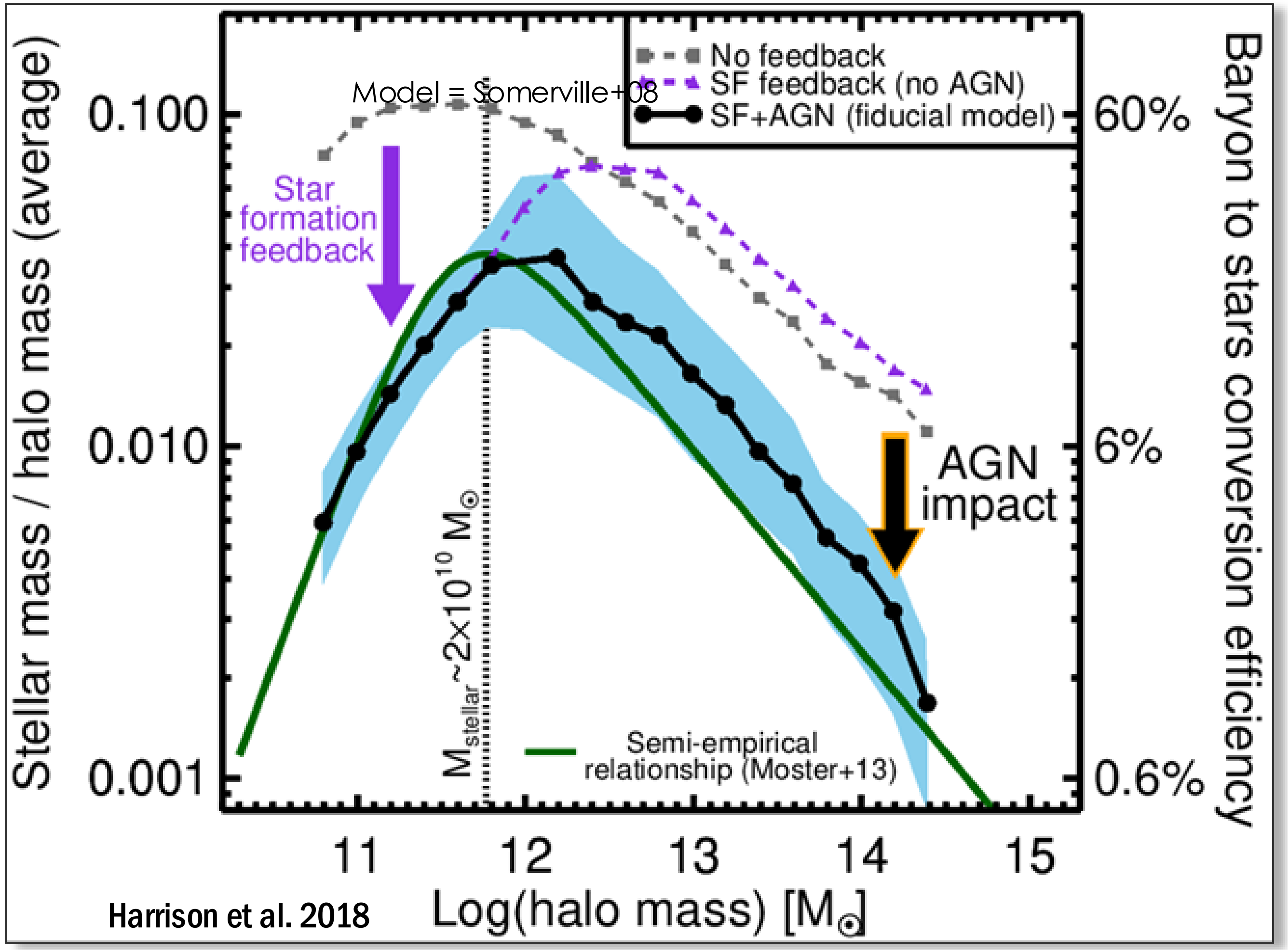
AGN outflows and jets

Vincenzo Mainieri (ESO)

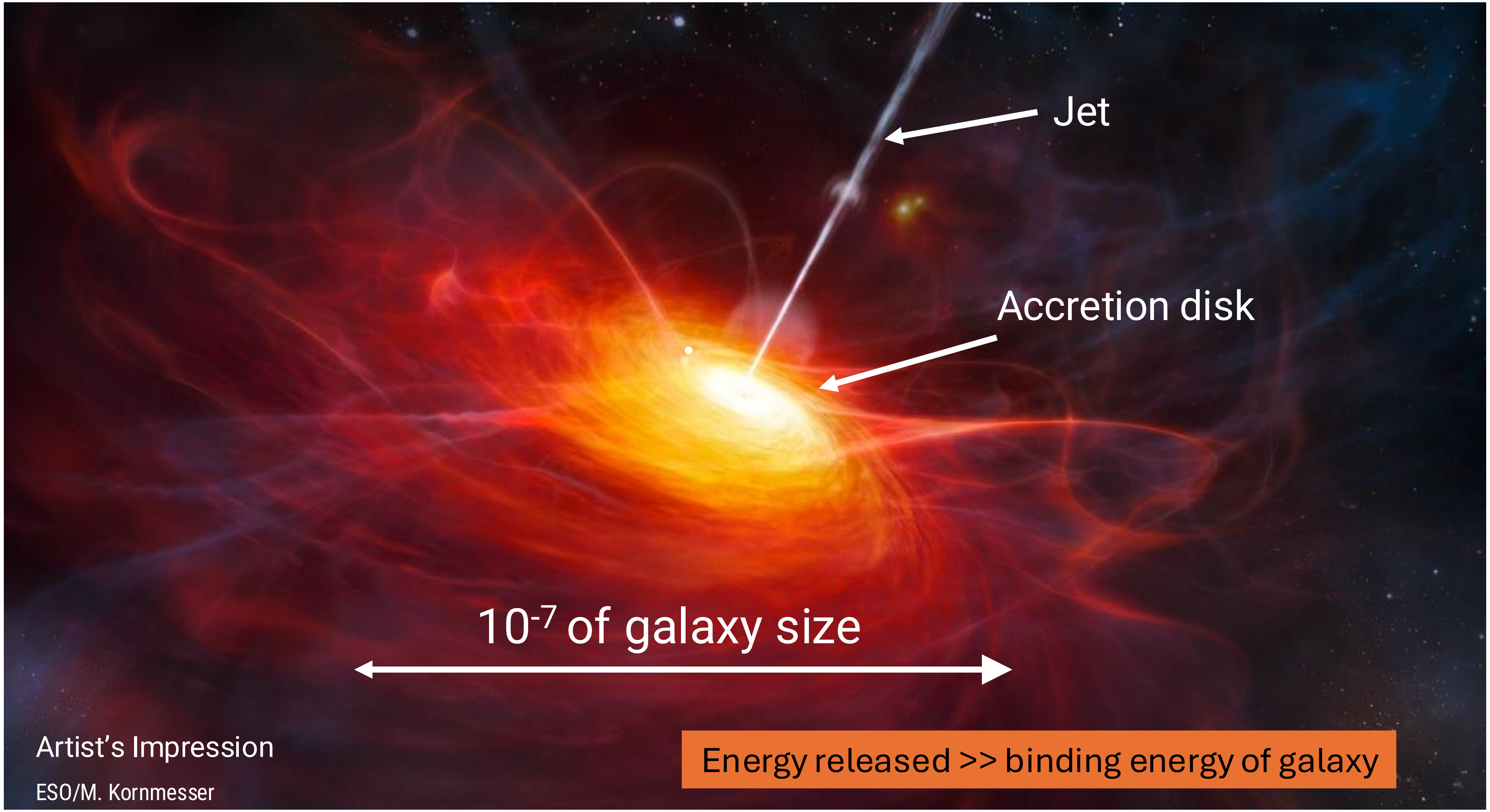
Chiara Circosta, Elena Bertola, Chris Harrison, Darshan Kakkad, Giulia Tozzi, Samuel Ward

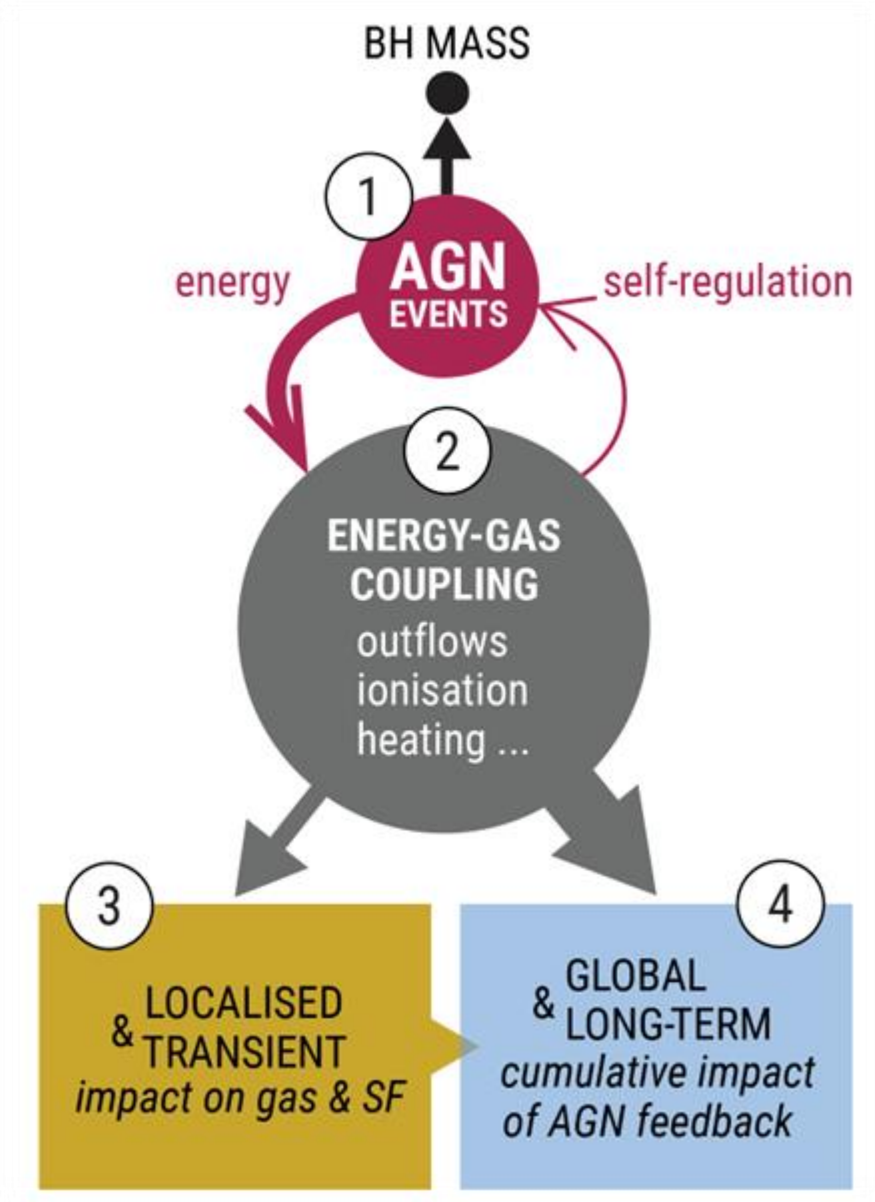
AGN FEEDBACK MOTIVATION



e.g., Croton+06; Bower+06; Gaspari+11; Dubois+13; Hirschmann+14; Khandair+14; Vogelsberger+14; Crain+15; Henriques+15; Choi+ 18 +++

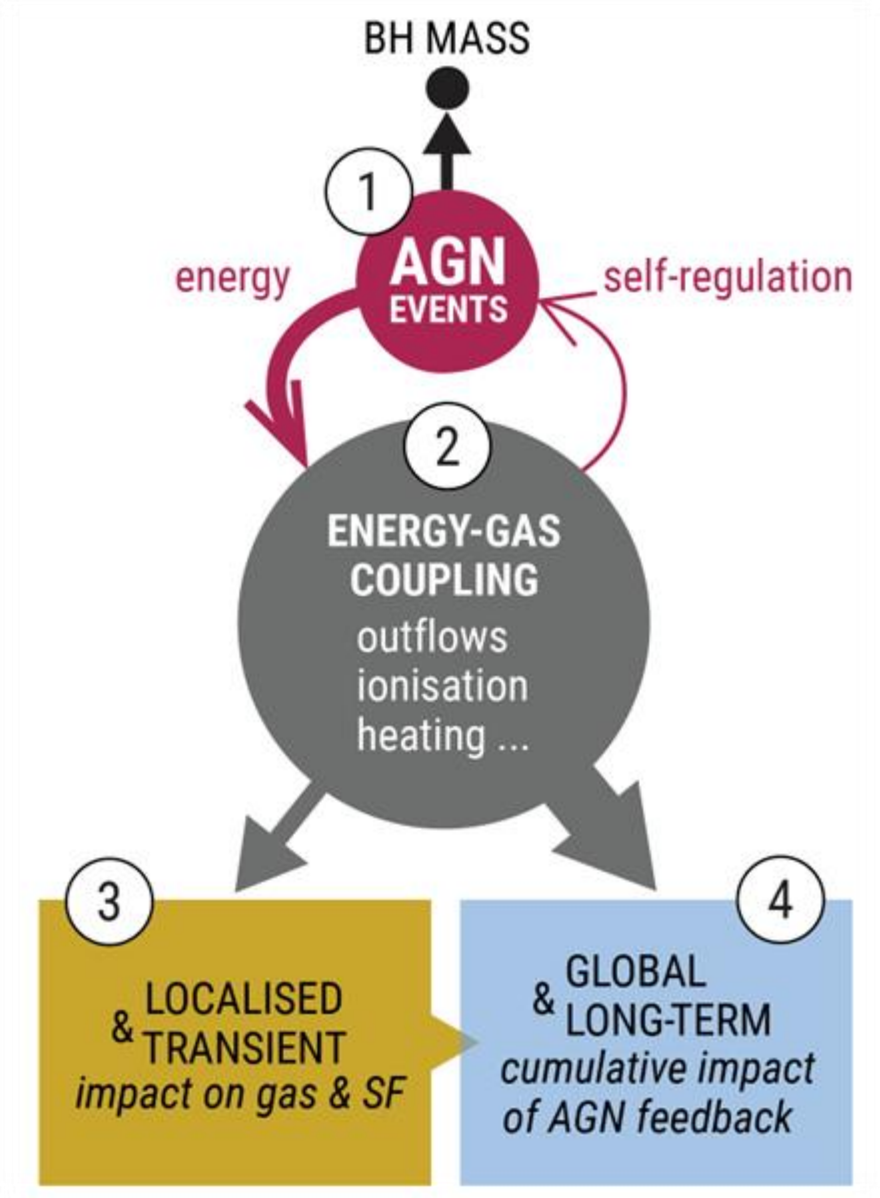
AGN as a main actor in galaxy evolution?





