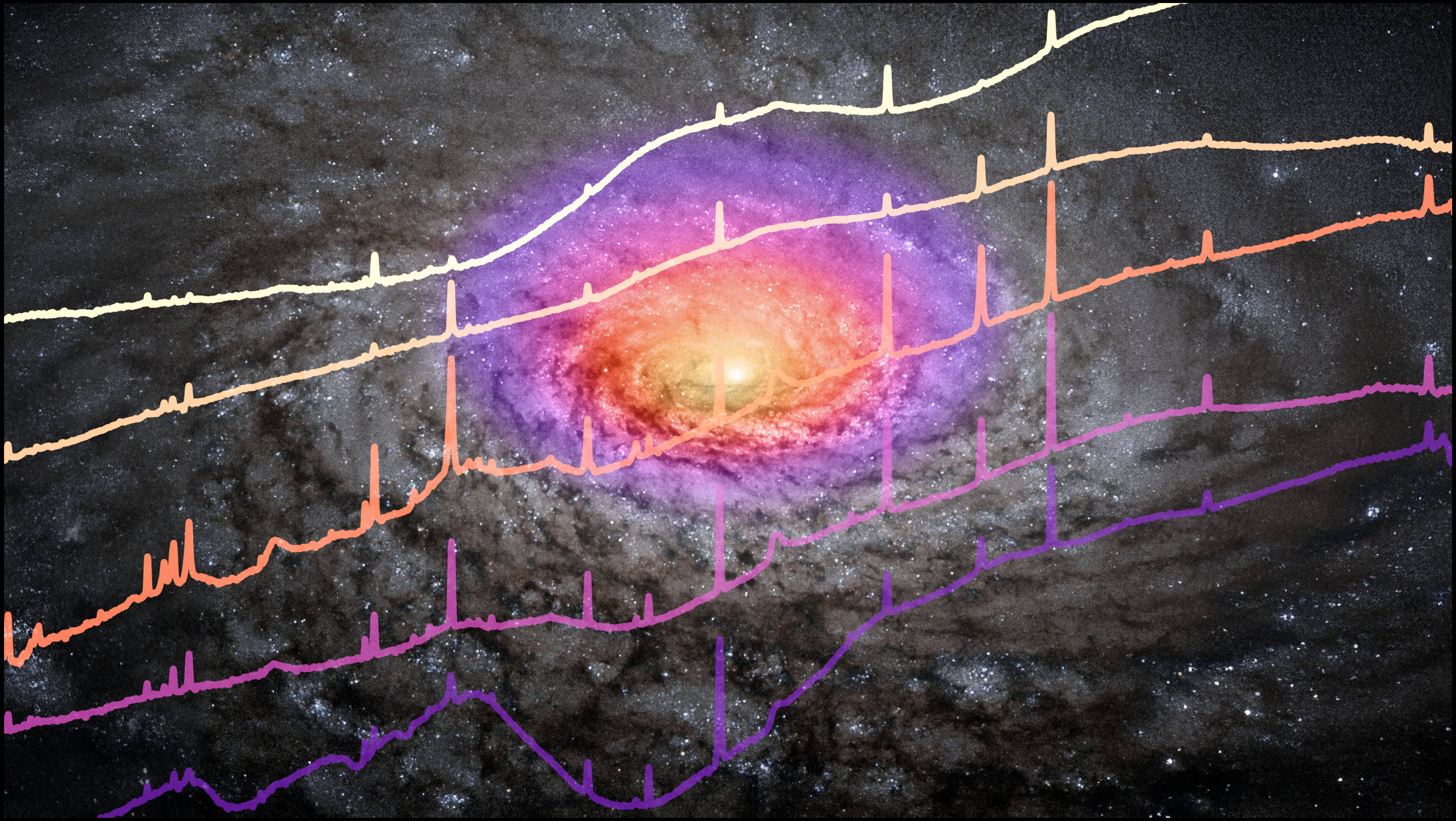
# Multi-wavelength observations of AGN feedback



Cristina Ramos Almeida
Instituto de Astrofísica de Canarias (IAC)

