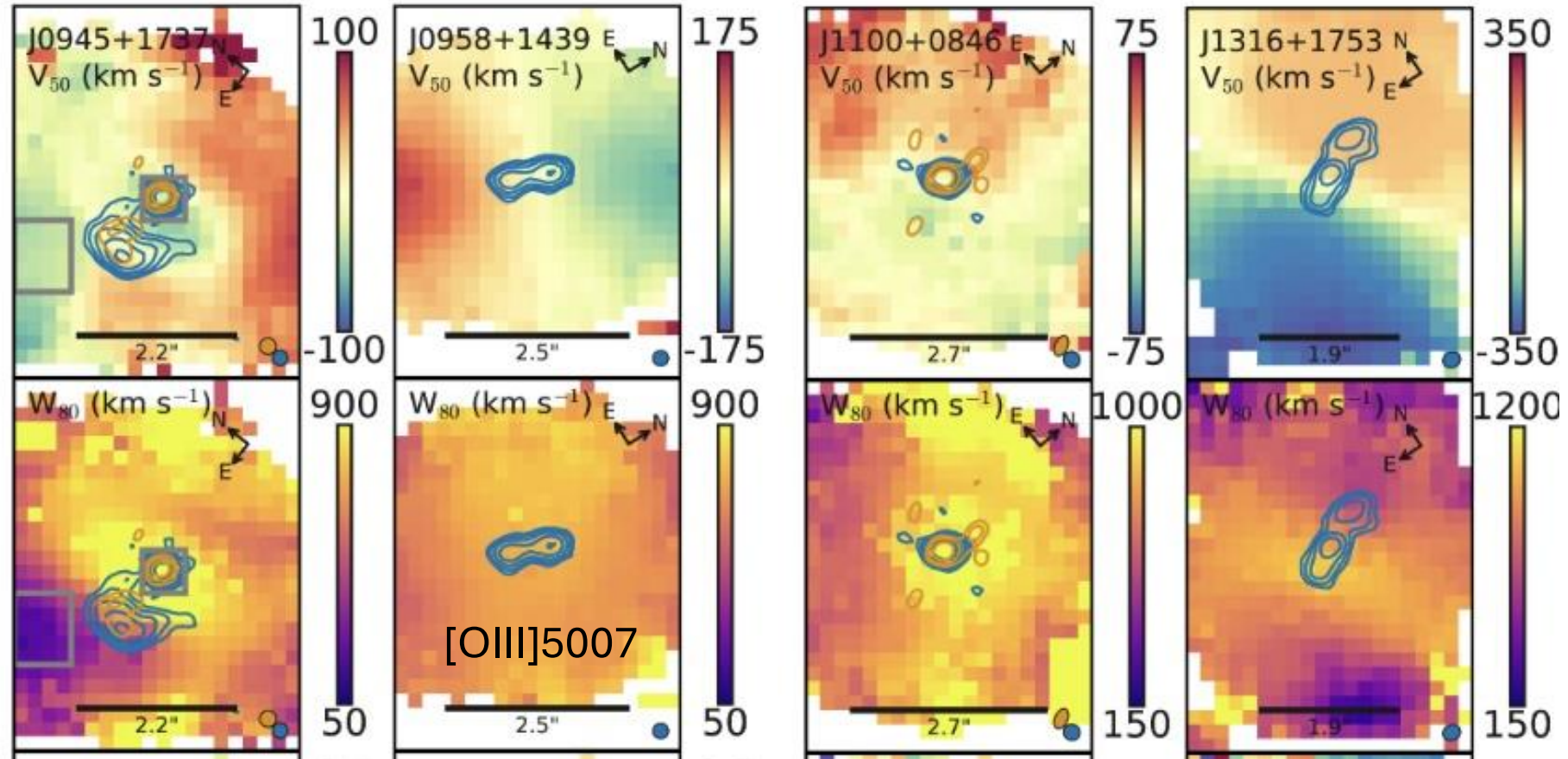


Jarvis+19

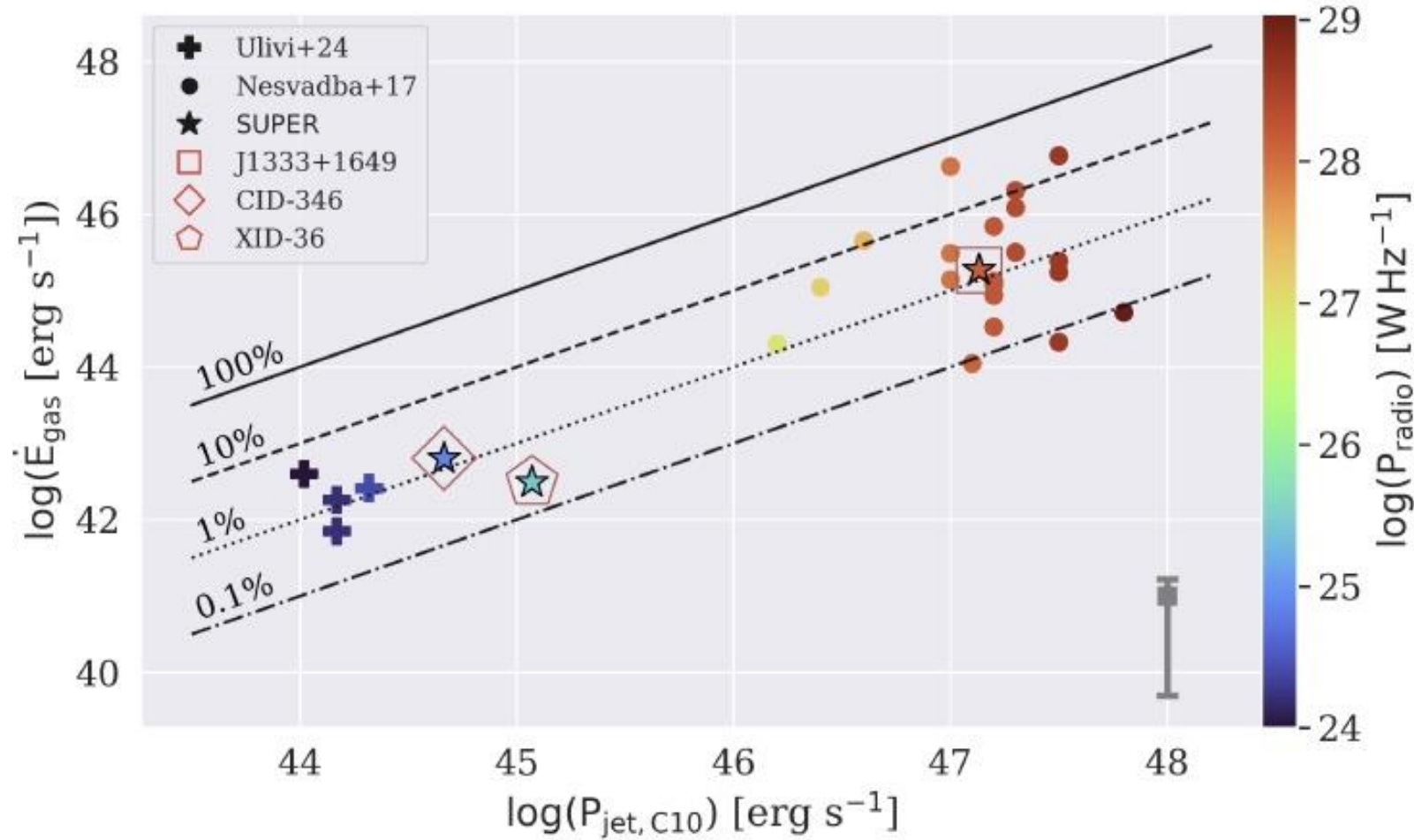


JVLA (FWHM $\sim 0.25''$)





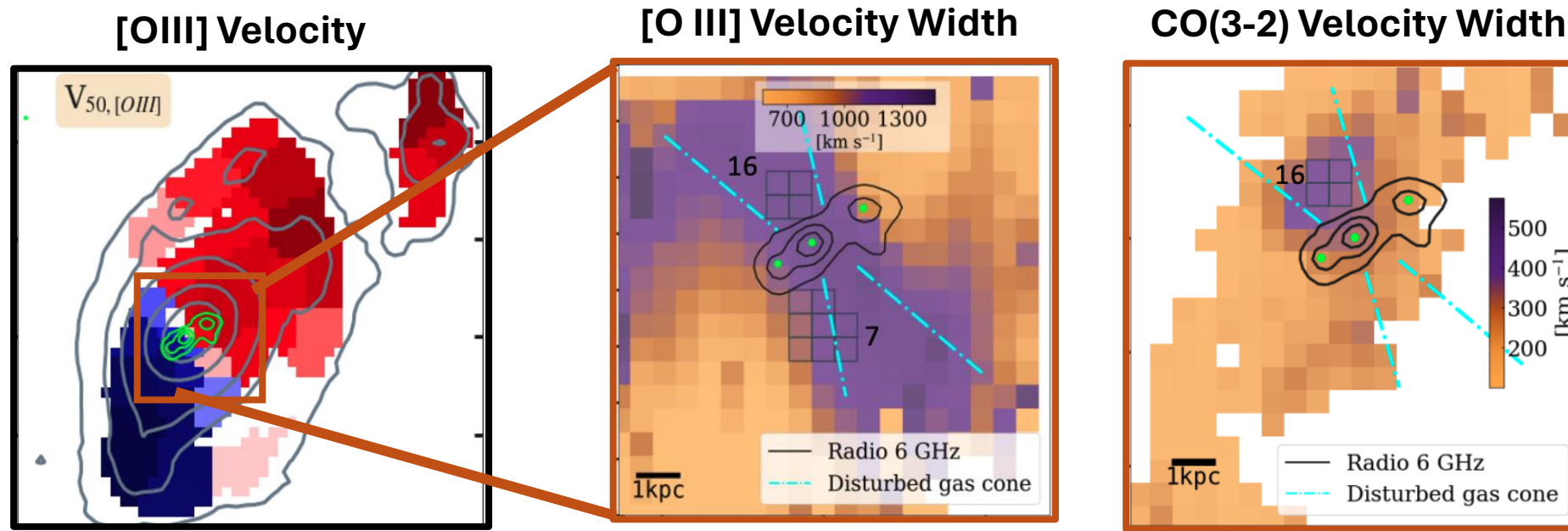
Jarvis+19



- ☐ Strong correlation between the kinetic energy of the ionized outflows and the P_{jet}
- ☐ In average a $\sim 1\%$ coupling between the jet and the ionized ISM

Low-power jets as the driver of the galaxy scale outflows?