Harrison & Ramos Almeida 2024

- AGN are events
- Single events can have a localized impact
- Cumulative events can have a global impact



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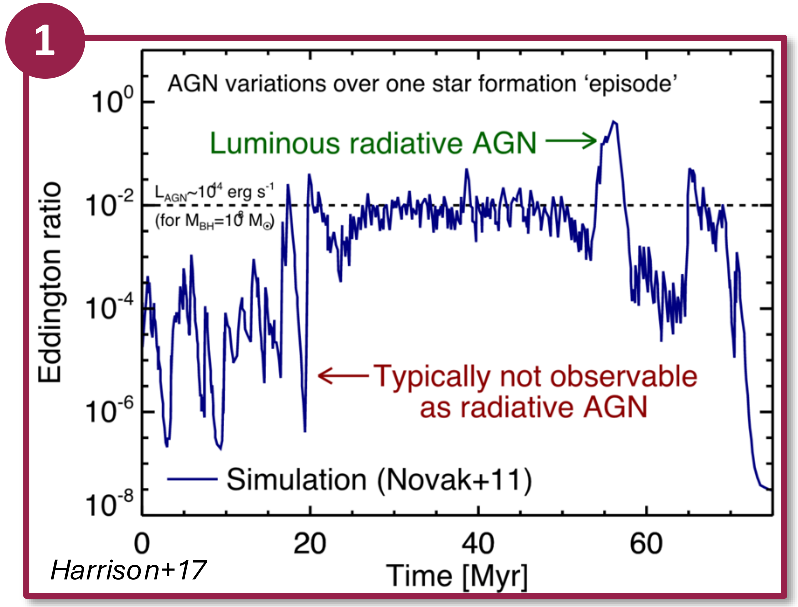
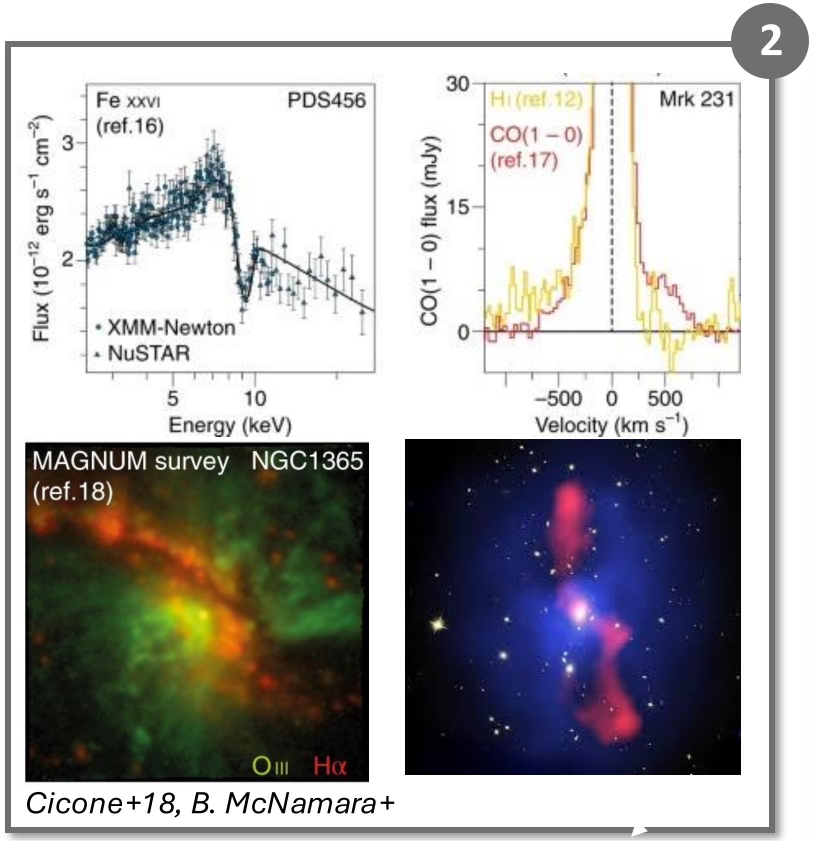
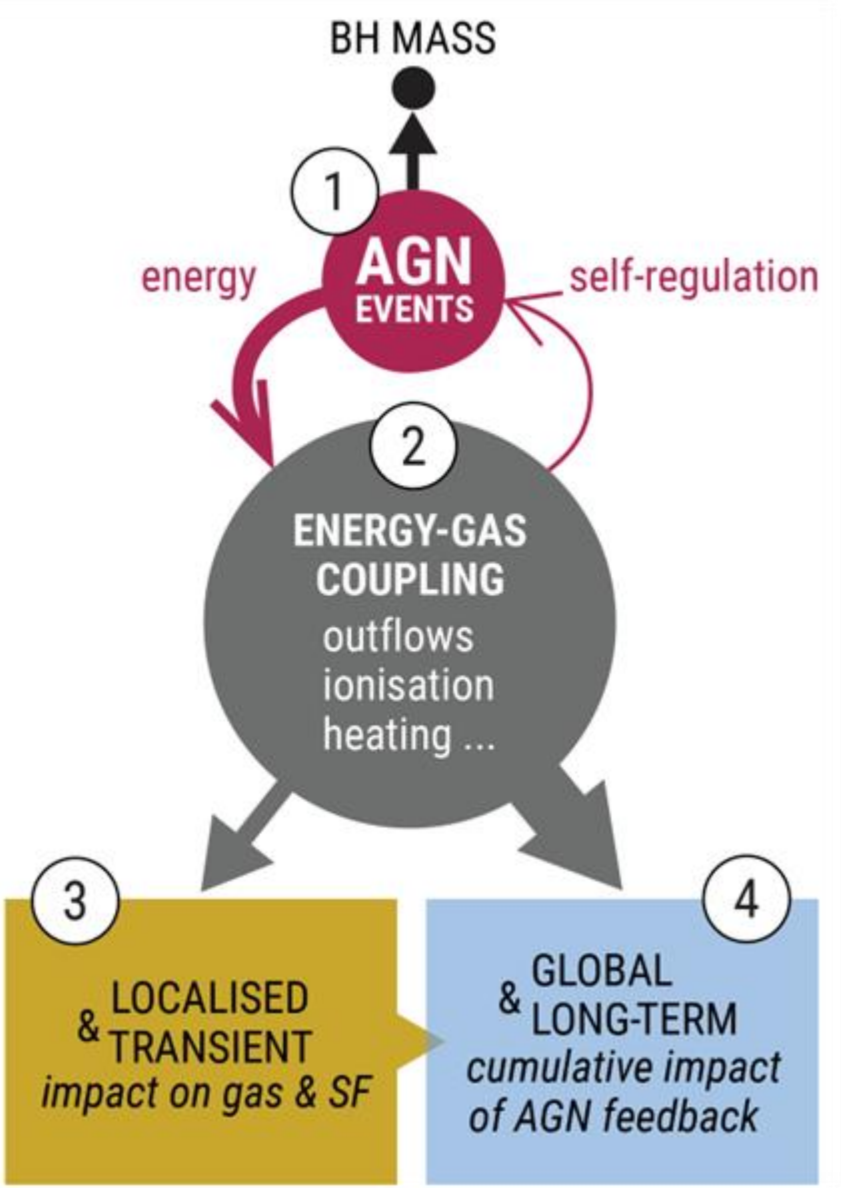




Cicone+18, B. McNamara+



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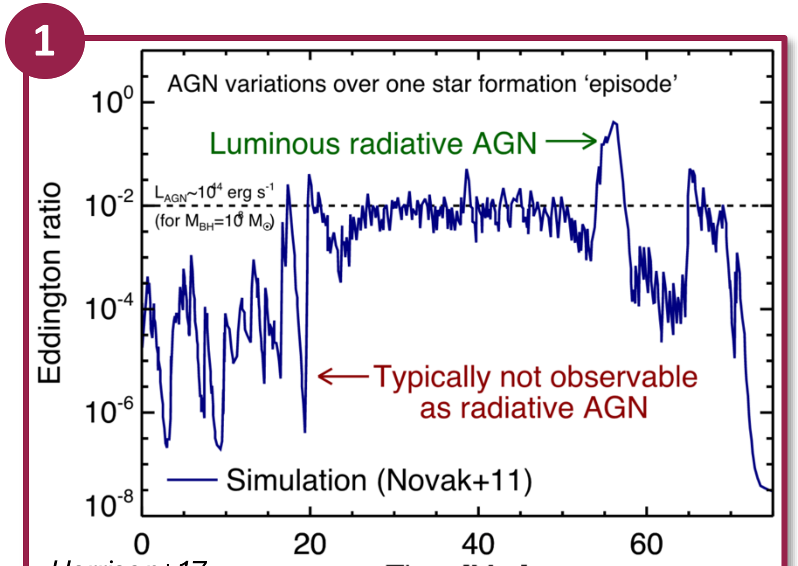

Harrison+17

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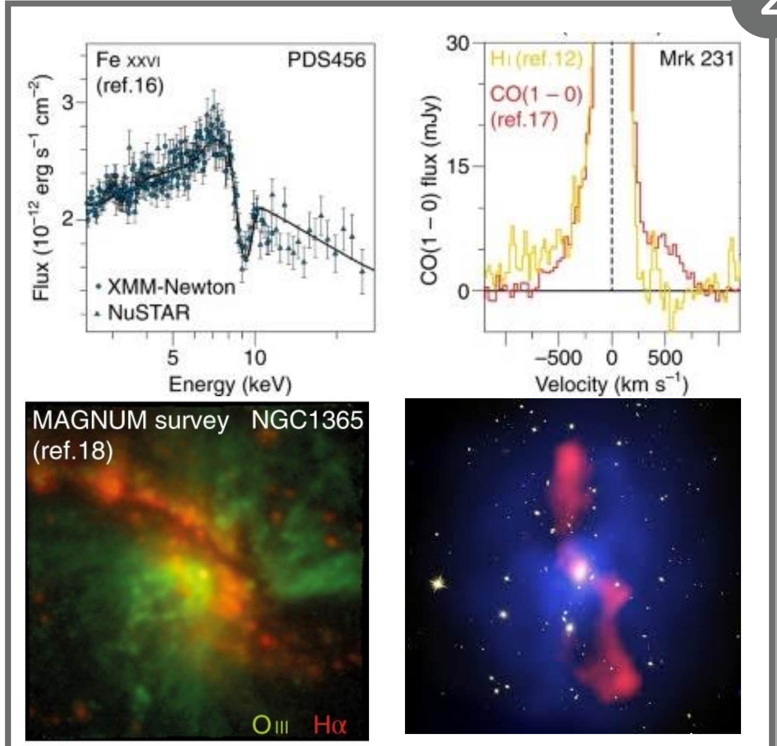