QSOFEED
quasar feedback project

Review

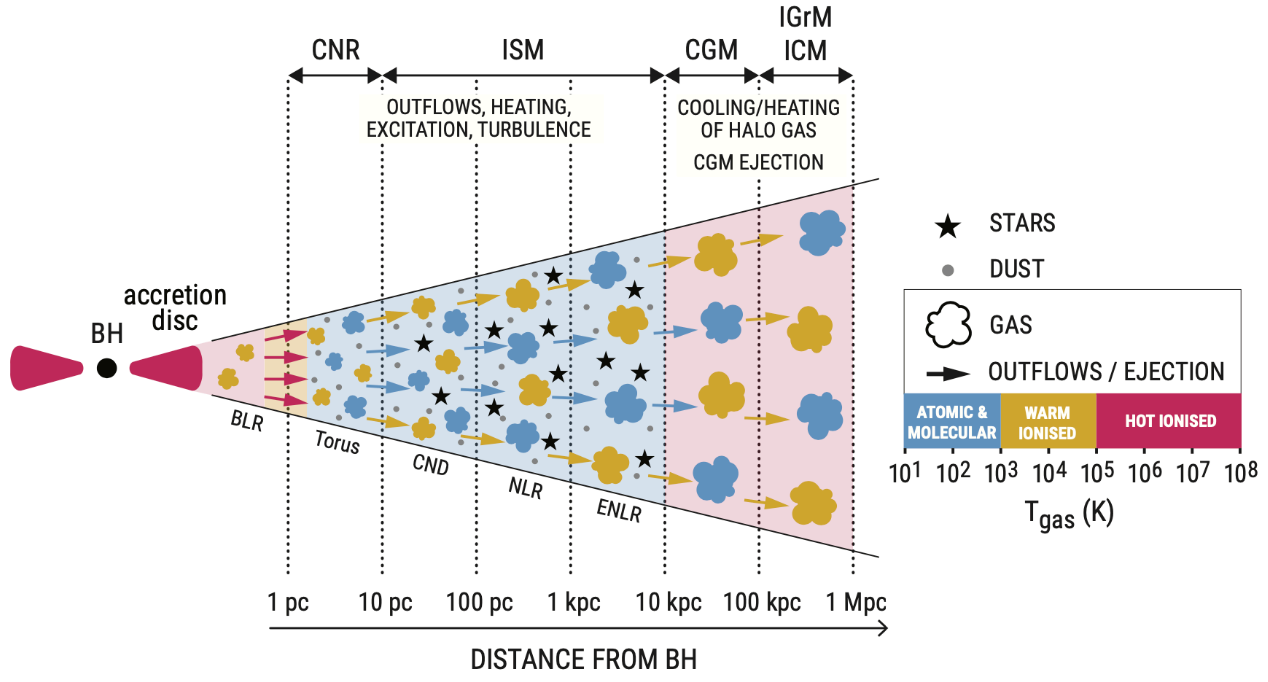
# Observational Tests of Active Galactic Nuclei Feedback: An Overview of Approaches and Interpretation

Chris M. Harrison and Cristina Ramos Almeida

## Special Issue

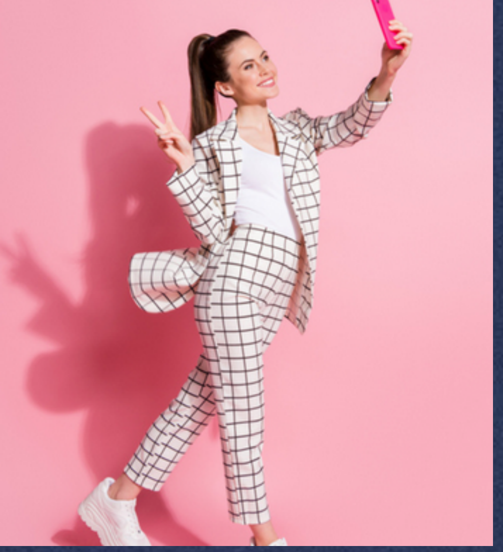
Multi-Phase Fueling and Feedback Processes in Jetted AGN