- The low-power jet inclined into the disk increase the turbulence of the ISM in multiple gas phases.

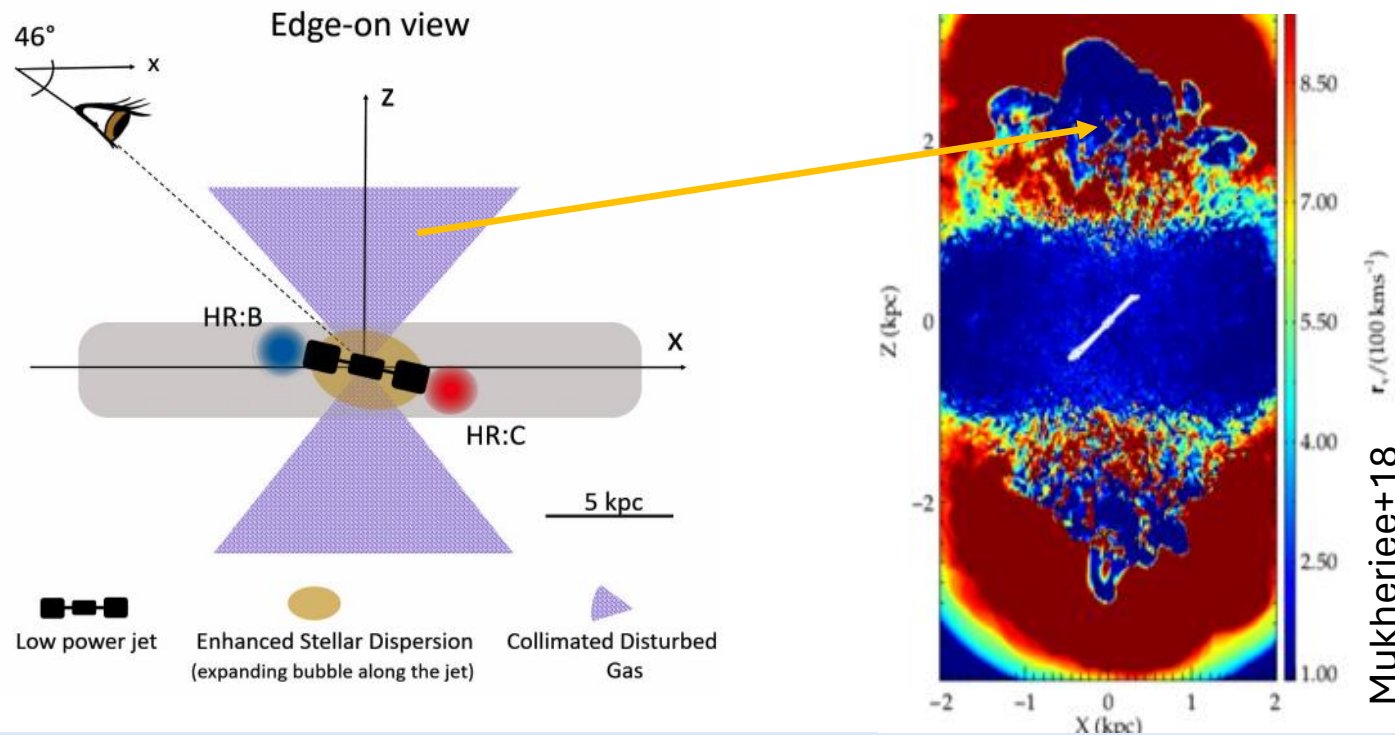


Girdhar et al. (2022); $z \sim 0.1$ 'radio quiet' quasar, $\sim 1 \text{ kpc}$ low power jet inclined into disk

Also see, e.g., Nesvadba+08,17a,b; Couto+13; Riffel+14; Mahoney+16; Aalto+16; Husemann+19; Bischett+19; Venturi+21; Fernandez-Ontiveros+20; Smethurst+21; Zanchettin+21; Bianchin+22; Speranza+22; Audibert+23; Zanchettin+23; Ulivi+24

Extreme gas kinematics: individual galaxies (spatially resolved)

Girdhar et al. (2022); $z \sim 0.1$ 'radio quiet' quasar, ~ 1 kpc low power jet inclined into disk



Low-power jets are "trapped" in the disk for longer times: their impact is amplified, stirring of the ISM which may inhibit star-formation

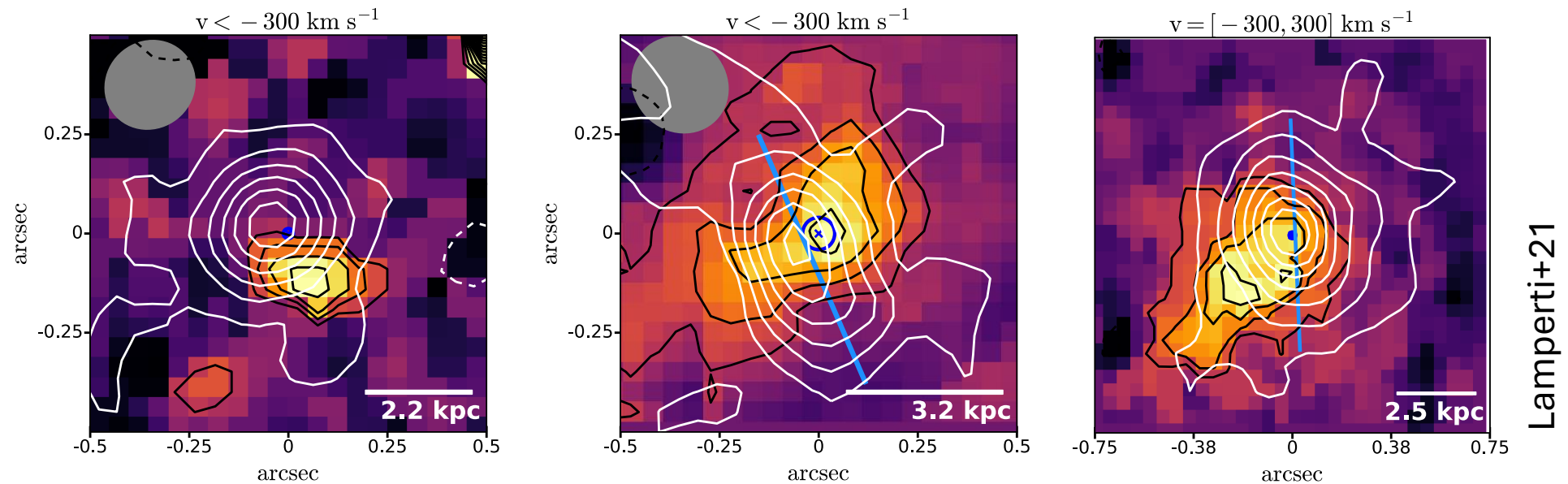
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Do AGN triggered outflows affect the
level of star formation in the host?

Direct measures

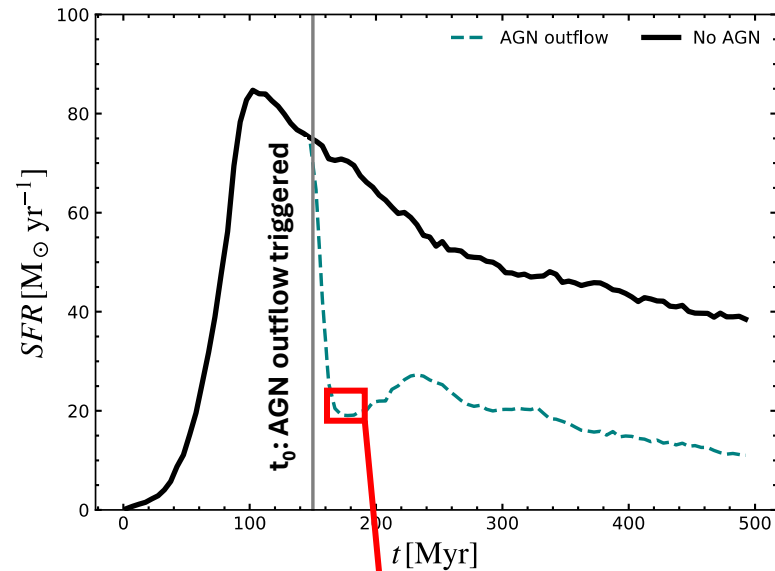
Do AGN triggered outflows affect the level of star formation in the host?