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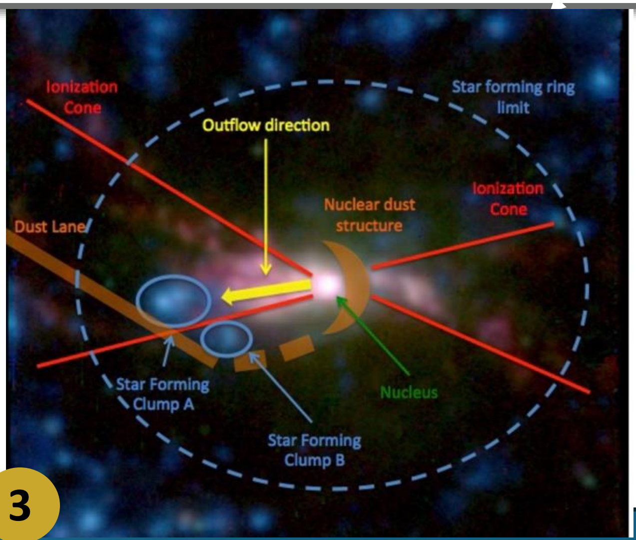
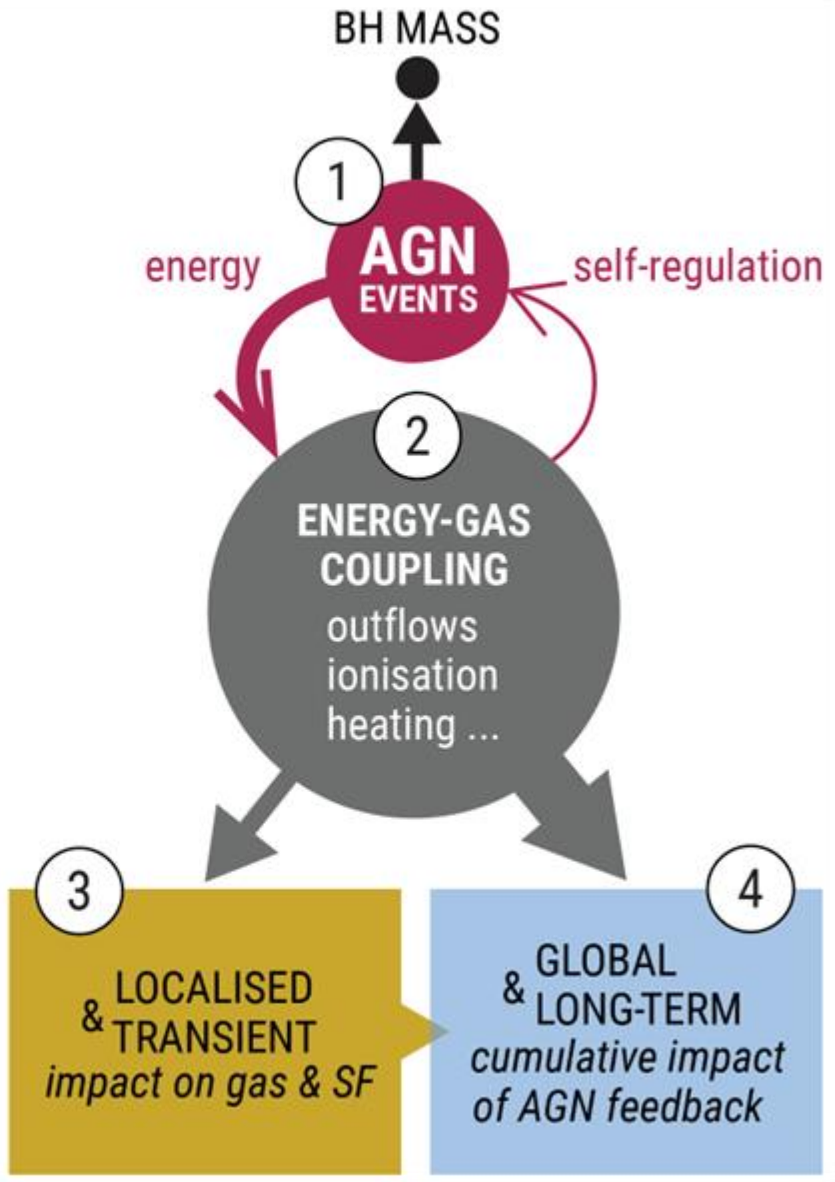
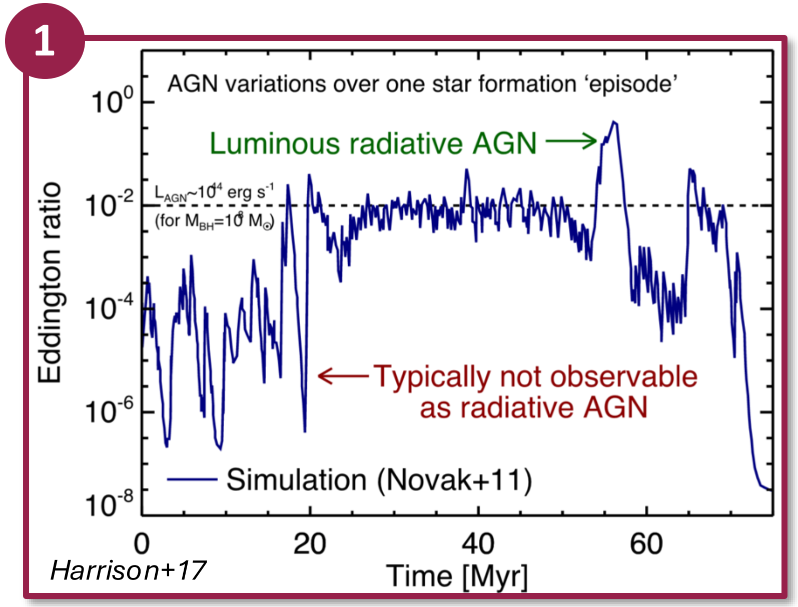
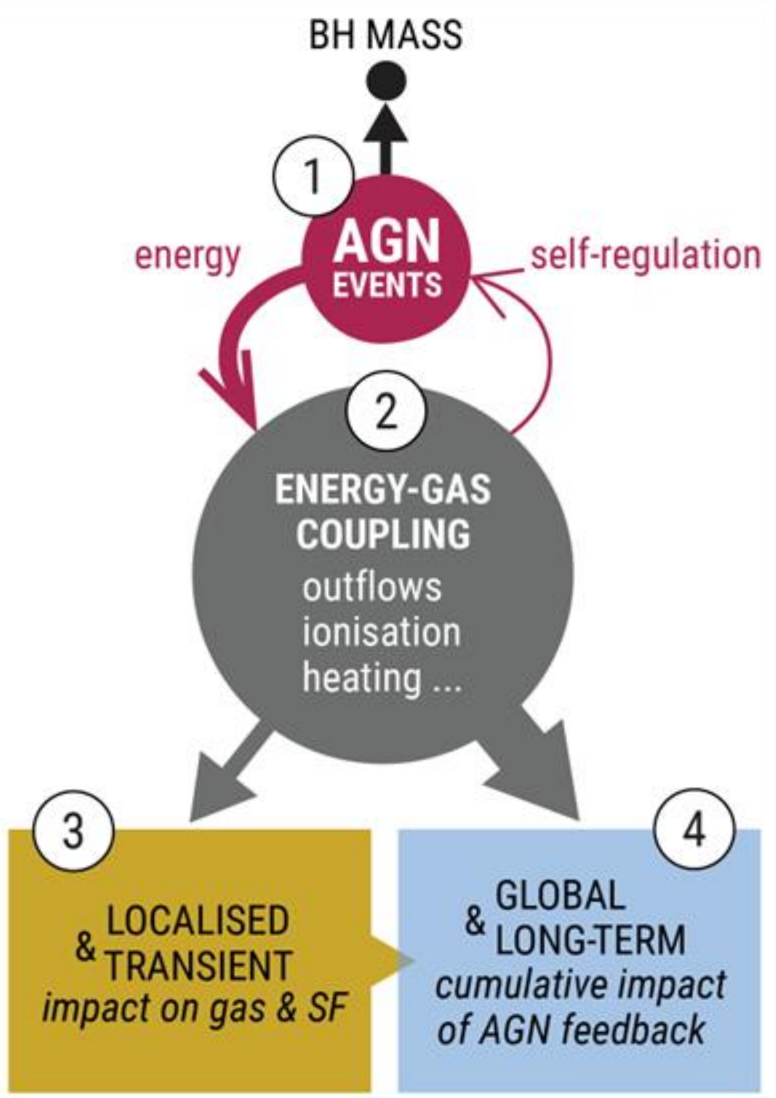


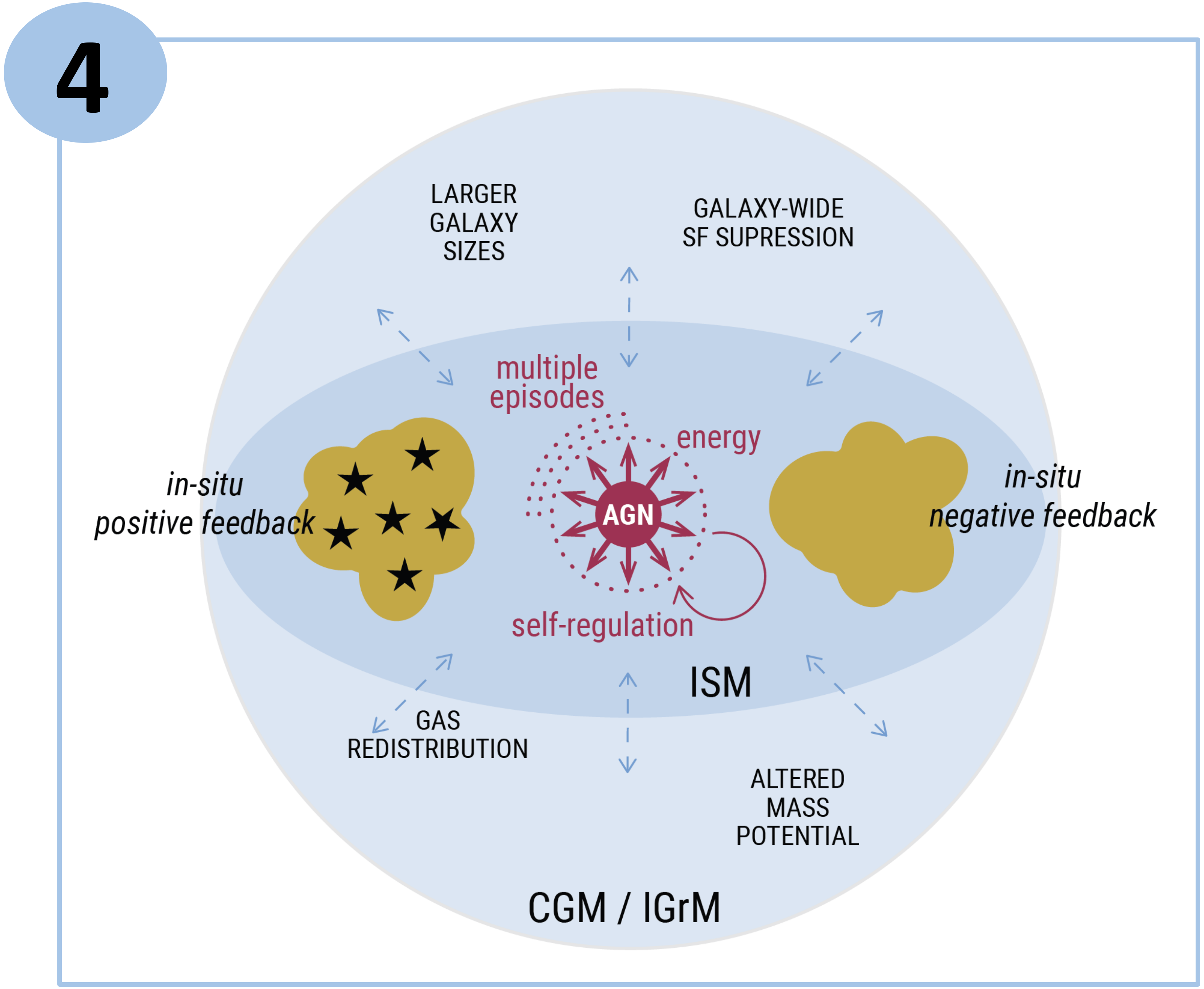


Harrison & Ramos Almeida 2024

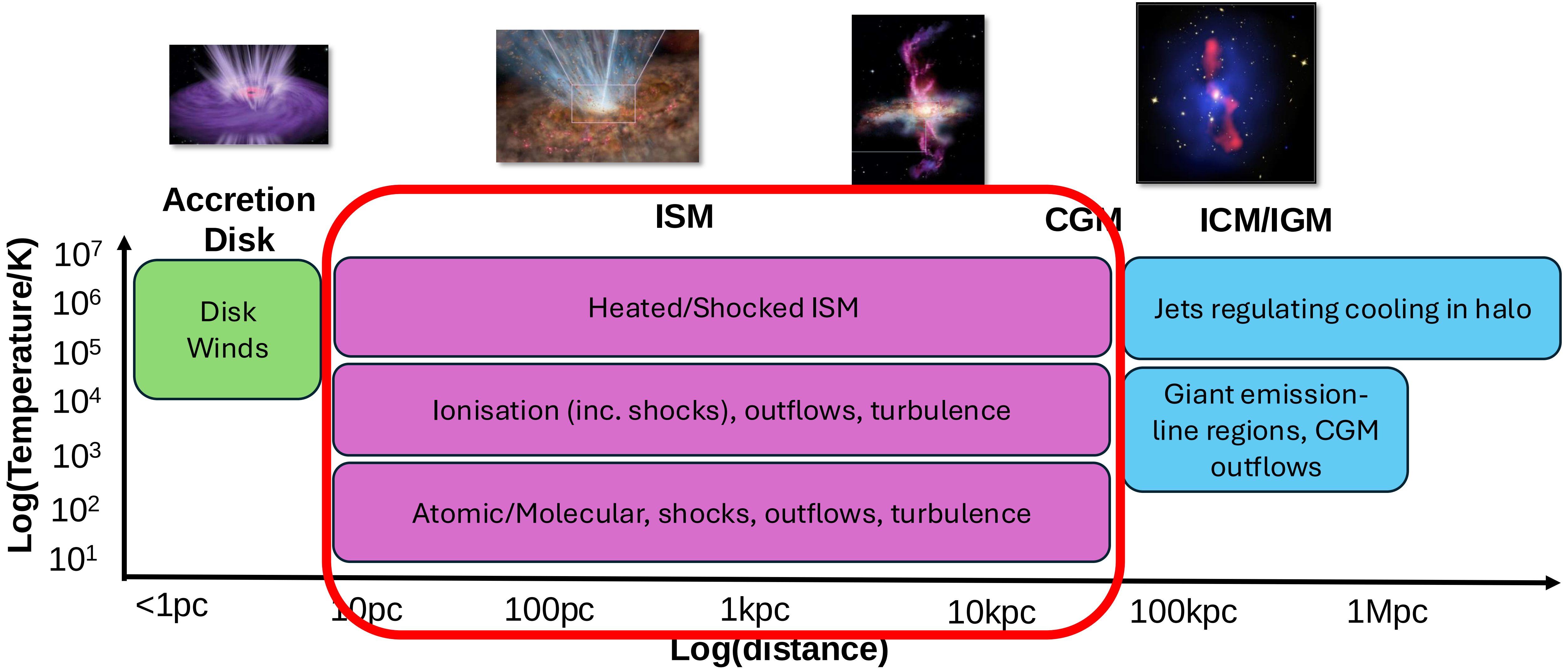




Harrison & Ramos Almeida 2024



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



In this talk...

Observational approaches/tests to AGN feedback

- ❑ Kinematics from emission and absorption lines: multi-phase outflows and gas turbulence
- ❑ Flux ratios: ionization/shocks/heating
- ❑ Infer potential impact indirectly: measure outflow rates, coupling efficiency
- ❑ "Direct" impact: measurements of gas content, star-formation and stellar populations

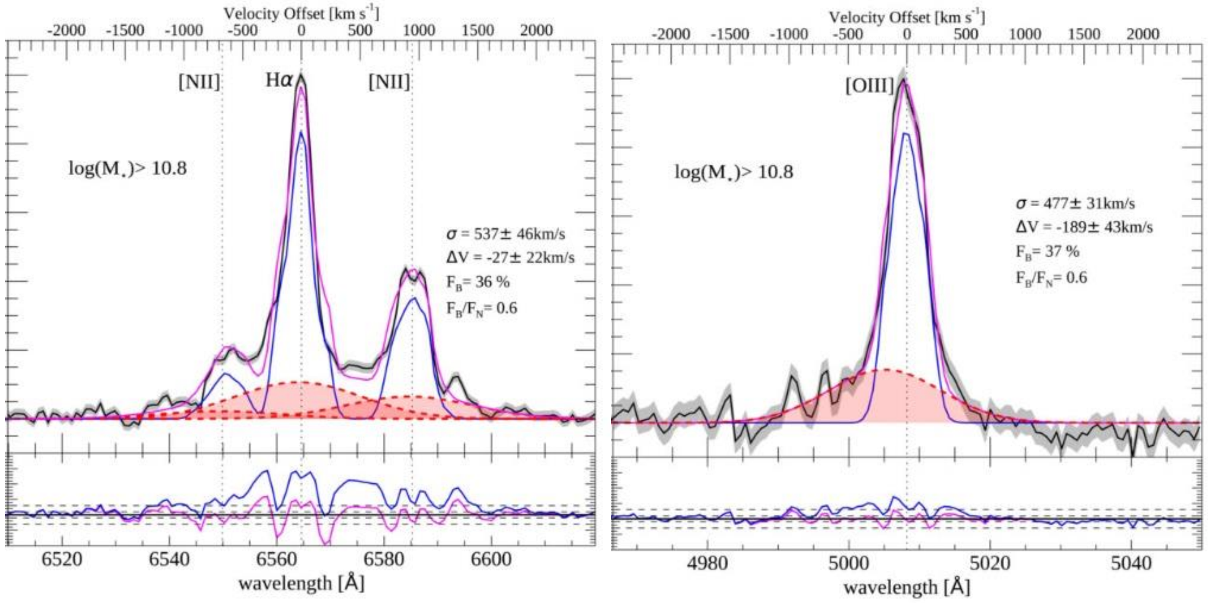
Jumping between z~0.1 and z~2

Theory

- ❑ "Observational experiments": what can we (not) learn from observed AGN outflow properties?