Edited by
Dr. Isabella Prandoni and Dr. Ilaria Ruffa




MDPI

https://doi.org/10.3390/galaxies12020017



# Why did AGN become so popular?

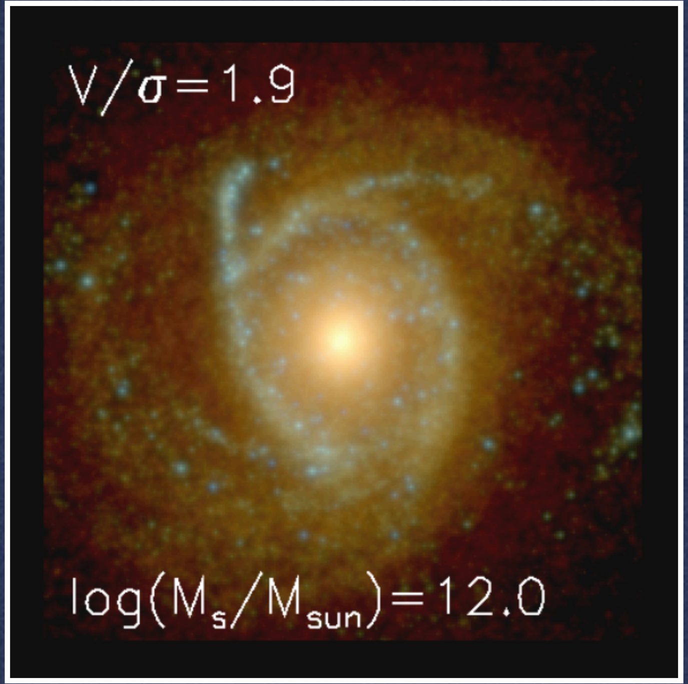
AGN feedback

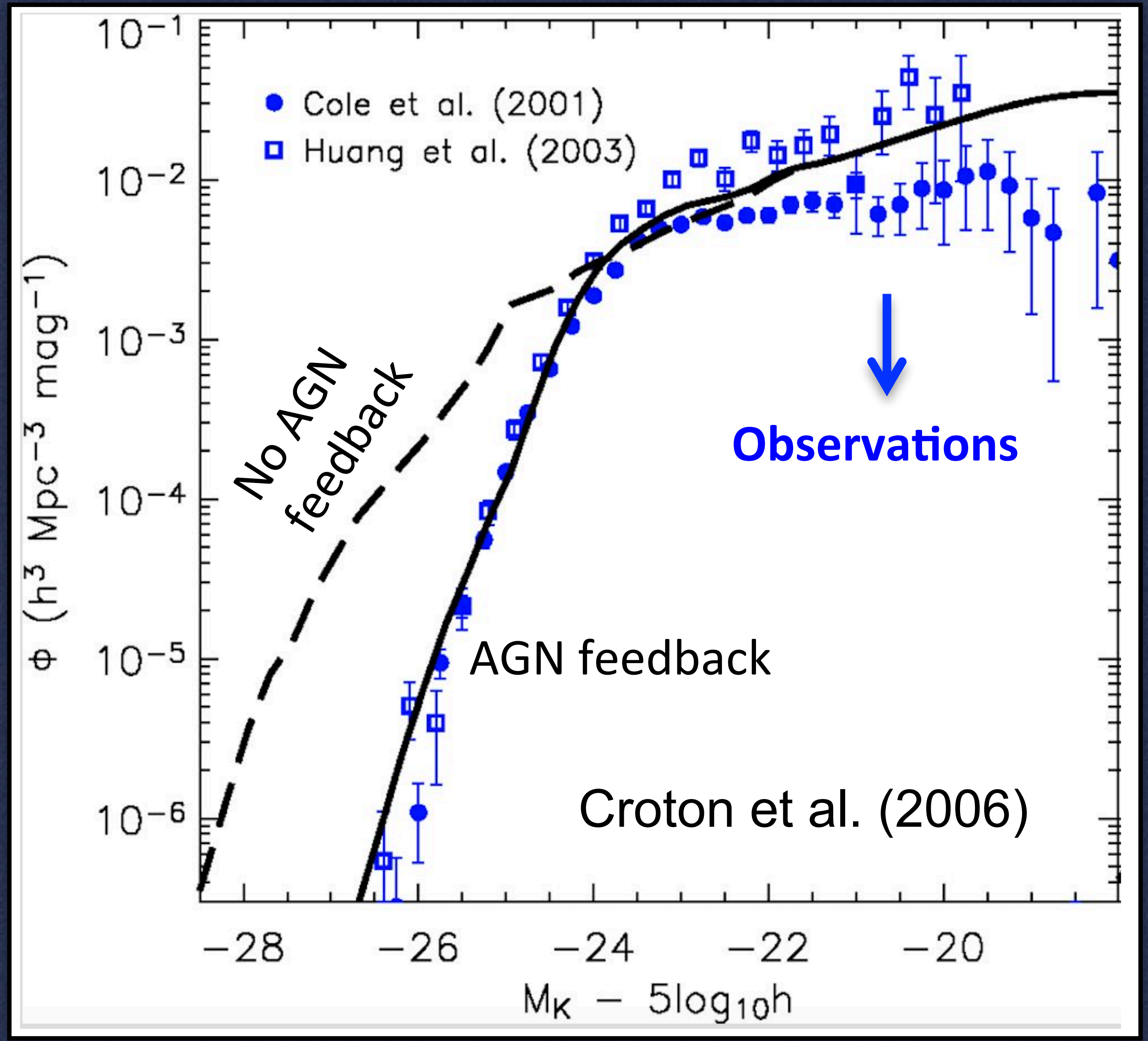
1) Observed correlations between BH mass and galaxy properties (Magorrian+98; Ferrarese+00)