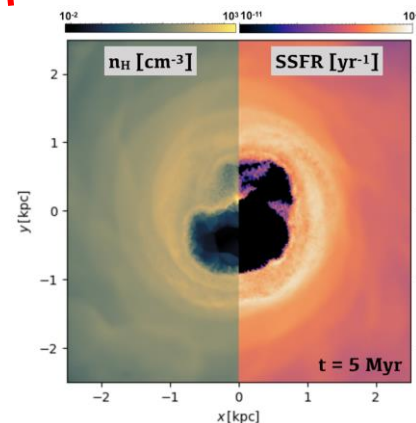
No clear sign of suppressed SF at the location of the outflow

- Impact on scales below our resolution ($\sim 2 \text{ kpc}$)
- An alternative tracer of “recent” star-formation?

Do AGN triggered outflows affect the level of star formation in the host?



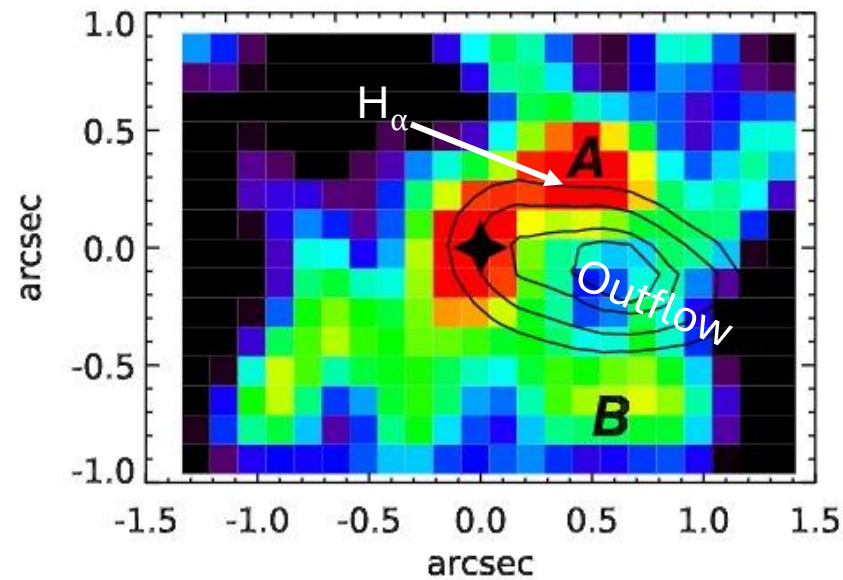
Costa+20



We need an “instantaneous” SFR tracer



H_{α} once removed the AGN contamination



Cresci+15



Do AGN triggered outflows affect the
level of star formation in the host?

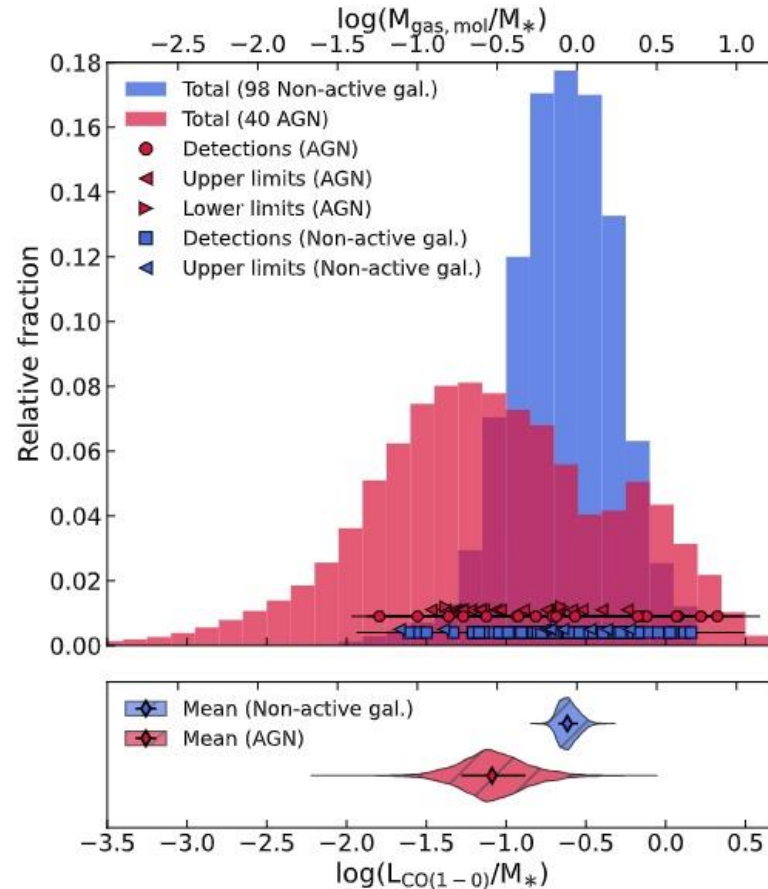
Indirect measures

Cold molecular gas reservoir

How is AGN feedback acting:

- ☐ The molecular gas is dissociated
- ☐ The molecular gas is pushed outside the galaxy
- ☐ The molecular gas is excited to higher temperature which are CO-dark

Bertola+24



The molecular gas fraction in AGN and non-AGN galaxies are statistically different: AGN activity depleting the cold gas reservoirs

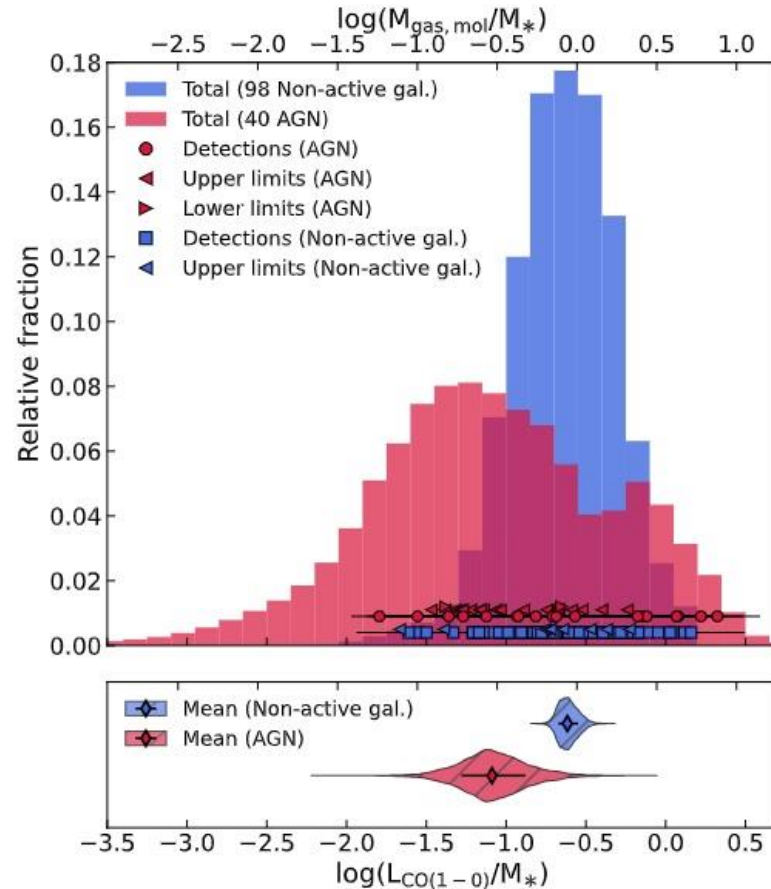
Also see e.g., Carniani+17; Brusa+18; Vietri+18; Perna+18; Loiaconoi+19; Bischetti+21; Frias Castillo+24

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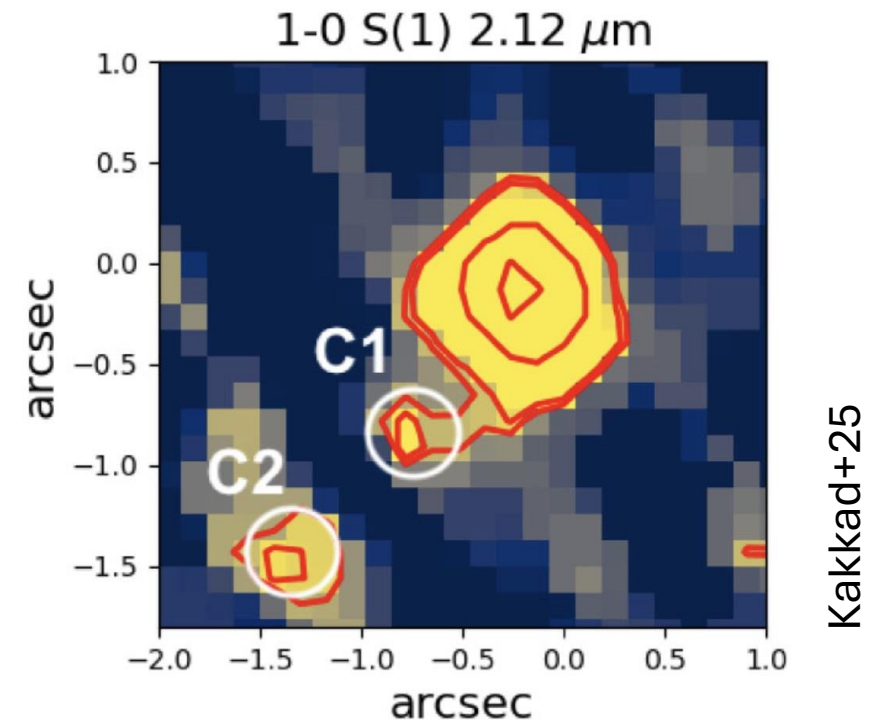
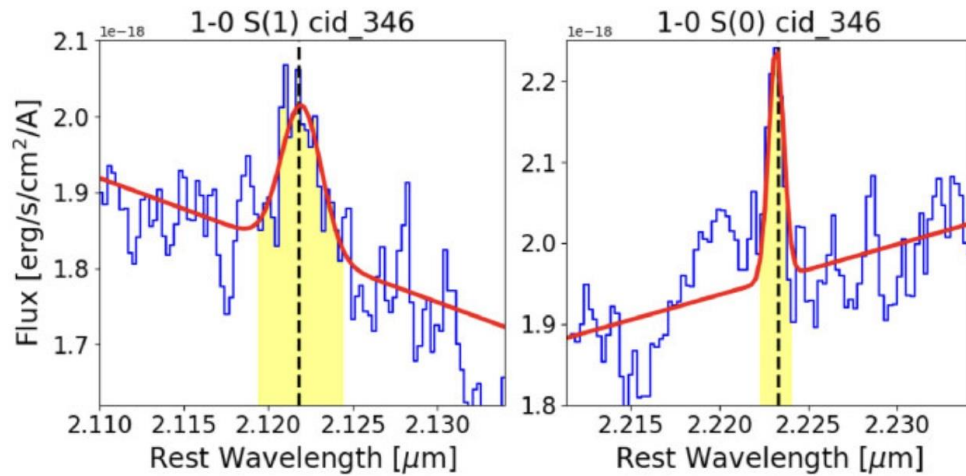