Extreme gas kinematics: statistical approach

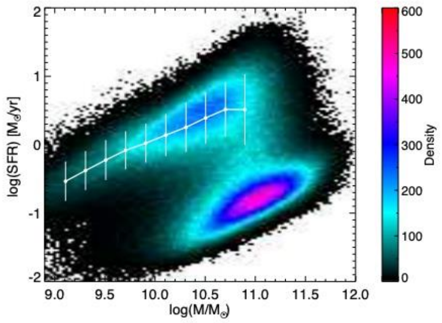
- AGN-driven ionized outflows dominated the most massive bin ($\log M_{star}>10.8\ M_{Sun}$)



Concas+22

141 MS galaxies at 1.2<z<2.6

z~0 SDSS



z~0.7

WAVES

4MOST surveys

f(M_{star}, SFR, density)

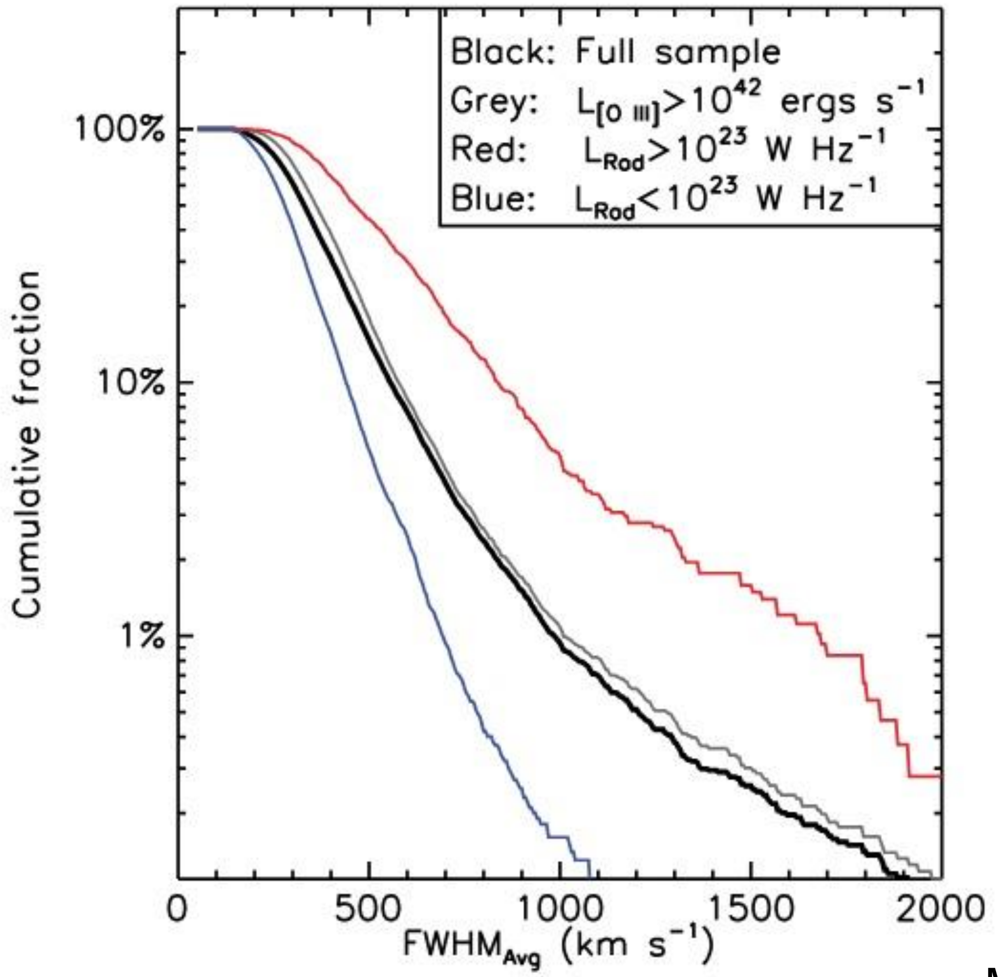
MOONS: z>1

Radio-ISM interaction

Extreme gas kinematics: statistical approach

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

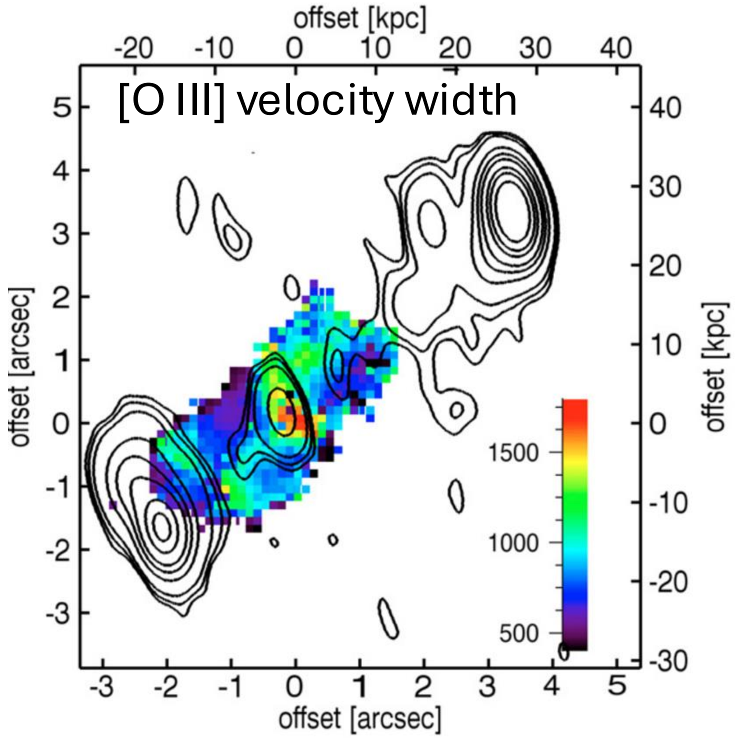
Also see, e.g., Zakamska & Greene 2014; Bischetti+17; Molyneux+19; Kukreti+23



Mullaney+13

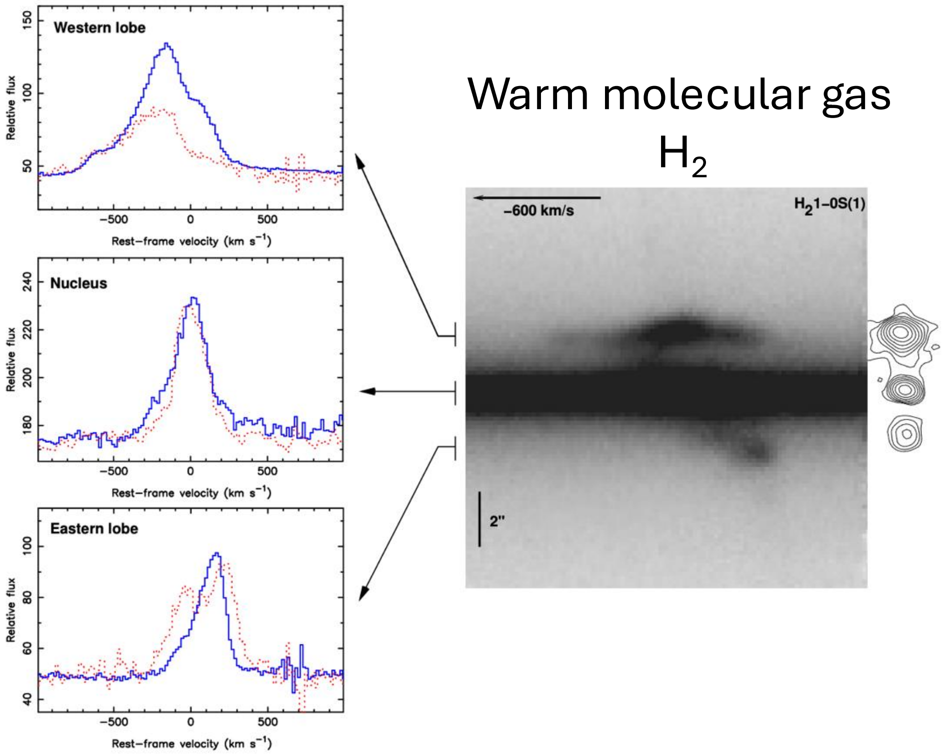
Extreme gas kinematics: individual studies

Nesvadba+08; z~2 powerful radio galaxy (and quasar)



Tahunter+14; z~0 Seyfert; moderate radio;

Warm molecular gas H_2

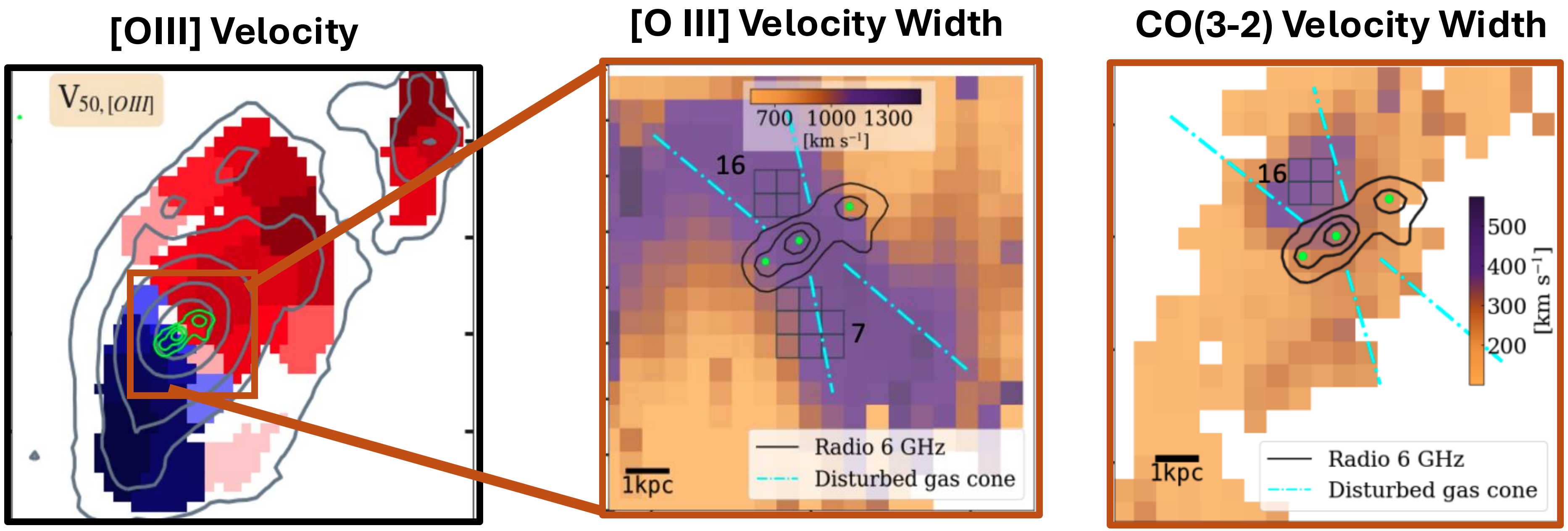


High velocities (and shocks/ionization) alignment with jets

Radio-ISM interaction

Extreme gas kinematics: individual galaxies (spatially resolved)

Girdhar et al. (2022); z~0.1 'radio quiet' quasar, ~1kpc 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

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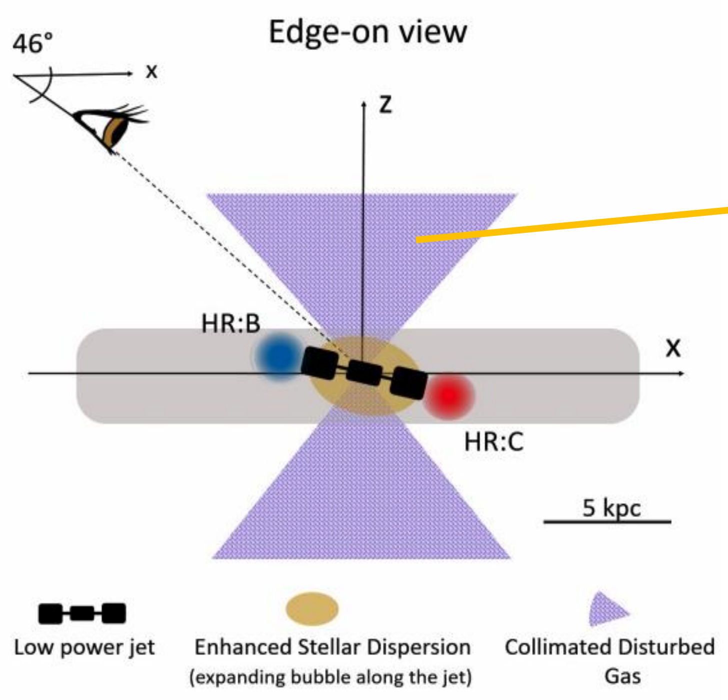