2) Lower-than-expected rate of gas cooling identified around the most massive galaxies (Binney+95)

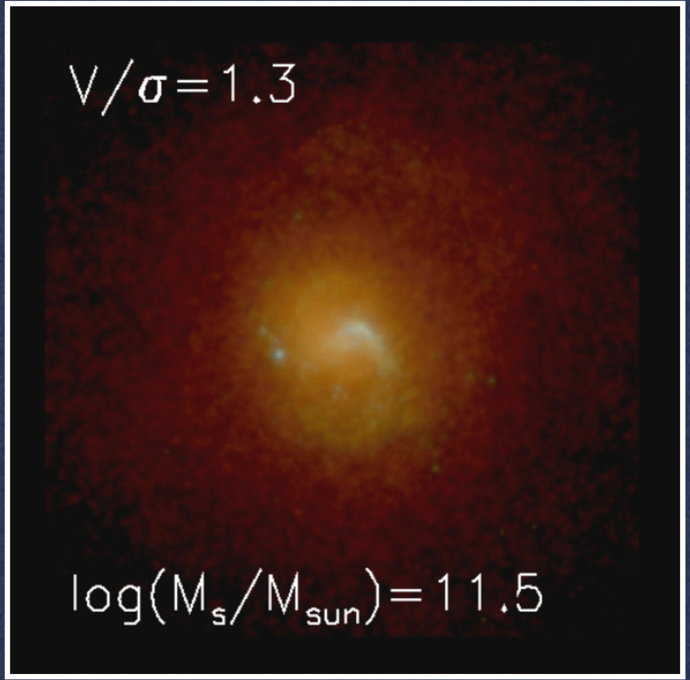
3) Simulations require AGN feedback for producing realistic numbers of massive galaxies and color bi-modality (Benson+03, Springel05).