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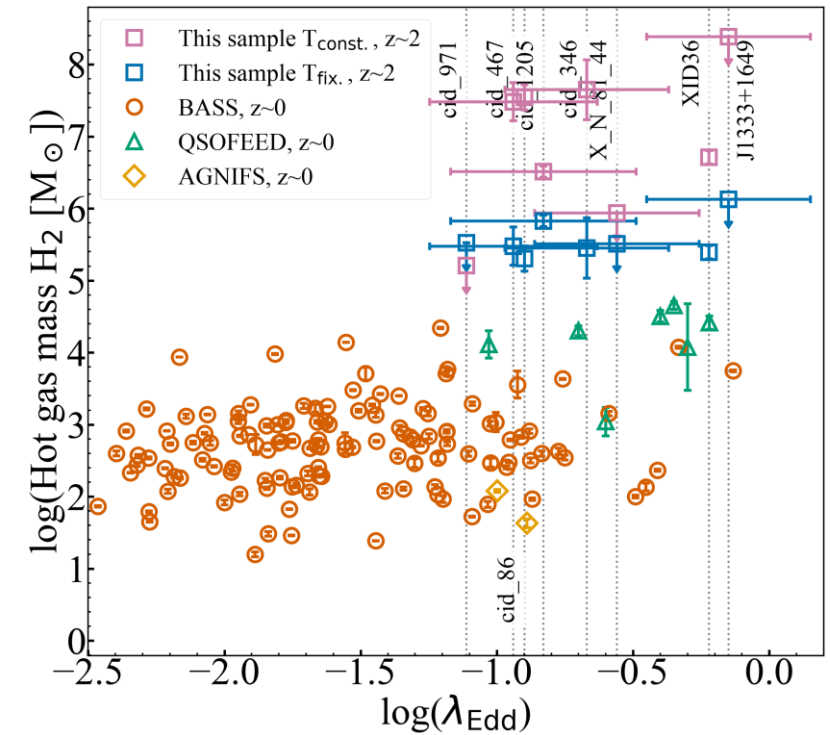
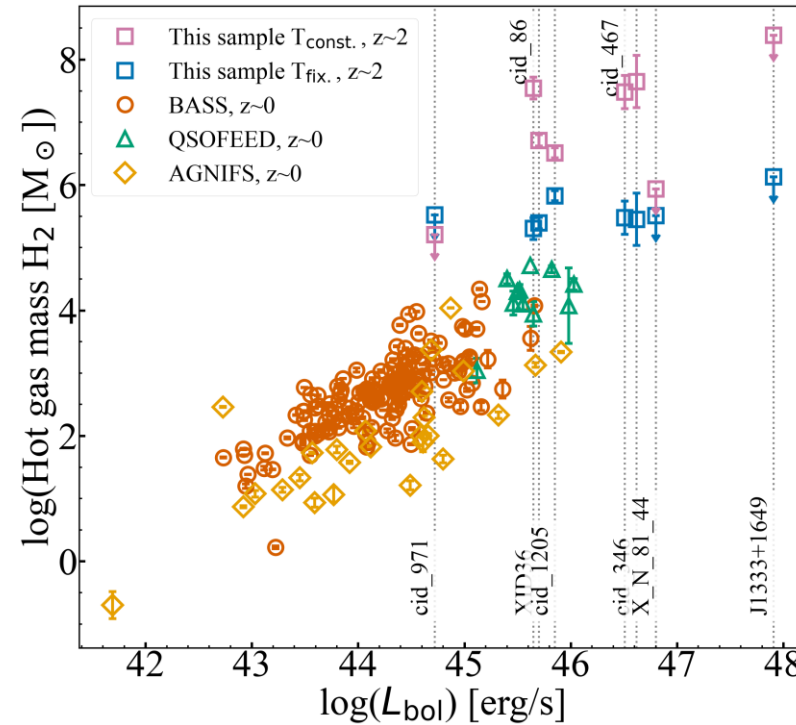
Warm molecular gas content and kinematics in AGN with ionized outflows
MIRI-MRS follow-up in Cy-1 and Cy-2.



Kakkad+25



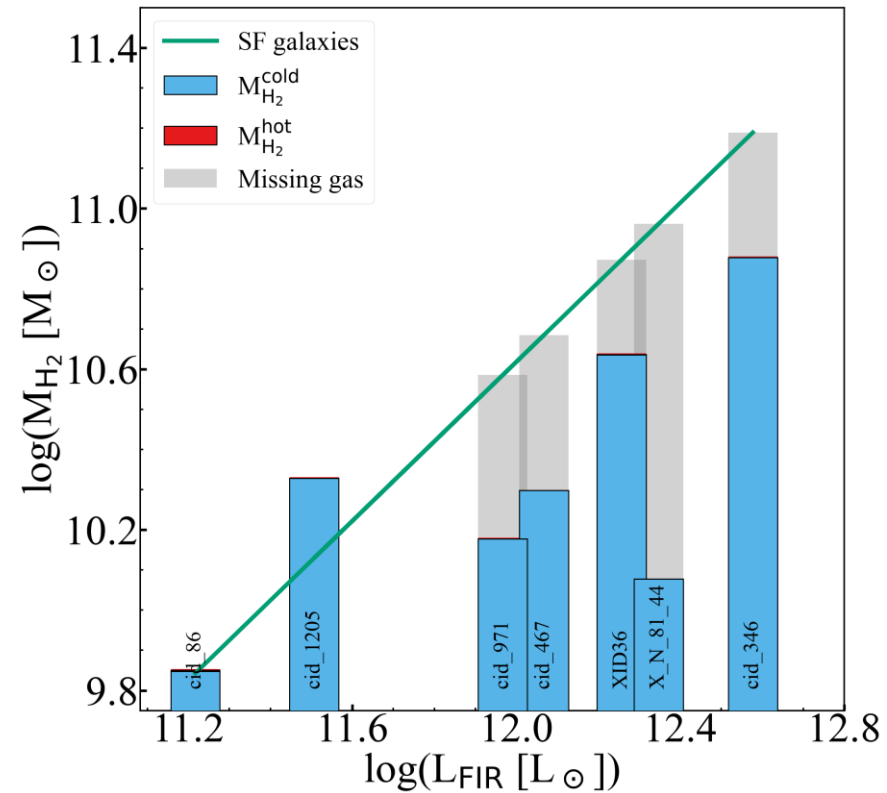
Warm molecular gas content increase with AGN bolometric luminosity and Eddington ratios.



Rueda Vargas +26

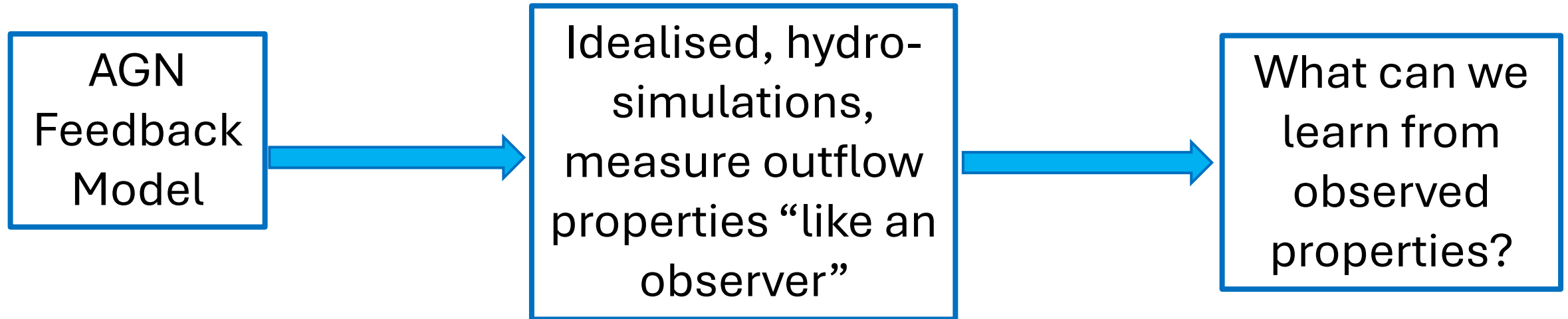


The detected warm molecular gas account for a small fraction of the "missing" cold molecular gas.