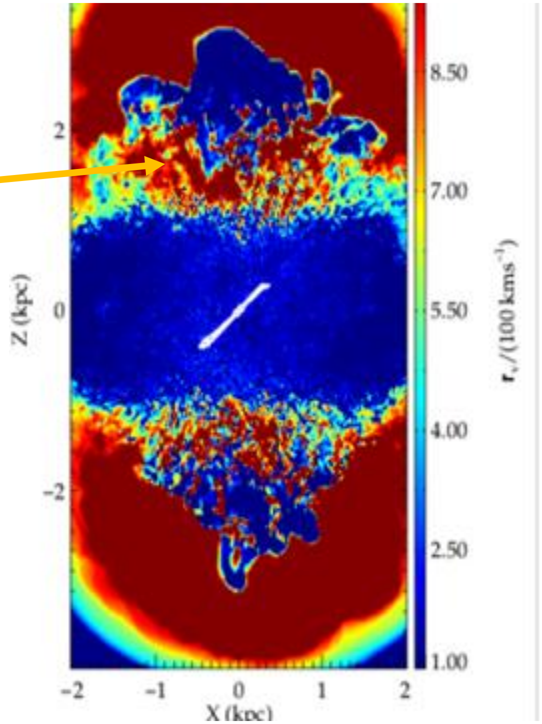

Mukherjee+18

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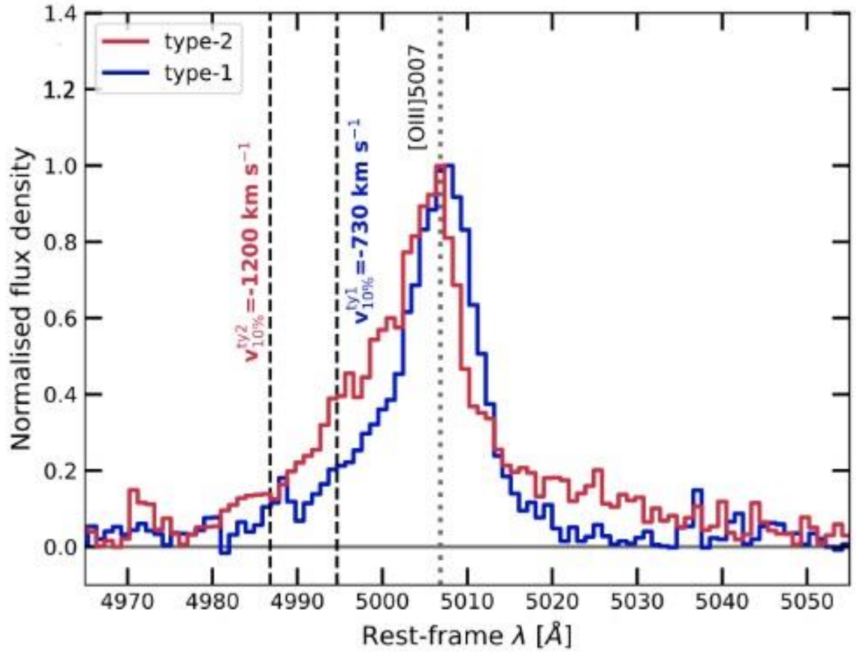
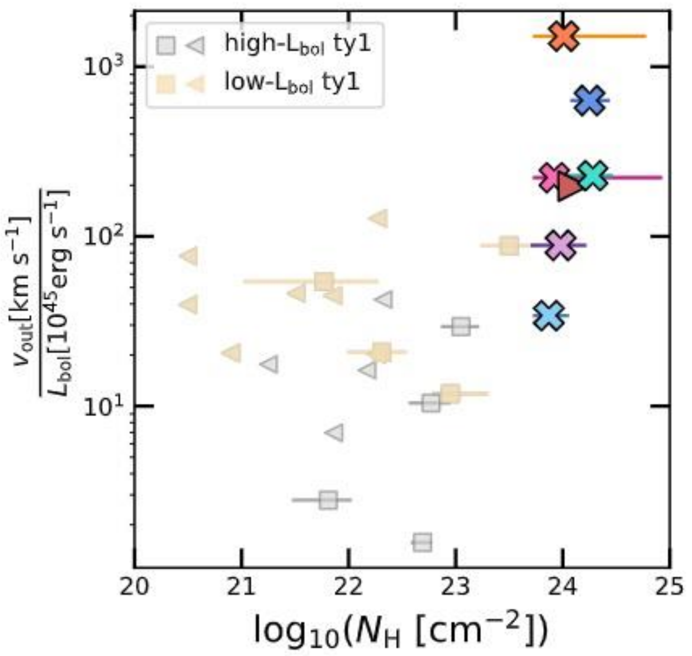
AGN feedback is multi-scale and multi-phase

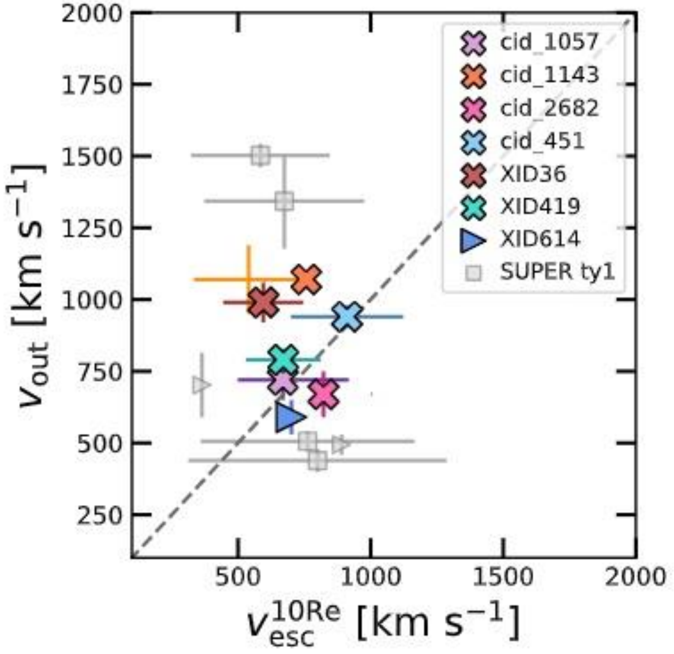
Extreme gas kinematics: statistical approach at z~2 (Tozzi+24, SUPER)

- 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



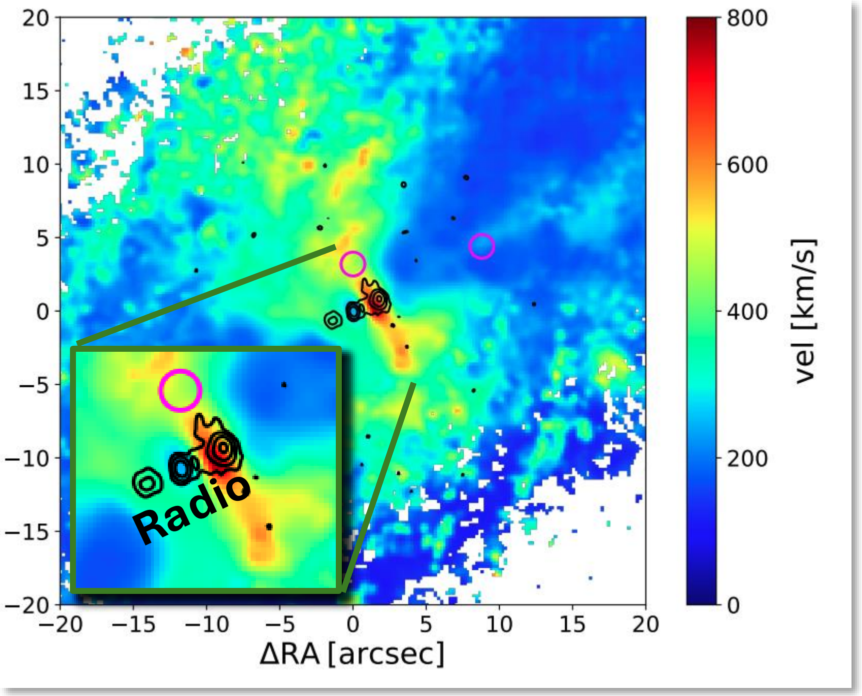




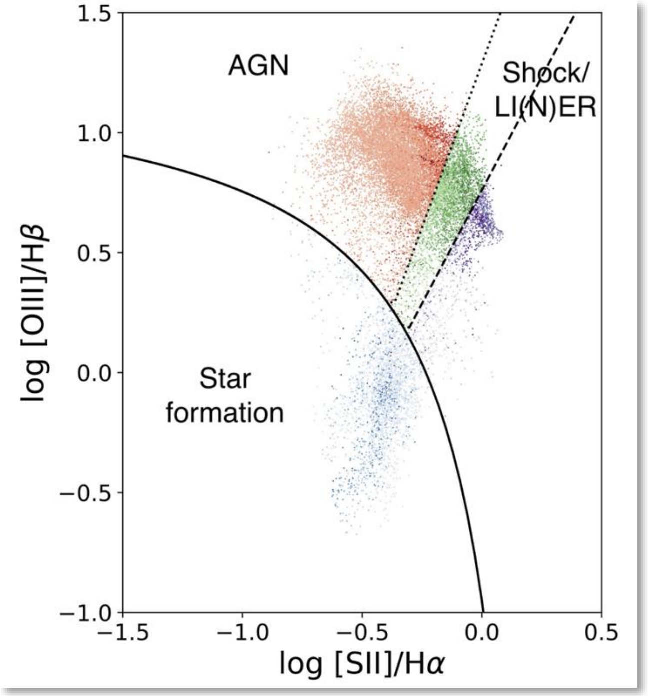
Ionization/shocks of ionized gas

- AGN-driven outflow (± 200-100 km/s) along the ionization cone
- Jet-disk interaction induces shock and increase the turbulence of the gas in perpendicular direction to the ionization cone and jet axis

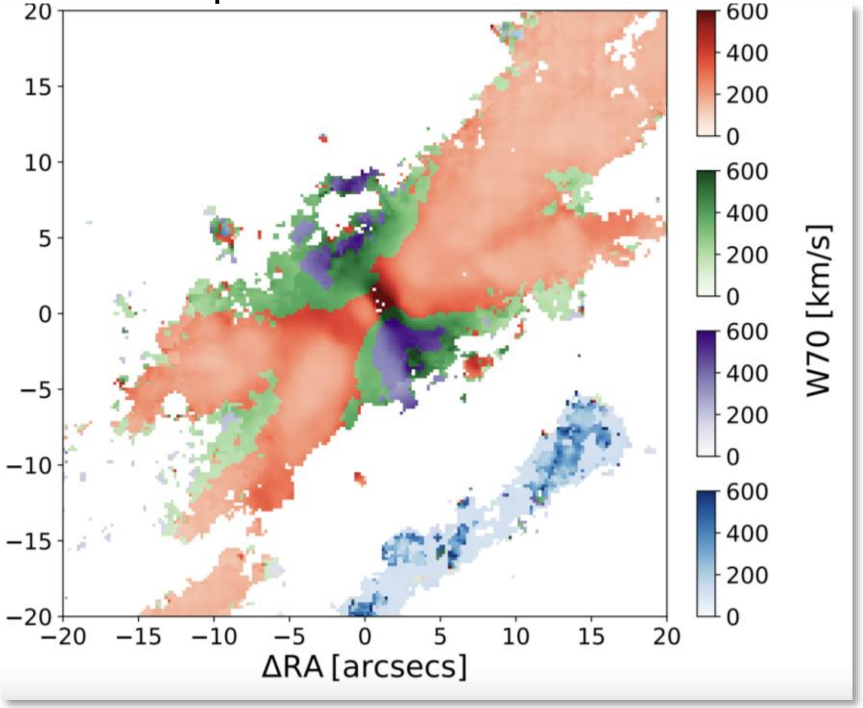
Velocity Width [OIII] W70



Emission-line ratios

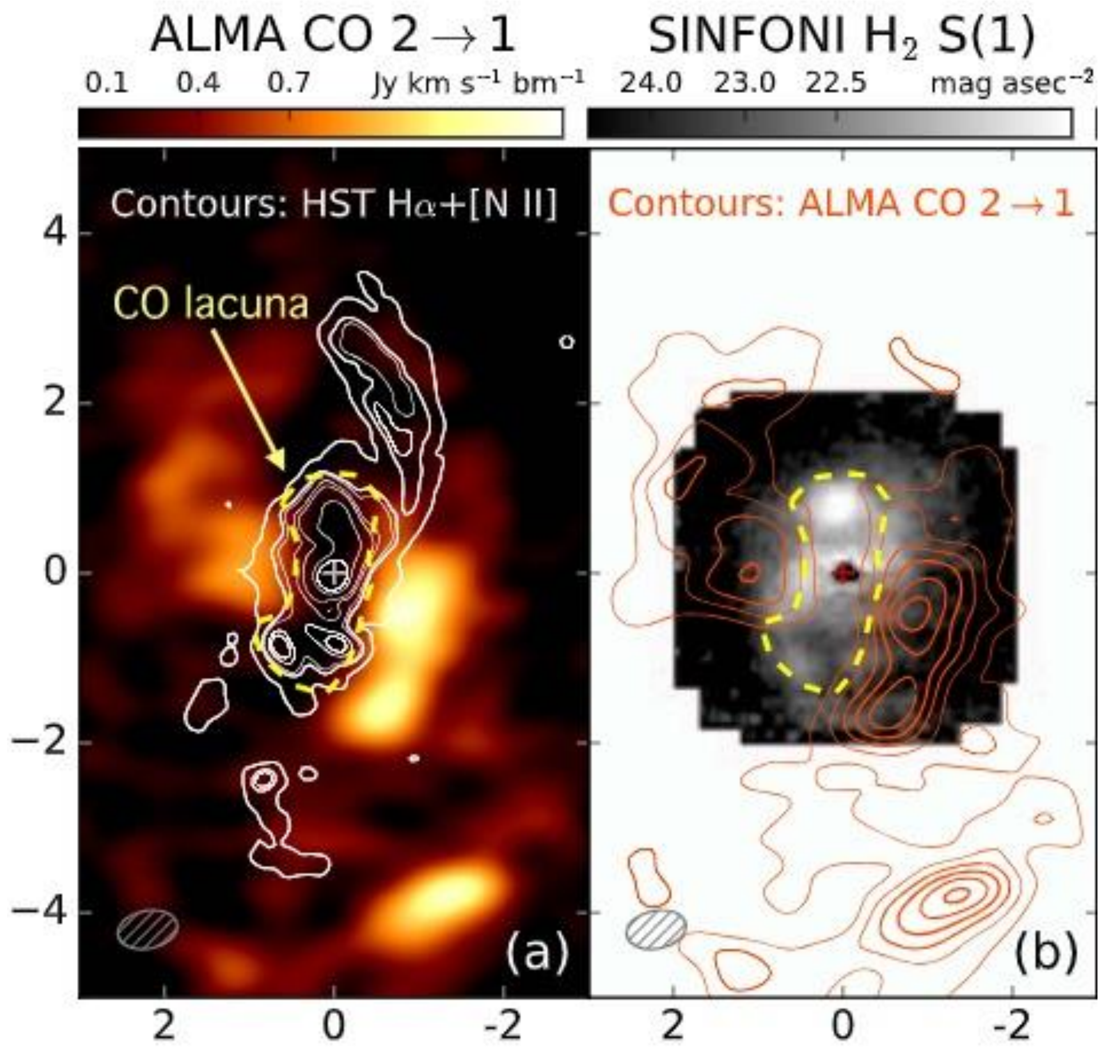


Map of ratios and widths



Venturi+21: IC 5063; z~0 Seyfert; low power jet in disk (MAGNUM survey)