AGN feedback OFF



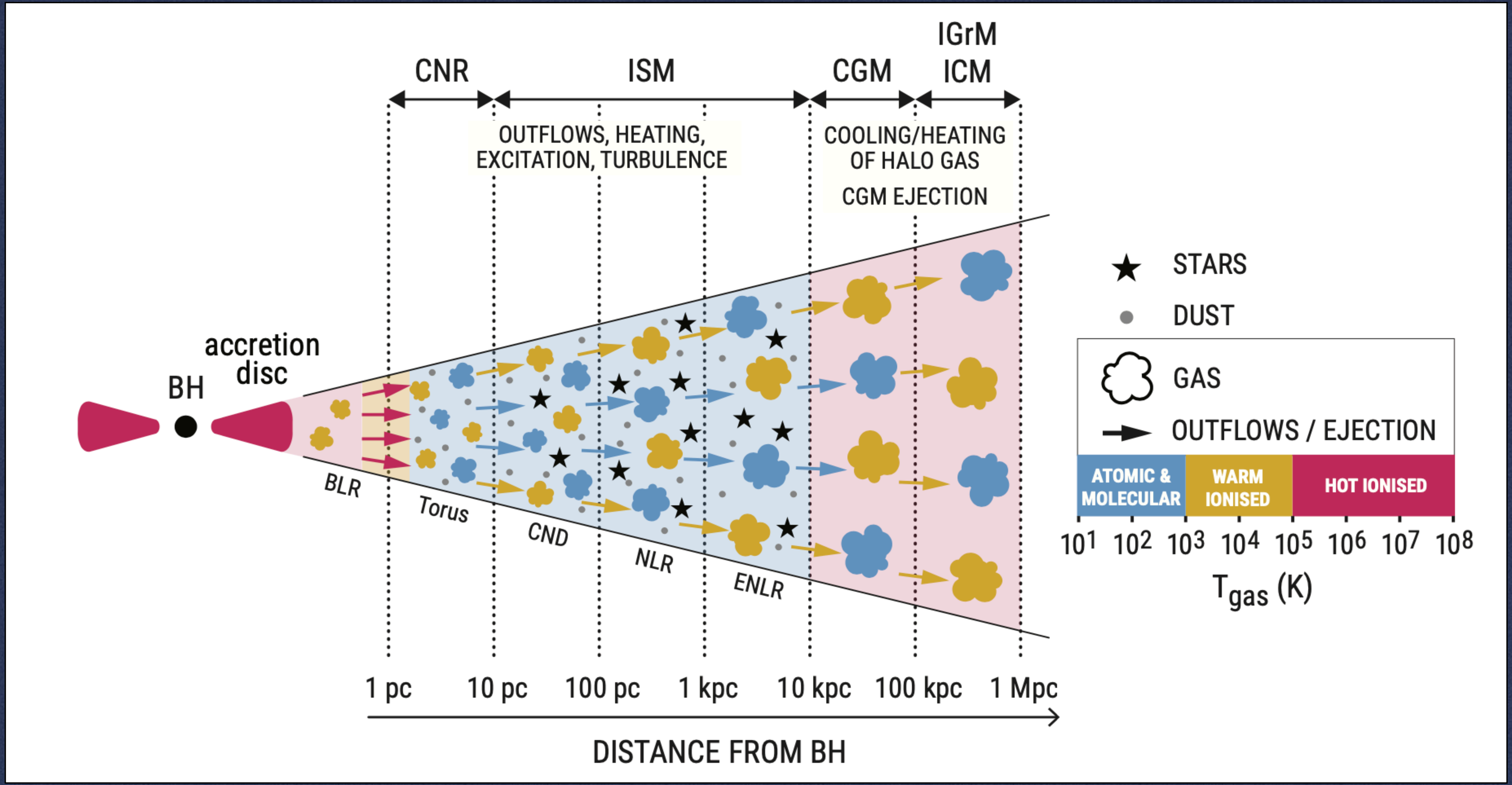

AGN feedback ON




Dubois+2016

# Multi-scale & multi-phase AGN feedback

Understanding AGN feedback and its role in galaxy evolution is something we will only achieve by putting together all pieces of information, but challenging to interpret results within the context of one another, and of theory.