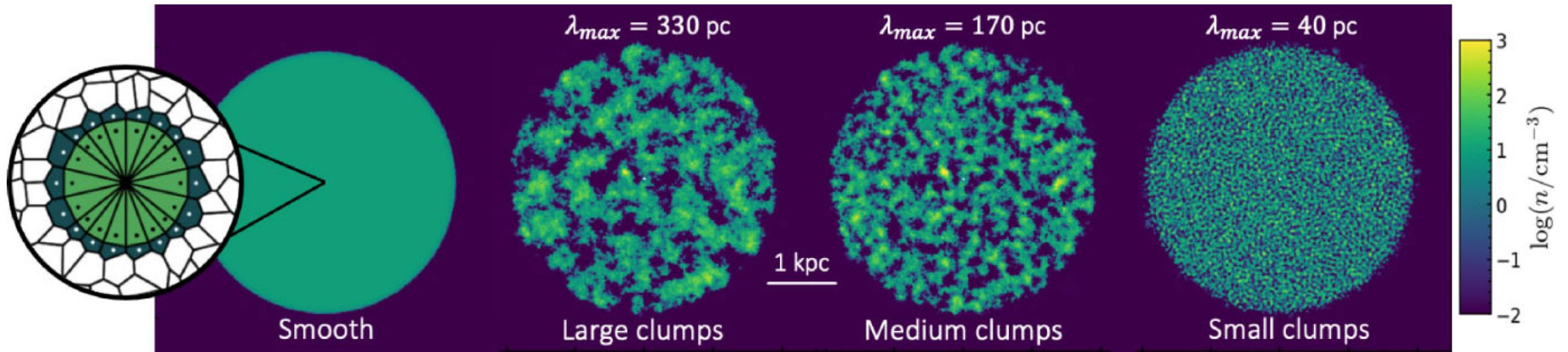


"Observational experiments"



Ward, Costa, Harrison & Mainieri (2024)

Inject quasar winds into galaxy disks



Inject AGN wind into static disk:
(model from Costa+20)

$$\dot{E}_w = \frac{v_w}{2c} L_{AGN}$$

Fiducial model:

$$L_{AGN} = 10^{45} \text{ erg/s}$$

$$V_w = 10^4 \text{ km/s}$$

Disk: d=4kpc, h=1kpc

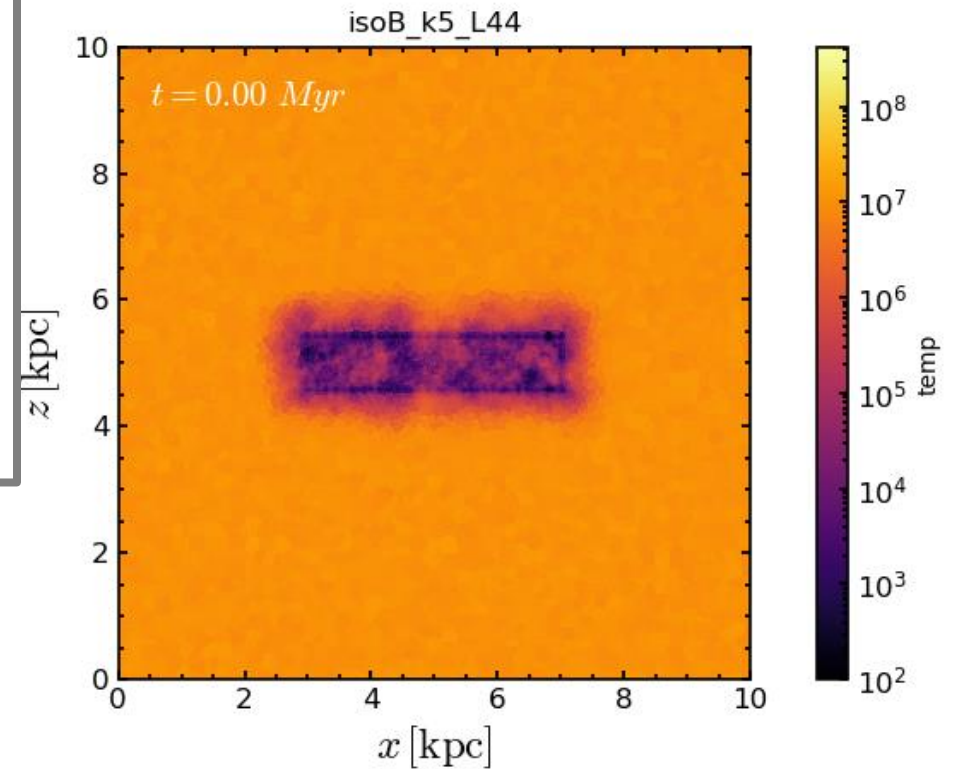
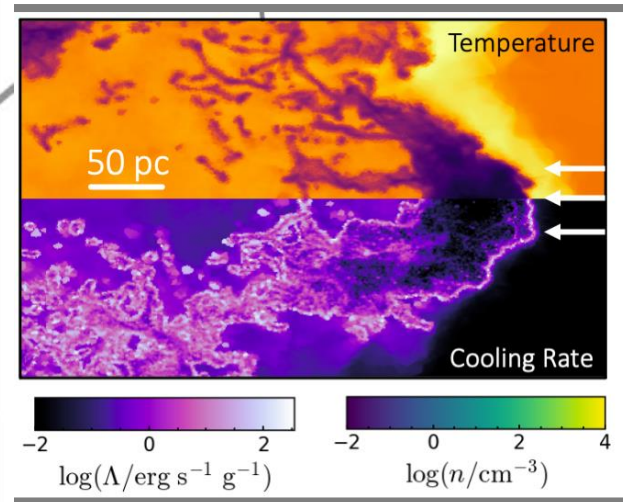
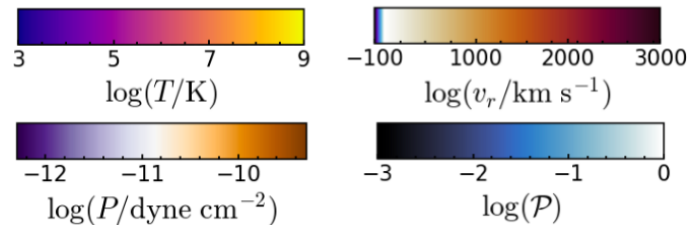
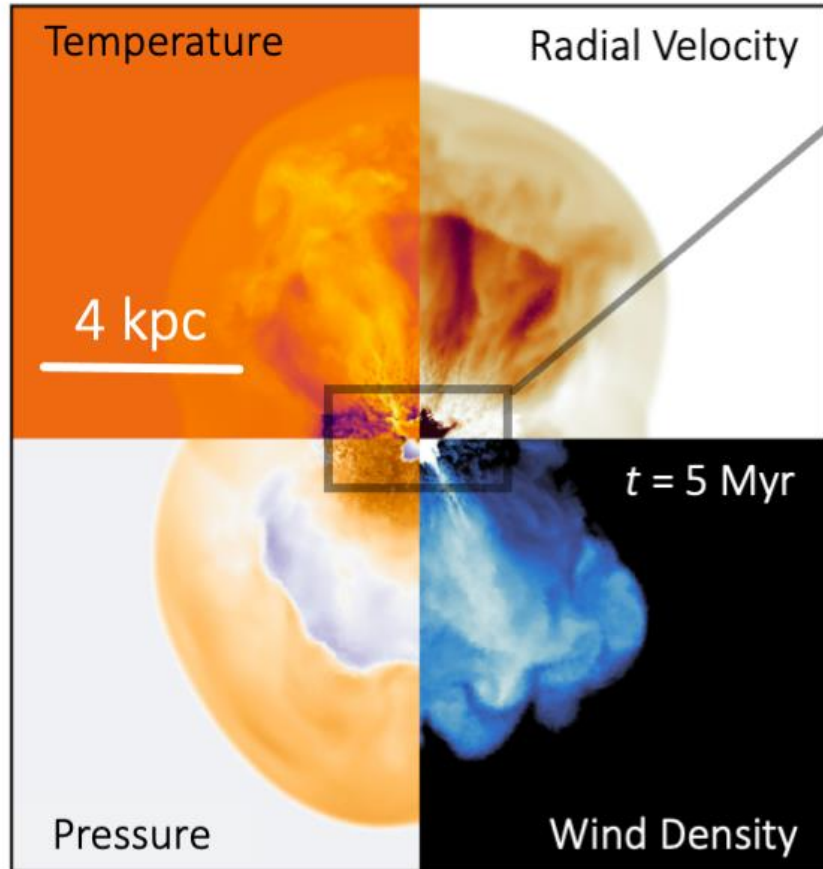
Hydro-code: AREPO:

Resolution: reaches ~1pc

Includes primordial cooling

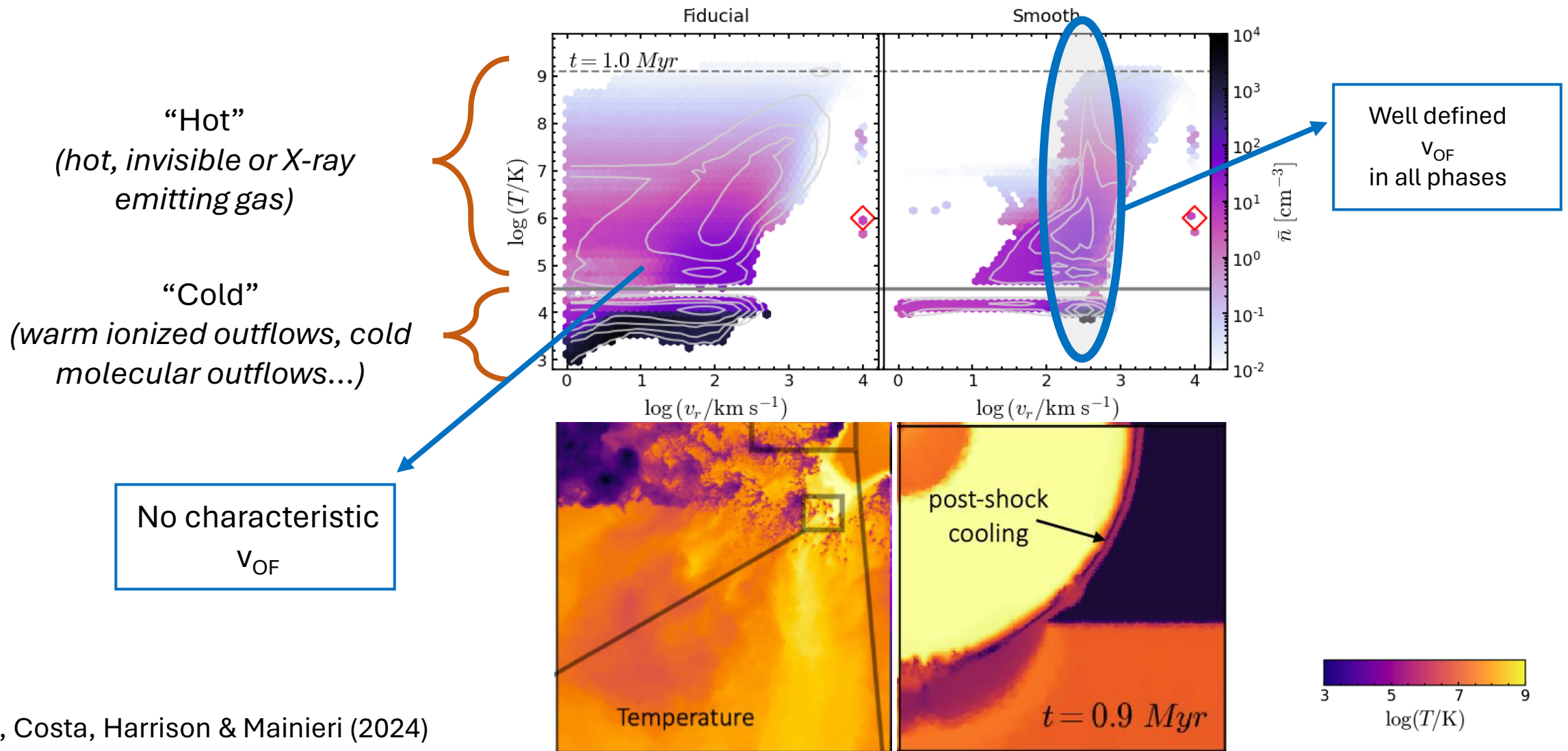
Ward, Costa, Harrison & Mainieri (2024)

Outflows “vents” through paths of least resistance



- ❑ Large-scale collimated outflow (wind injected spherically on small scales)
- ❑ Cold clumps inside hot diffuse outflow

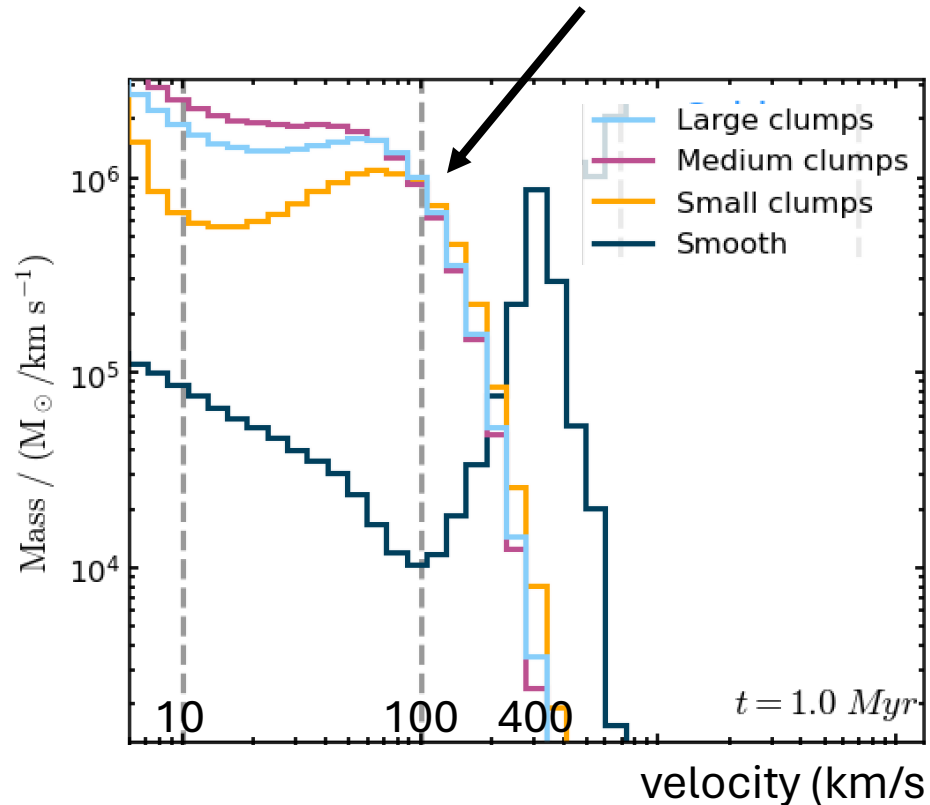
Realistic ISM leads to very different predictions



Ward, Costa, Harrison & Mainieri (2024)

Challenges in defining outflow velocities

Clumpy disks: No characteristic velocity
A lot of **outflowing** mass at low velocities

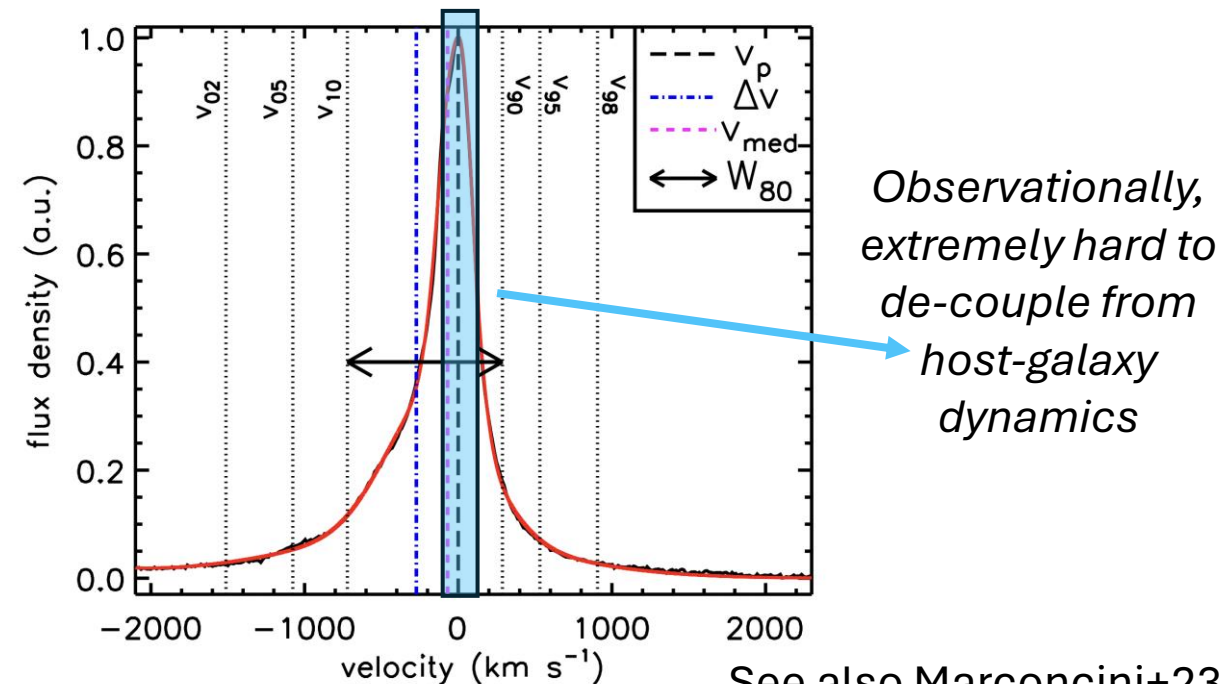


Ward, Costa, Harrison & Mainieri (2024)