Gas heating

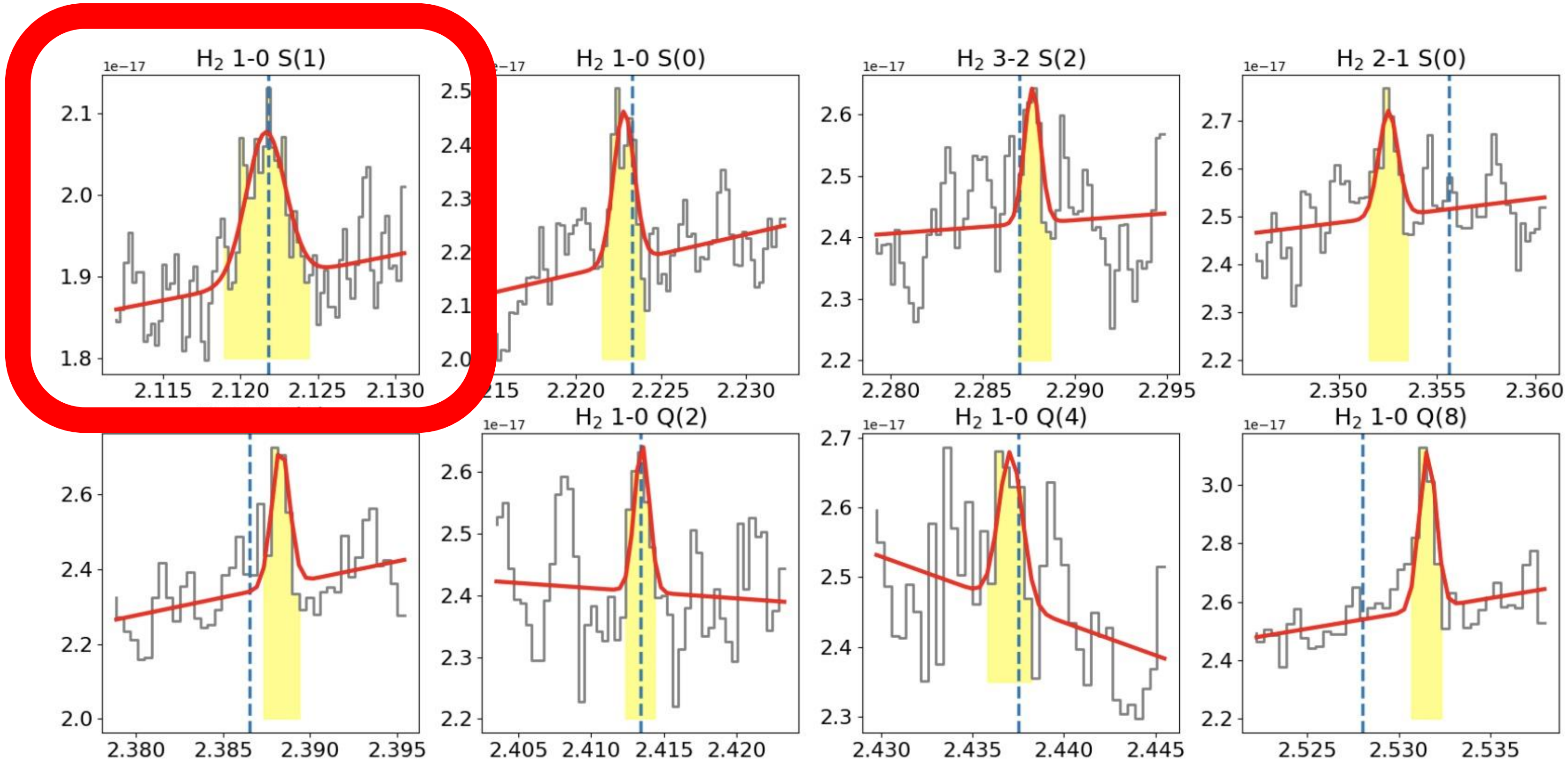


Rosario et al. 2019; NGC 2110; local Seyfert

- AGN radiation or AGN induced shocks deplete of CO (cold molecular gas) the circum-nuclear region

Also see e.g., Nesvadba+11; Riffel+15; Shimizu+19; Zovaro+19a,b; Santoro+20; Ramos Almeida+22; Murthy+22; Morganti+22; Ruffa+22

Warm molecular gas content and kinematics in AGN with ionized outflows
MIRI-MRS follow-up in Cy-1 and Cy-2 (SUPER; Kakkad et al. in prep)



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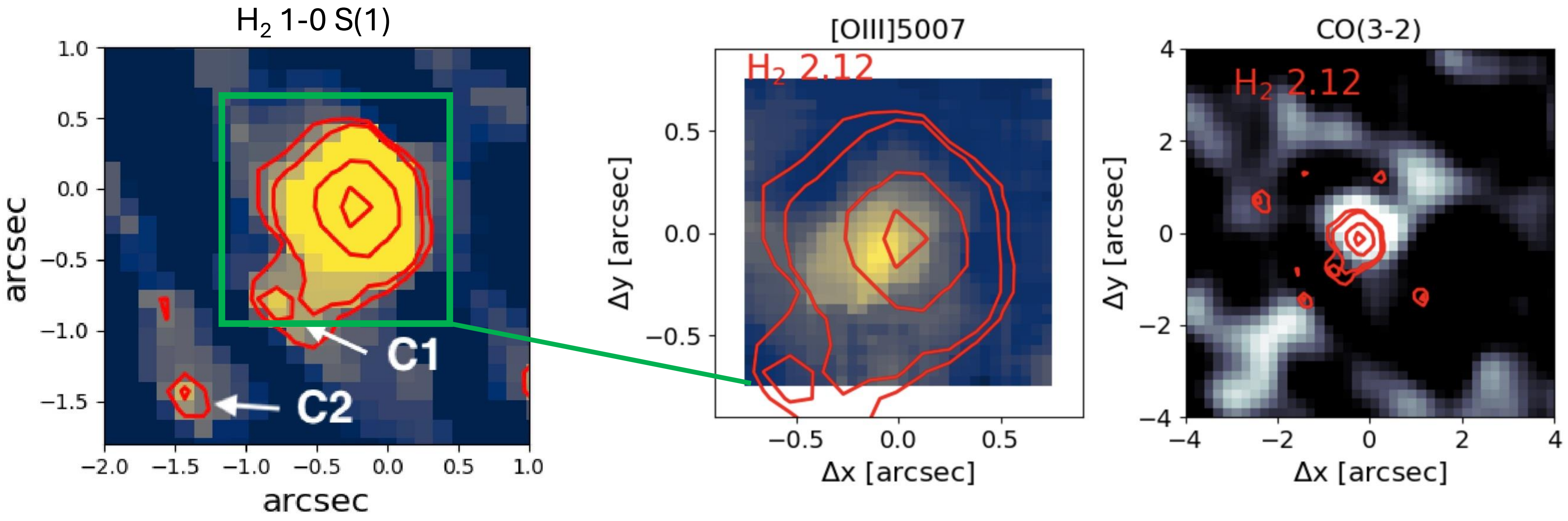

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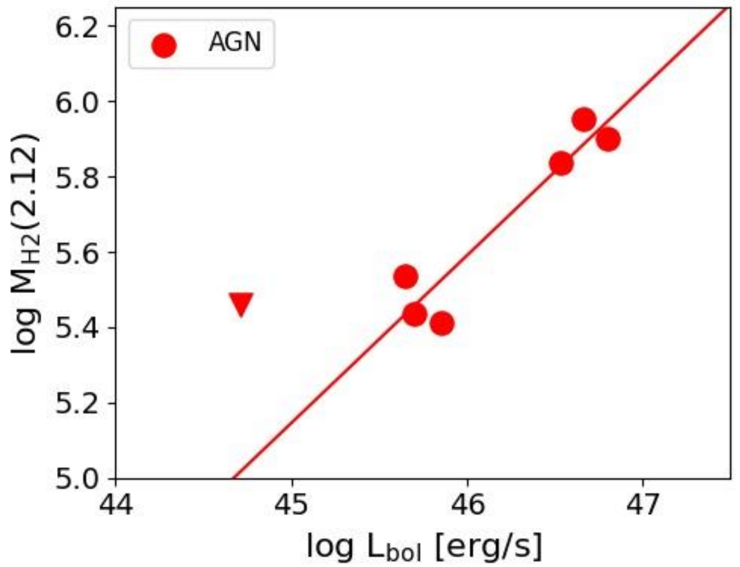
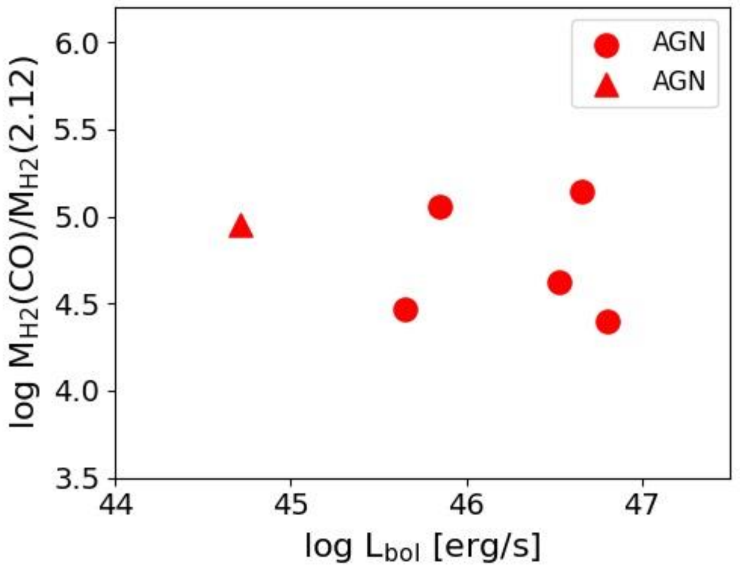
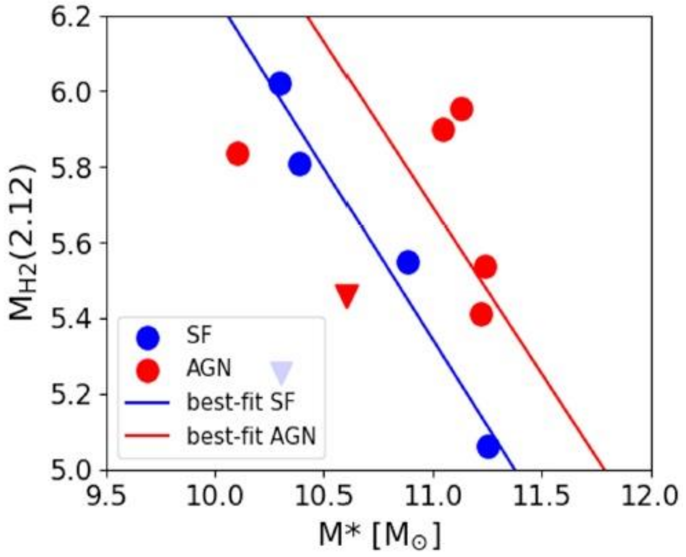
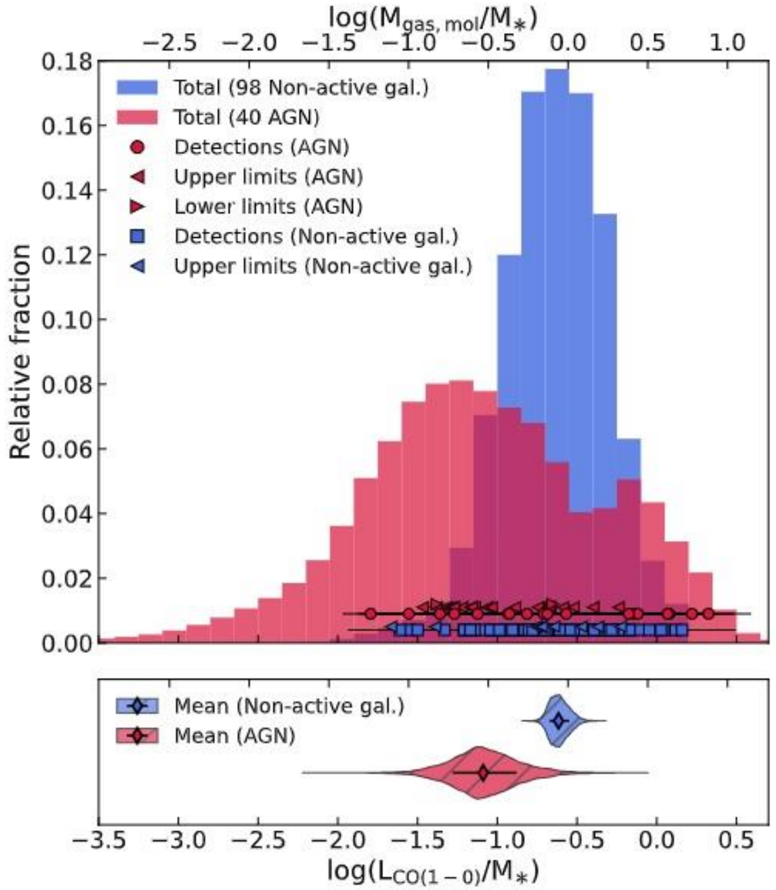


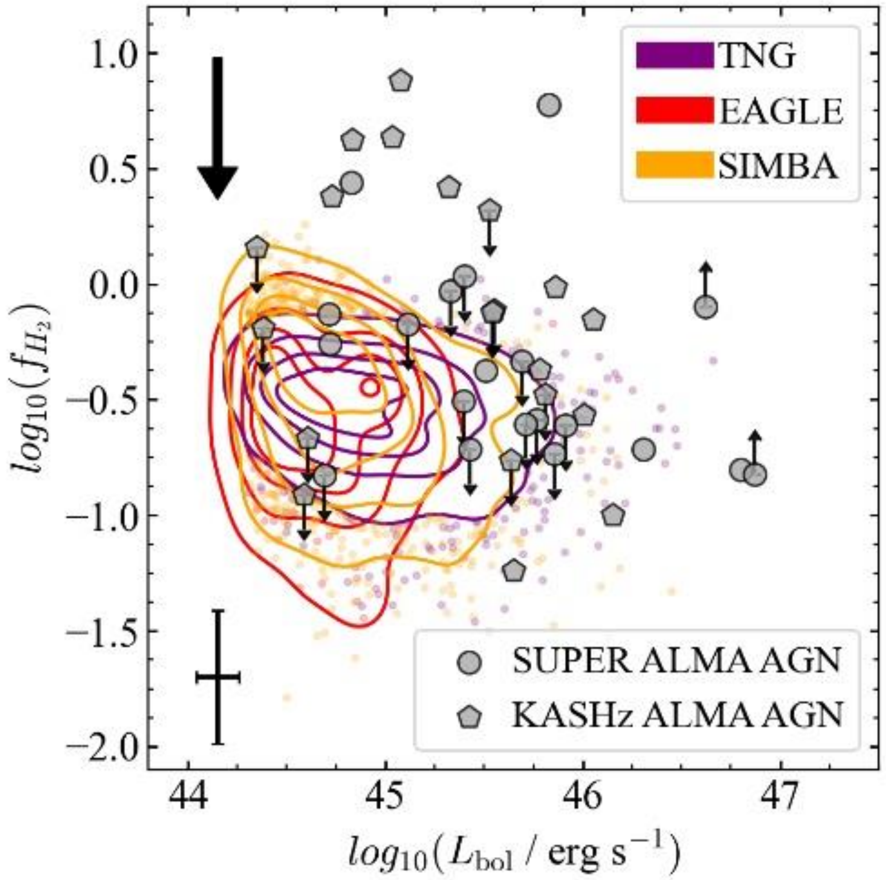




Cold molecular gas reservoir

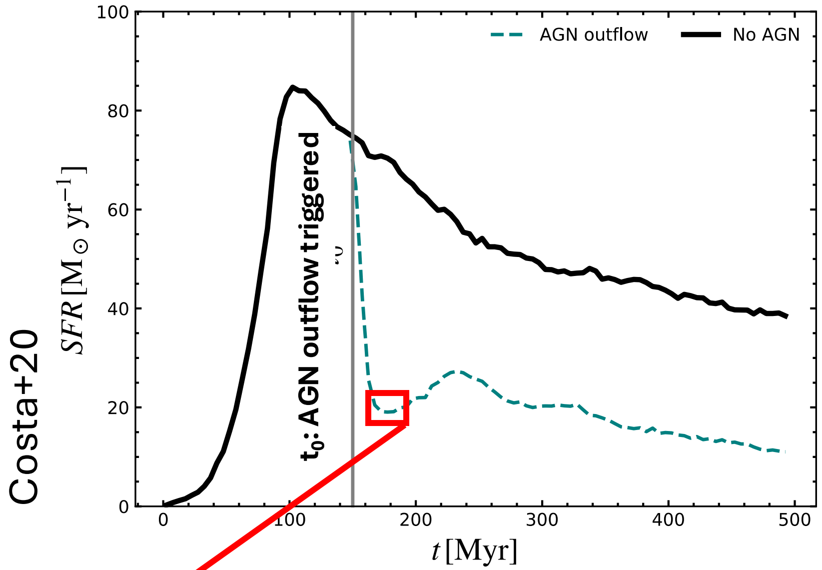
The molecular gas fraction in AGN and non-AGN galaxies are statistically different: AGN activity depleting the cold gas reservoirs? (SUPER+ KASHz; Bertola+24)