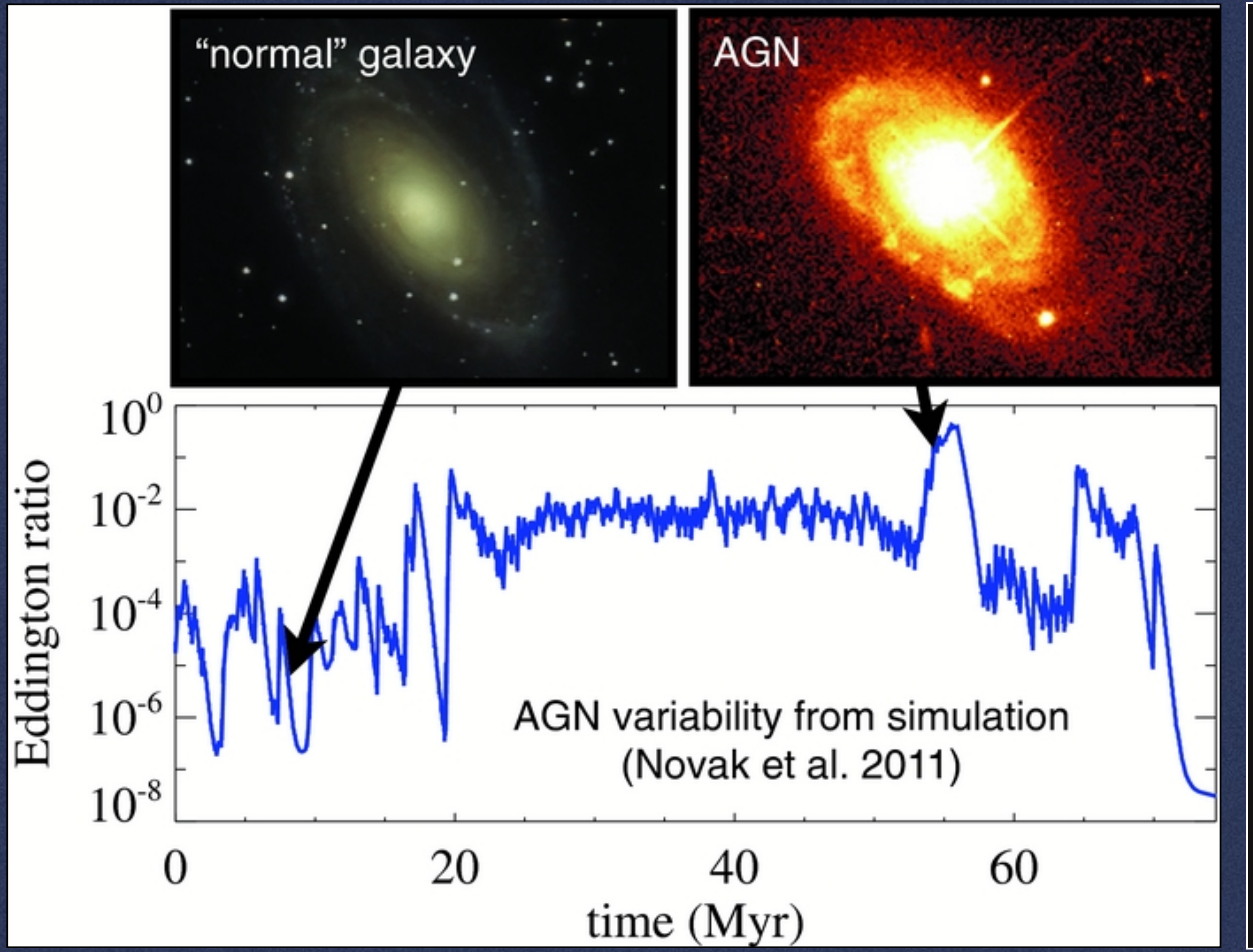


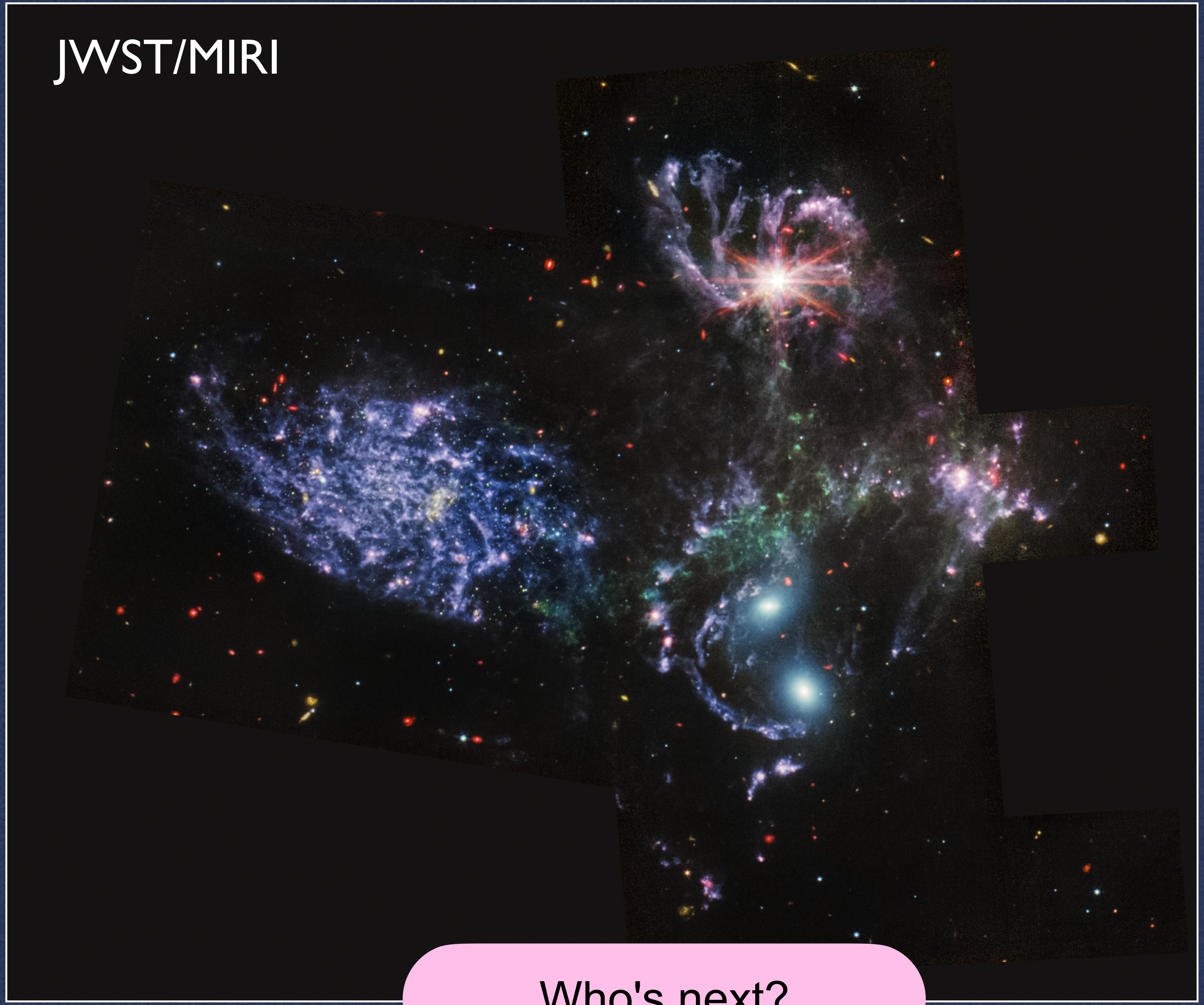

Harrison & Ramos Almeida 2024

# AGN are events!

AGN = short active phase of ~0.1-100 