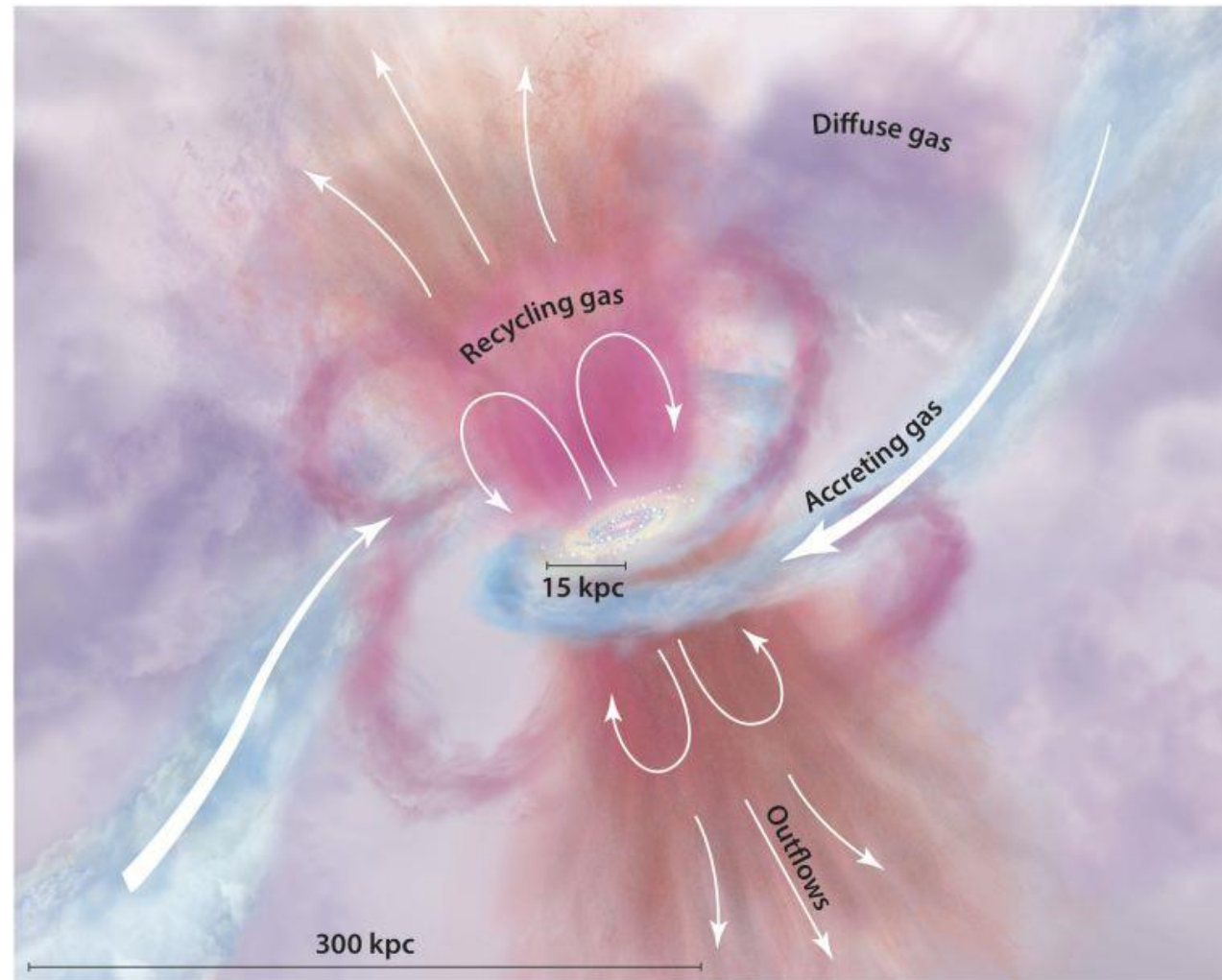
$$M_{\text{OF}} = \sum_i m_i \quad \text{for } v_i > v_{\min}$$

$v_{\min} = 10 \text{ km/s}$ (physical & “complete”)

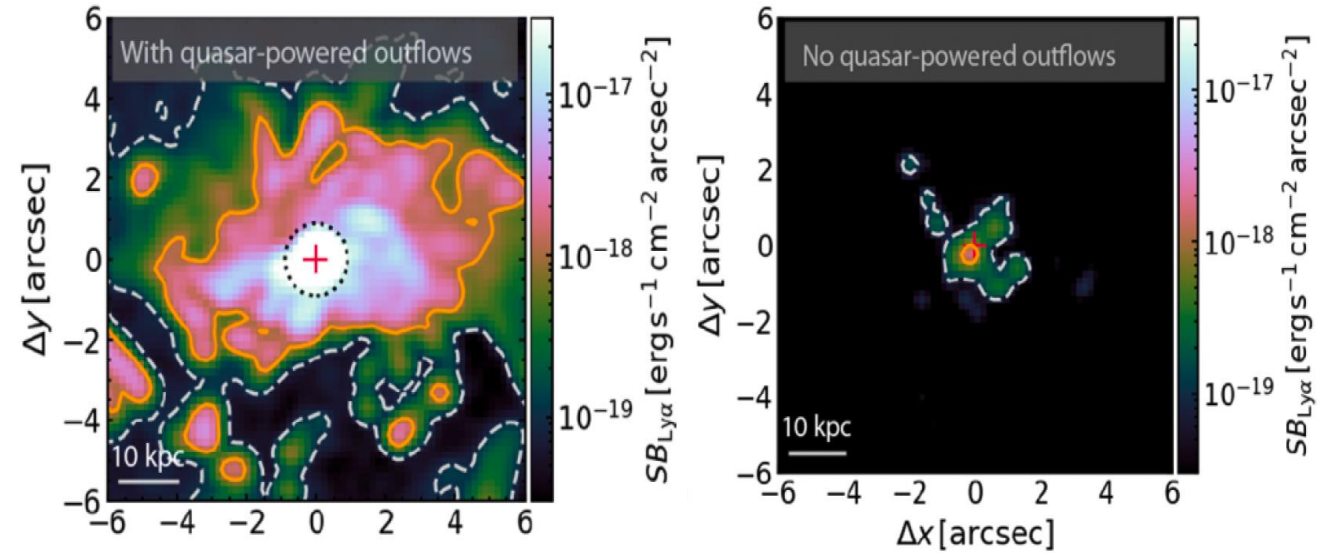
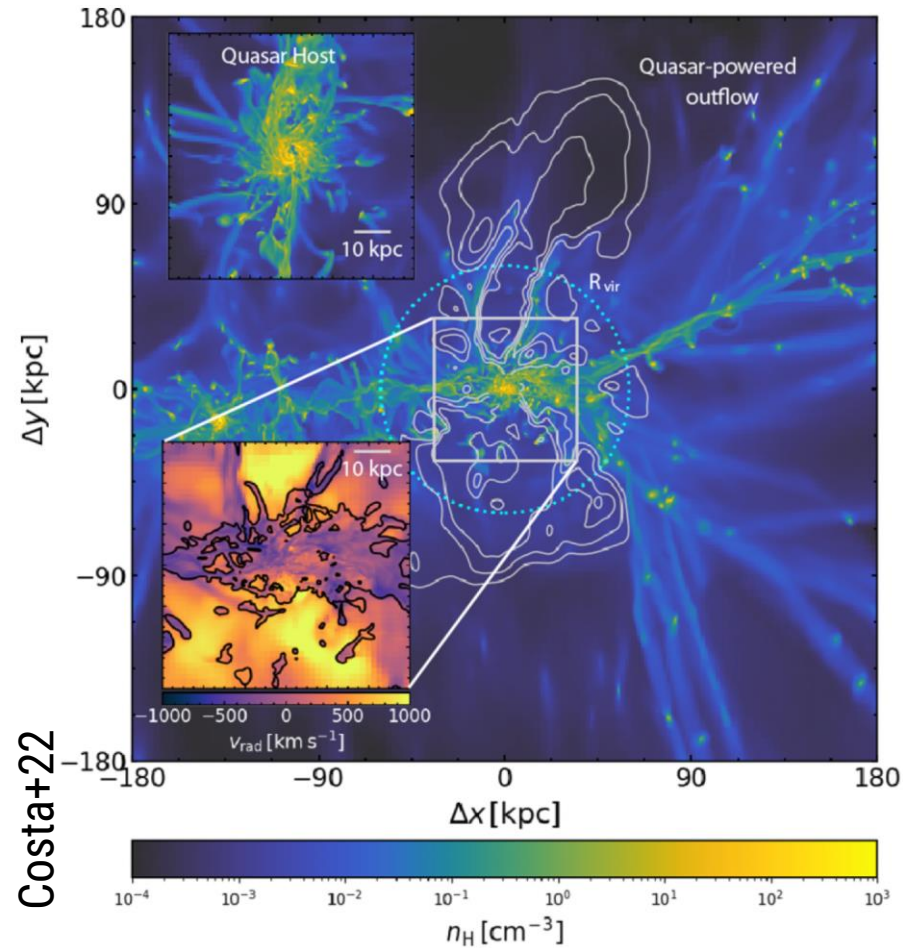
$v_{\min} = 100 \text{ km/s}$ (representative observational limit)