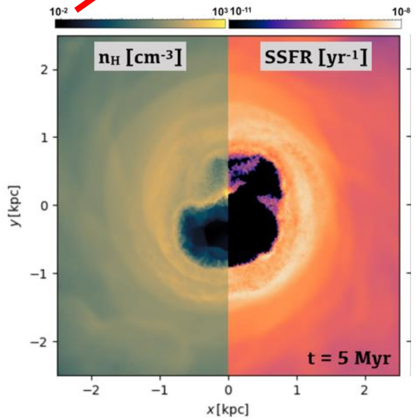


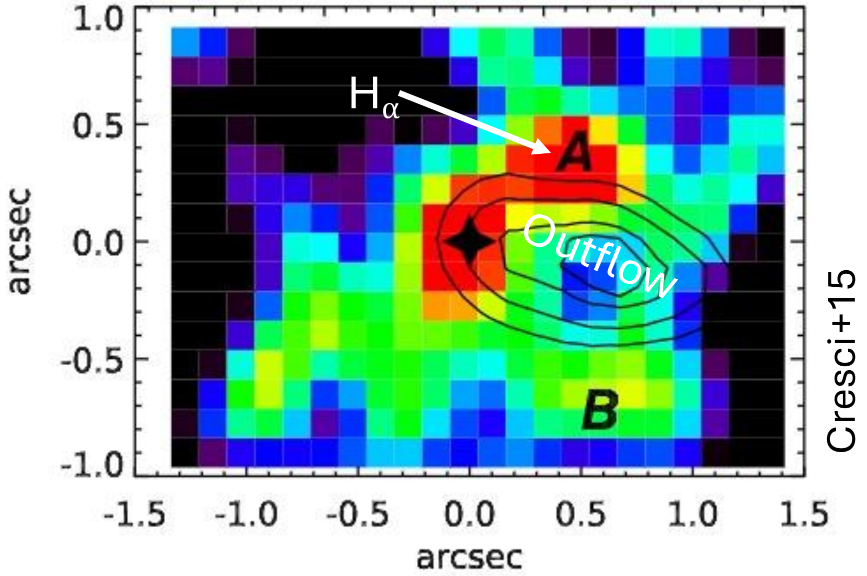


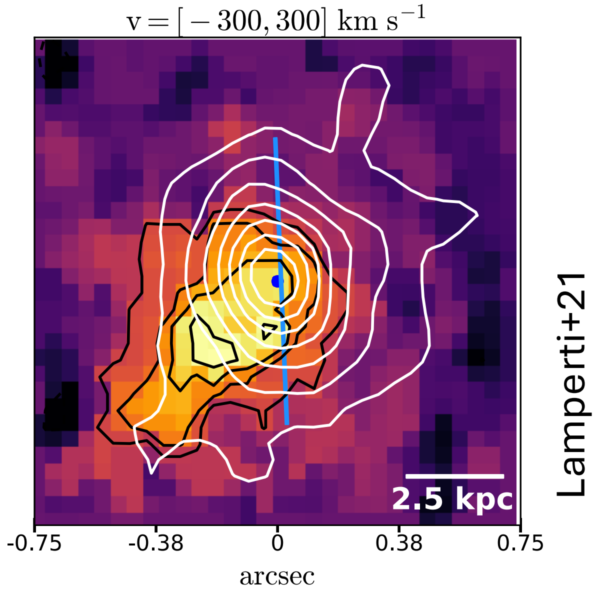
Also see e.g., Carniani+17; Brusa+18; Vietri+18; Perna+18; Loiaconoi+19; Bischetti+21; Frias Castillo+24

"Direct" impact on star-formation









SF as traced by narrow Hα removing the AGN contamination.

- The outflow is located in region with low SF (negative feedback?)
- Blobs of enhanced SF at the edge of the outflow (positive feedback?)

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

- Impact on scales below the resolution (~2 kpc)
- The wide time range sample may dilute recent (last Myrs) impact

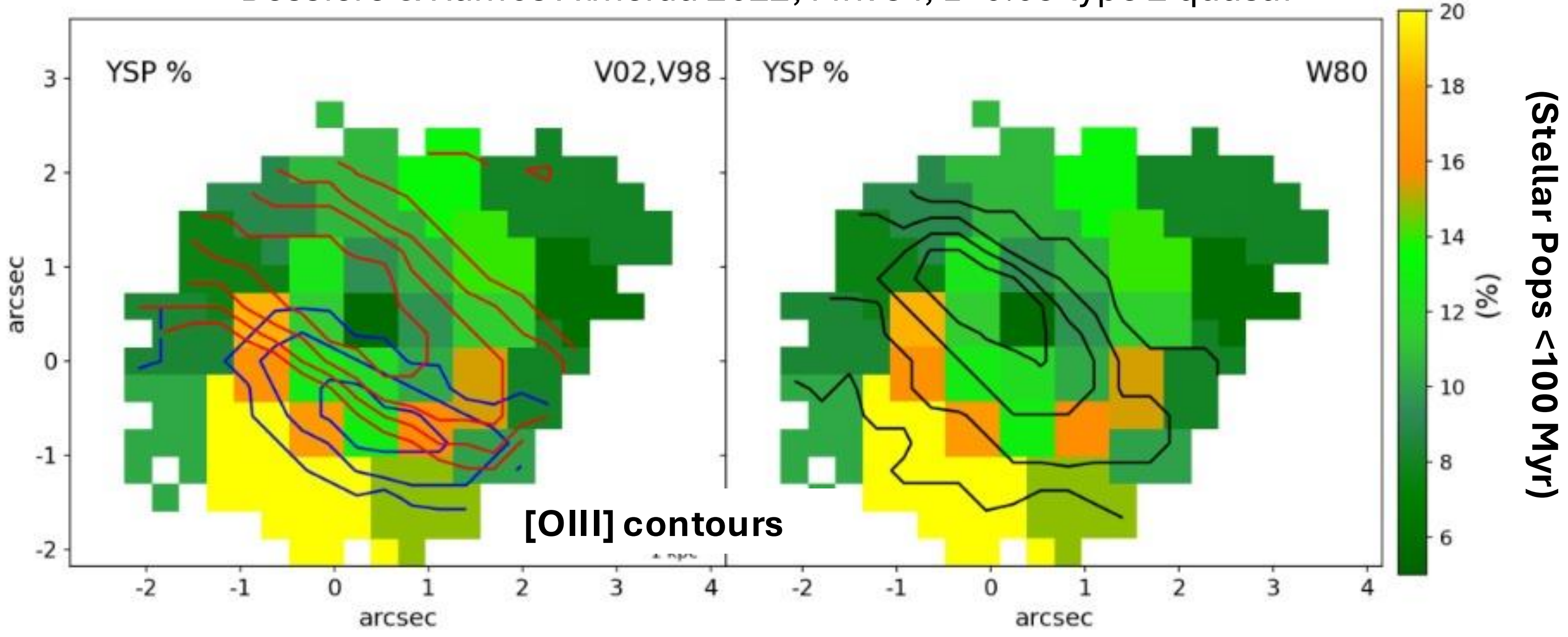
Also see e.g., Cano-Diaz+12; Carniani+16, but Balmaverde+16, Scholtz+21

“Direct” impact on star-formation

- Young Stellar Population (YSP, <100 Myr) enhance at the location of the highest blue-shifted velocities (positive feedback)

- YSP percentage not enhance in the location of highest gas turbulence (preventive feedback)

Bessiere & Ramos Almeida 2022; Mrk 34, z~0.05 type 2 quasar



Also see, e.g., Dey+97; Bicknell+00; Salomé+20; Cresci+15; Cresci & Maiolino 2018; Scholtz+20,21; Nesvadba+21; Girhdar+22; Capetti+22; Venturi+23

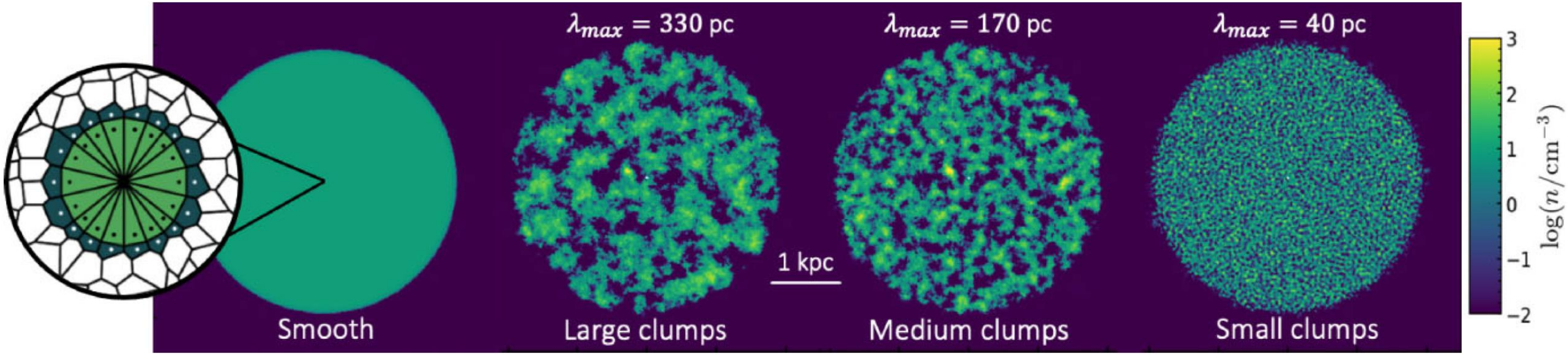
How do we tackle this complex topic?

“Observational experiments”

AGN Feedback Model → Idealised, hydro-simulations, measure outflow properties “like an observer” → What can we learn from observed properties?

Ward, Costa, Harrison & Mainieri (2024)

Inject quasar winds into galaxy disks



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

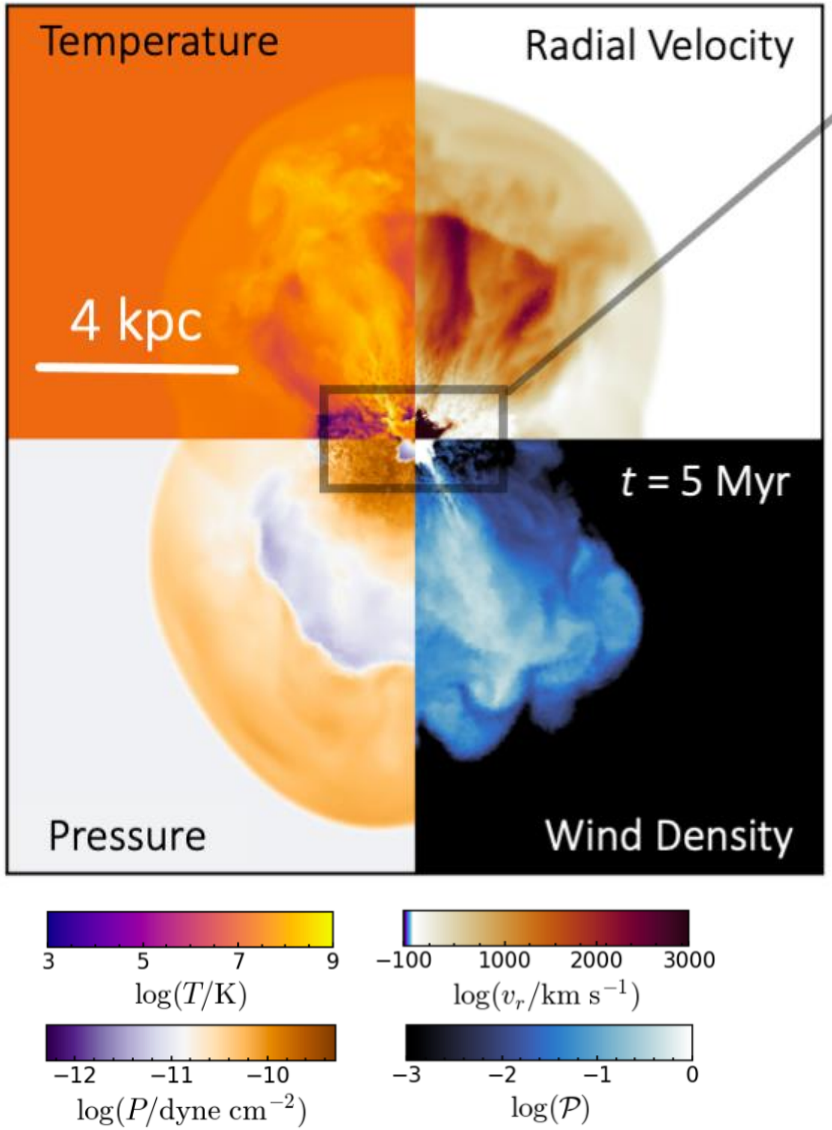
$$\dot{E}_w = \frac{v_w}{2c} L_{AGN}$$

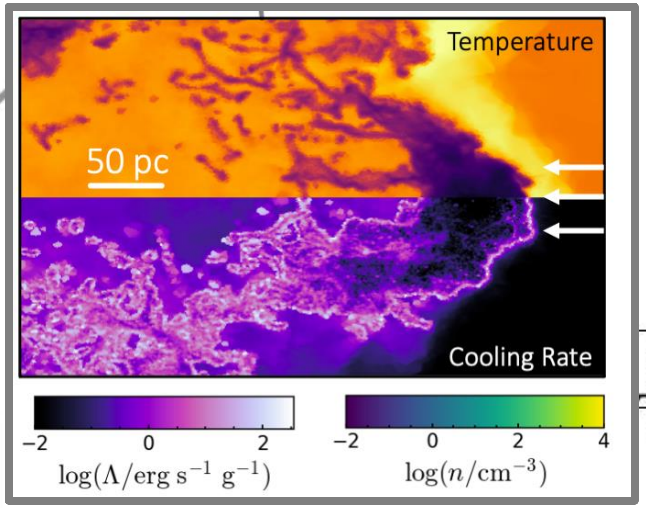
Fiducial model:
$L_{AGN} = 10^{45}$ erg/s
$V_w = 10^4$ km/s
Disk: d=4kpc, h=1kpc