Myr (Martini 2004, Novak+2011).

Several AGN episodes depending on gas supply (Hickox+2014, Schawinski+2015).

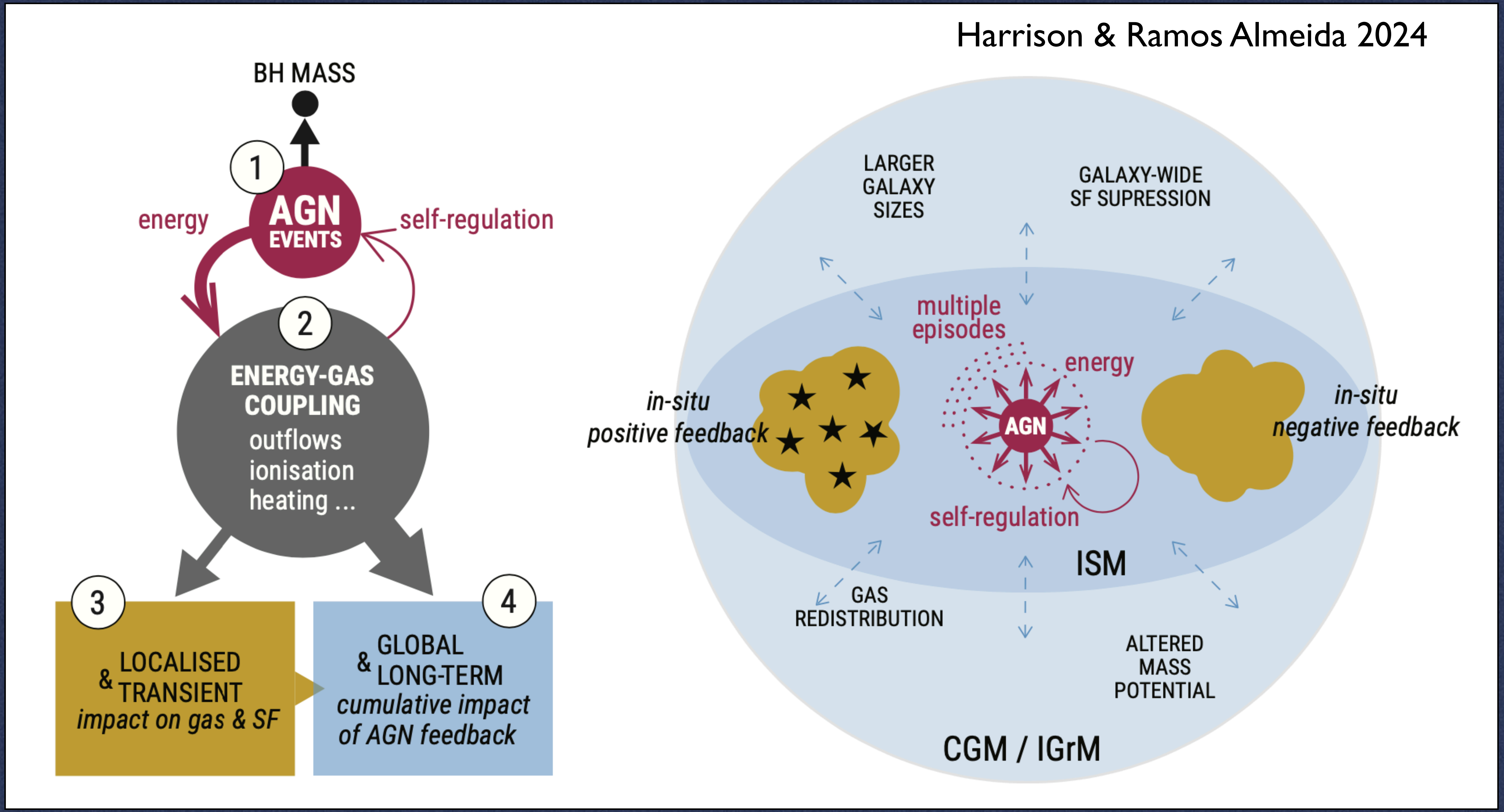



Who's next?