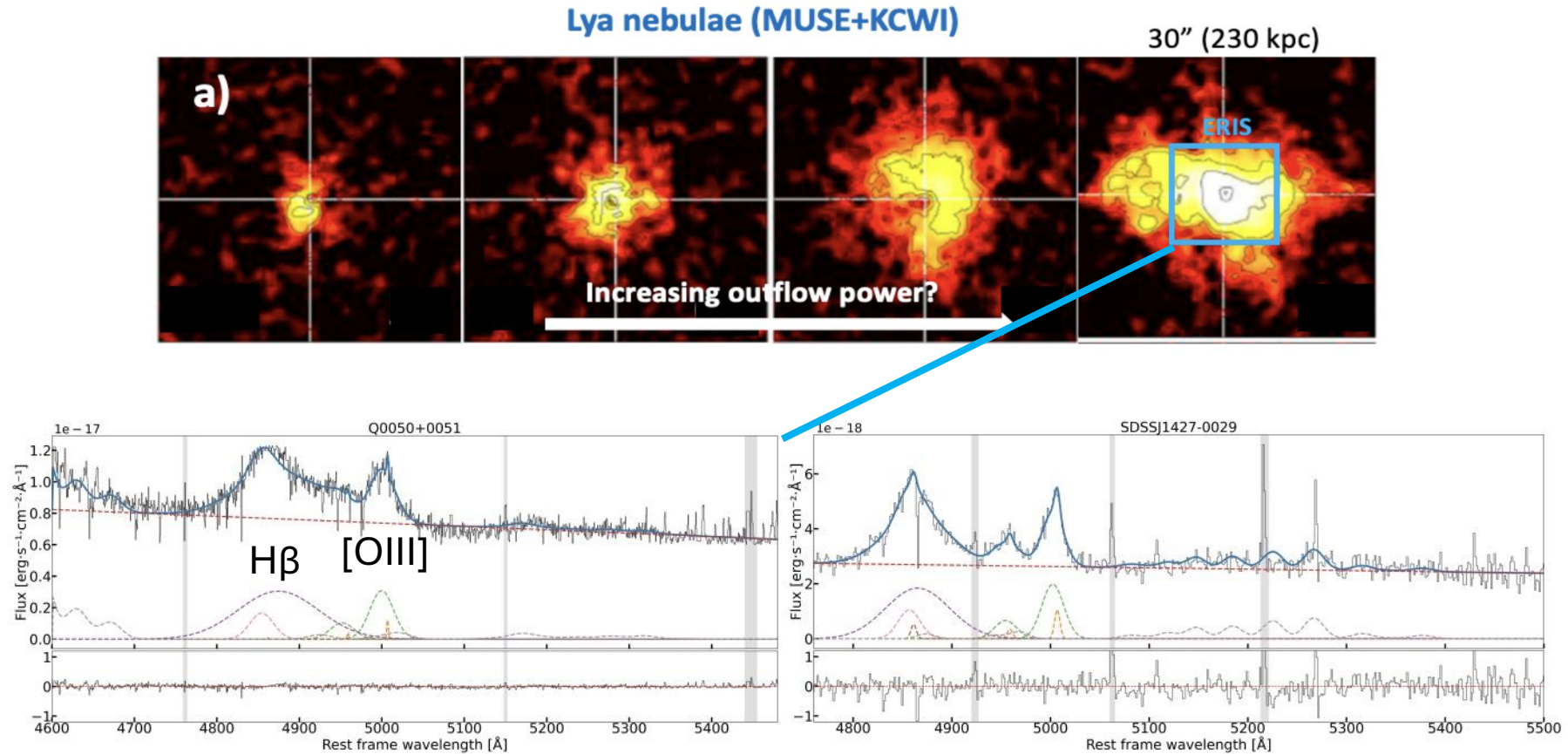
See also Marconcini+23



AGN driven outflows are a necessary ingredient to reproduce the observed Ly α halos around quasars on 100 kpc scales.

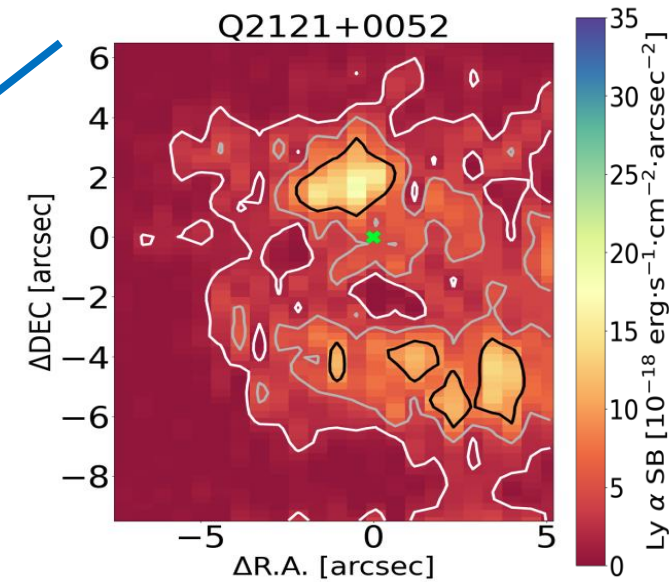
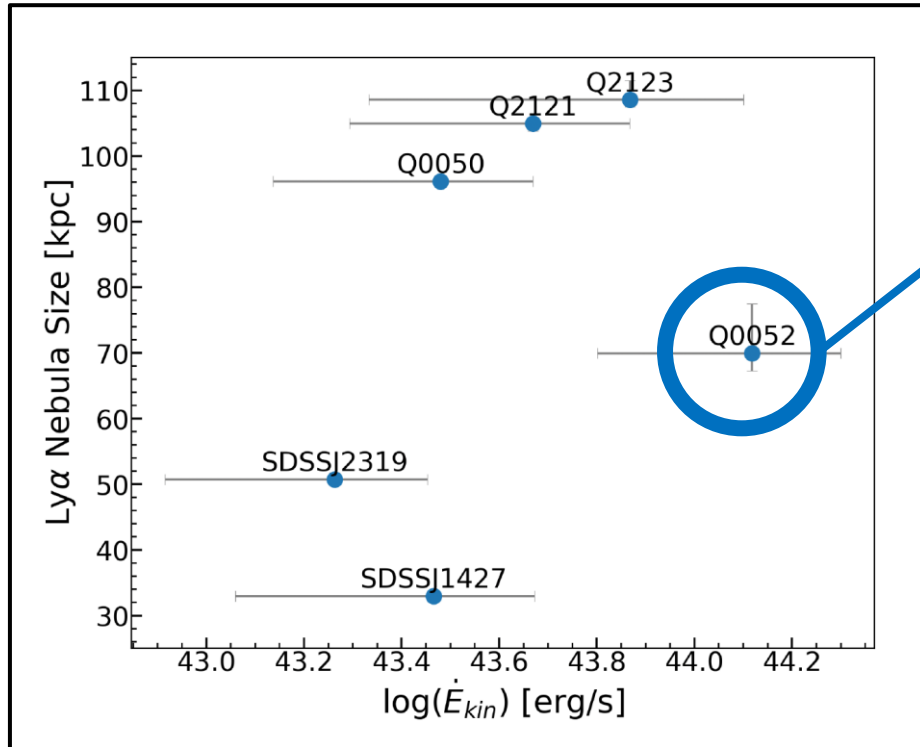


Rueda Varga+25



Galaxy scale ionized outflows detected at the centre of all nebulae.

Rueda Varga+25



ALTERNATIVE POWERING MECHANISMS
OF THE Ly- α NEBULAE

Positive correlation between outflow power and nebulae properties
(extension and luminosity)



ELT

ELT

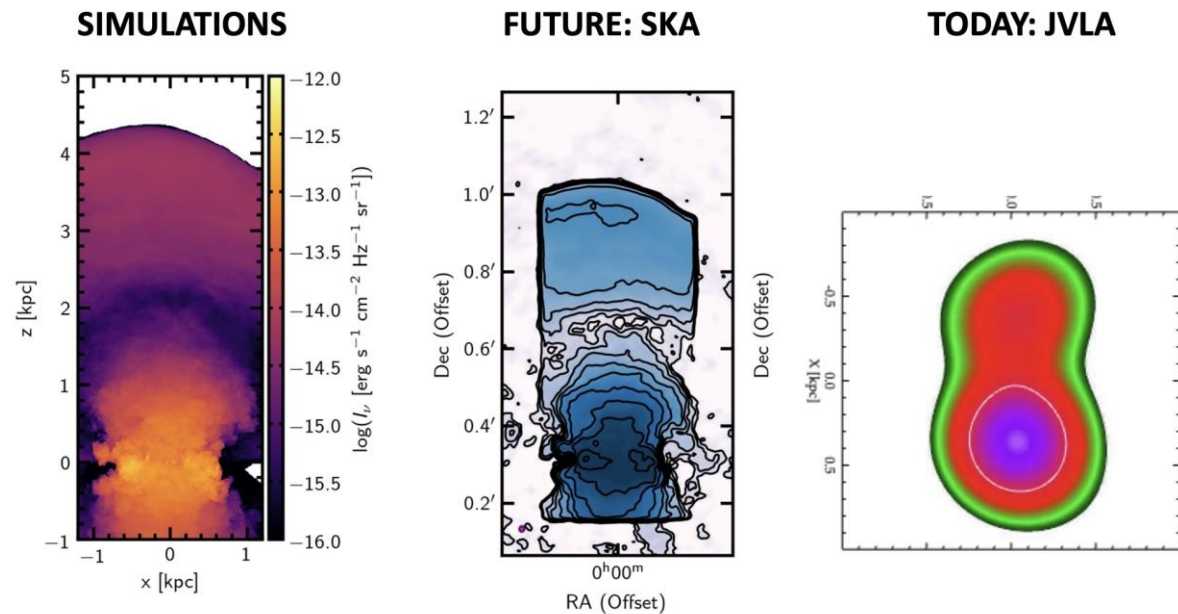
- Diffraction limited IFS observations (MICADO and HARMONI) to trace ionized gas kinematics on sub-kpc scales at $z > 2$



SKAO

SKA low + mid

- Continuum: collimated jets resolved at the same level of simulations
- HI: spatially resolved atomic gas out to intermediate redshift



Maccagni, Mainieri et al. 2026, SKAO science book



SKA low + mid

- Continuum: collimated jets resolved at the same level of simulations
- HI: spatially resolved atomic gas out to intermediate redshift

- ❑ AGN feedback is a multi-phase, multi-timescale, and multi-spatial problem.
- ❑ Observational evidence that AGN radiation/winds/jets may affect the ISM in multiple way: it does not have to be necessarily ejective.
- ❑ AGN are events in the life of a galaxy: the single AGN feedback episode may have localized impact; the cumulative effect of multiple such events can have a more global impact.



Large spatially resolved surveys across wl: JVLA (SKA), ALMA (WSU), opt-IR IFUs from the ground (ELT), JWST, X-ray (AXIS, Athena)

- ❑ Observed outflow properties can not trivially be used to determine outflow impact and driving mechanisms.

Carefully-constructed simulations to test “specific” models and reconstruct “observational experiments”