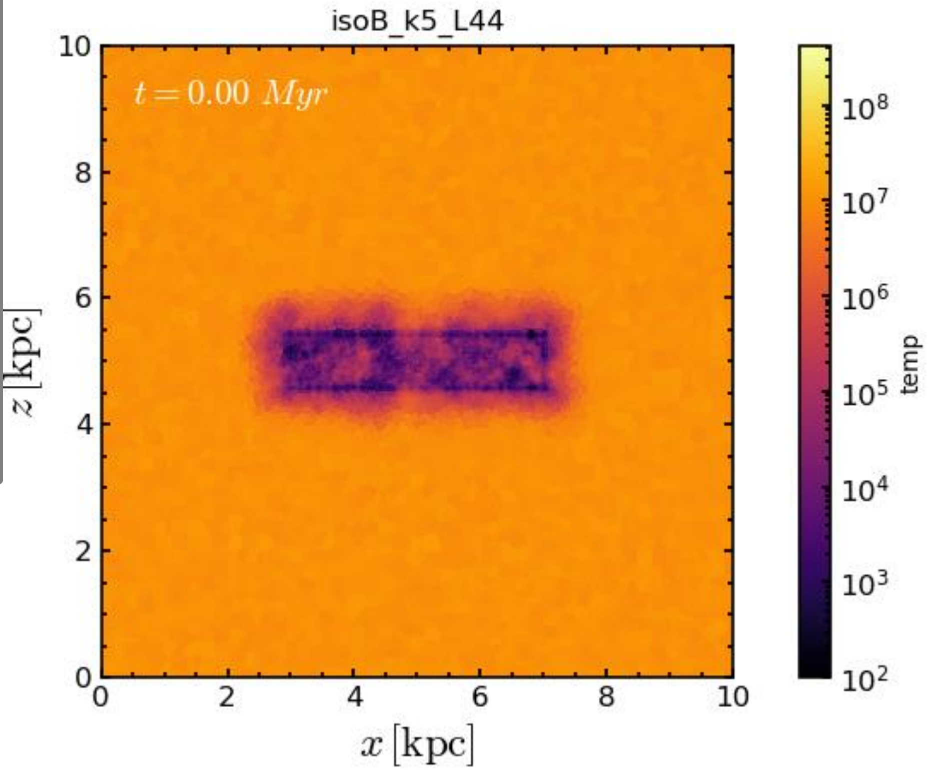
Hydro-code: AREPO:
Resolution: reaches ~1pc
Includes primordial cooling

Ward, Costa, Harrison & Mainieri (2024)

Outflows “vents” through paths of least resistence





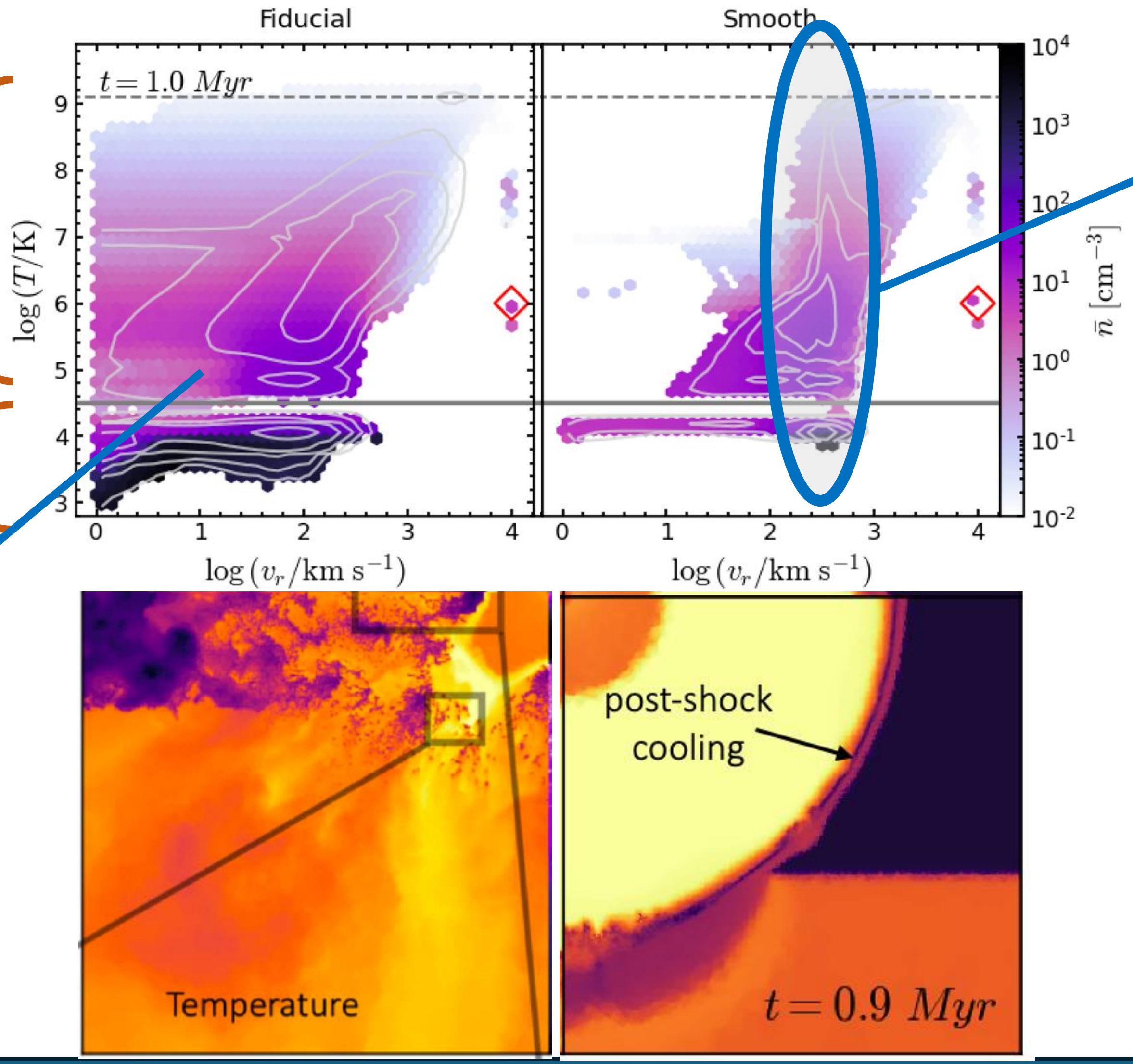


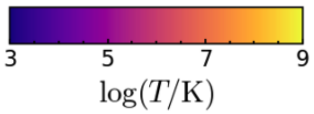
- Large-scale collimated outflow (wind injected spherically on small scales)
- Cold clumps inside hot diffuse outflow

Realistic ISM leads to very different predictions

"Hot"
(hot, invisible or X-ray emitting gas)

"Cold"
(warm ionized outflows, cold molecular outflows...)





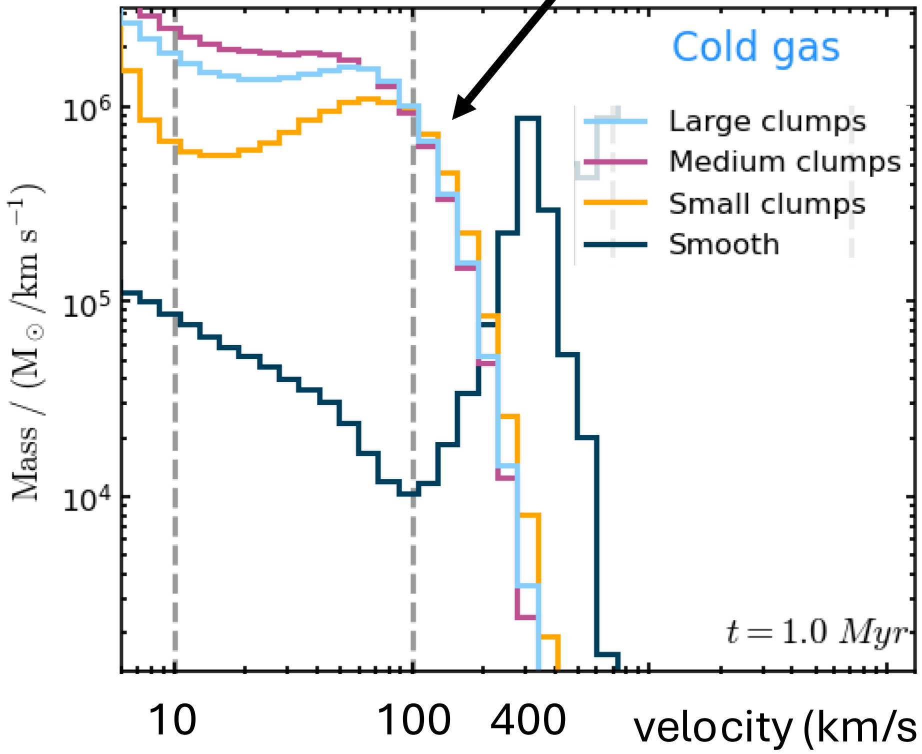
Well defined
v_{OF}
in all phases

No characteristic
v_{OF}

Ward, Costa, Harrison & Mainieri (2024)

Challenges in defining outflow velocities

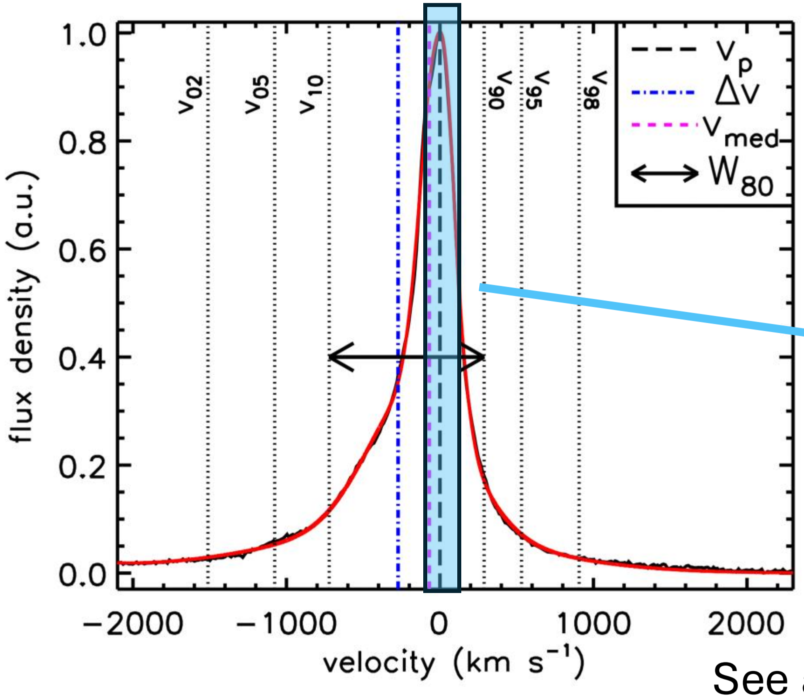
Clumpy disks: No characteristic velocity
A lot of **outflowing** mass at low velocities



Ward, Costa, Harrison & Mainieri (2024)

$$M_{\rm OF} = \sum_{i}^{\text{for } v_i > v_{\rm min}} m_i$$

v_{min} = 10 km/s (physical & “complete”)
v_{min} = 100 km/s (representative observational limit)

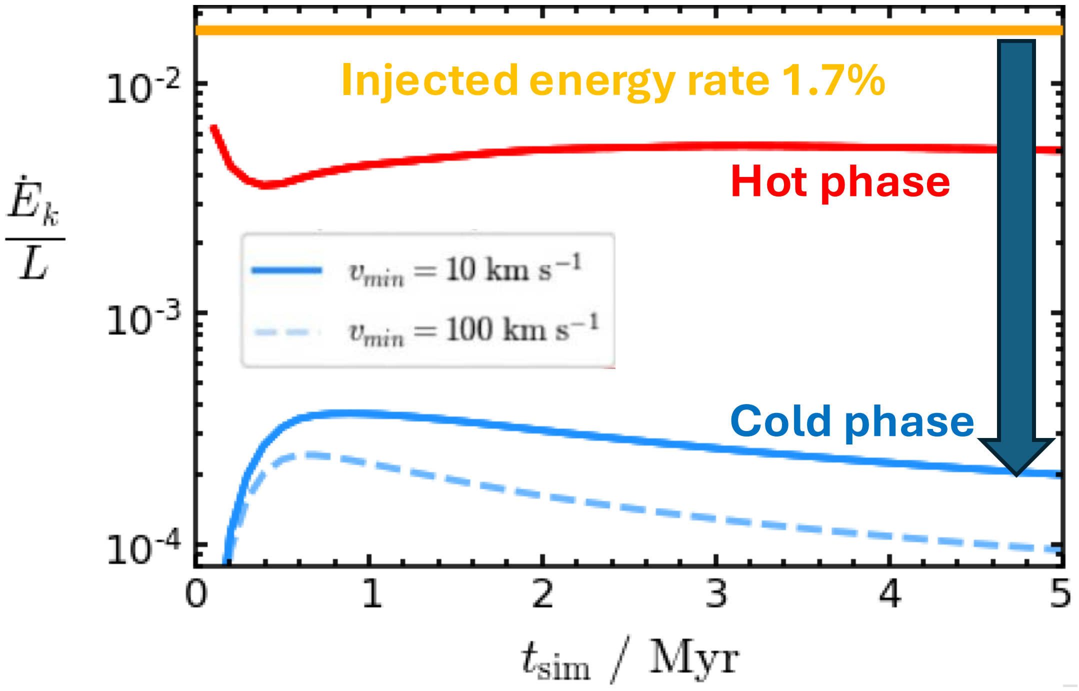


Observationally, extremely hard to de-couple from host-galaxy dynamics

See also Marconcini+23

Challenges interpreting kinetic powers

How efficiently the AGN wind couples to the ISM?



Low measured kinetics coupling efficiencies:

- Energy losses (gravitational work, radiative cooling)
- Missing phases

Observed kinetic coupling efficiencies may provide limited information on potential impact!

Note: "Feedback Efficiencies" in cosmological feedback models are NOT the same as kinetic coupling efficiencies.

Ward, Costa, Harrison & Mainieri (2024)

Take away messages

- 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”