# How do we design our experiments?

AGN = events > Difficult to directly relate a single accretion episode to a significant, global impact on galaxy properties.

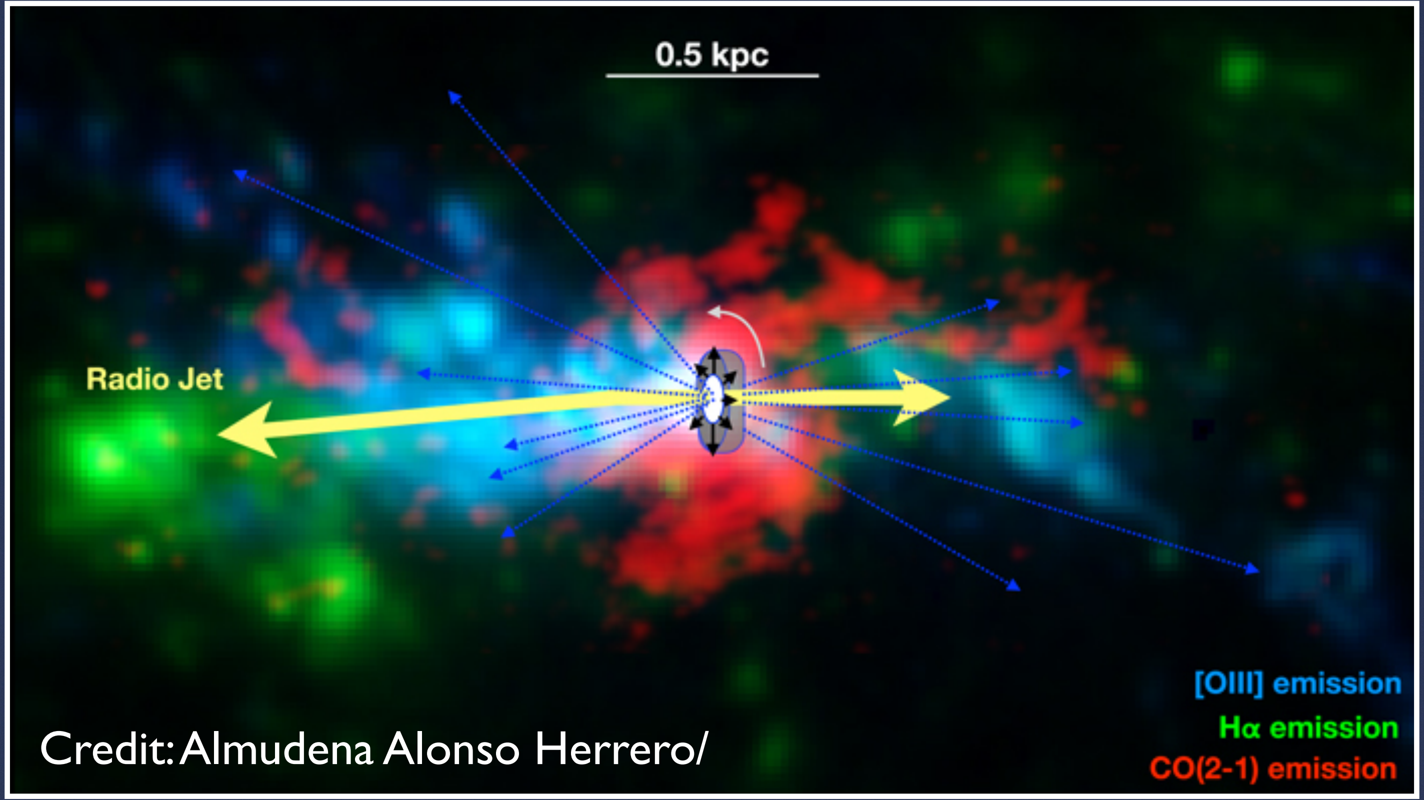


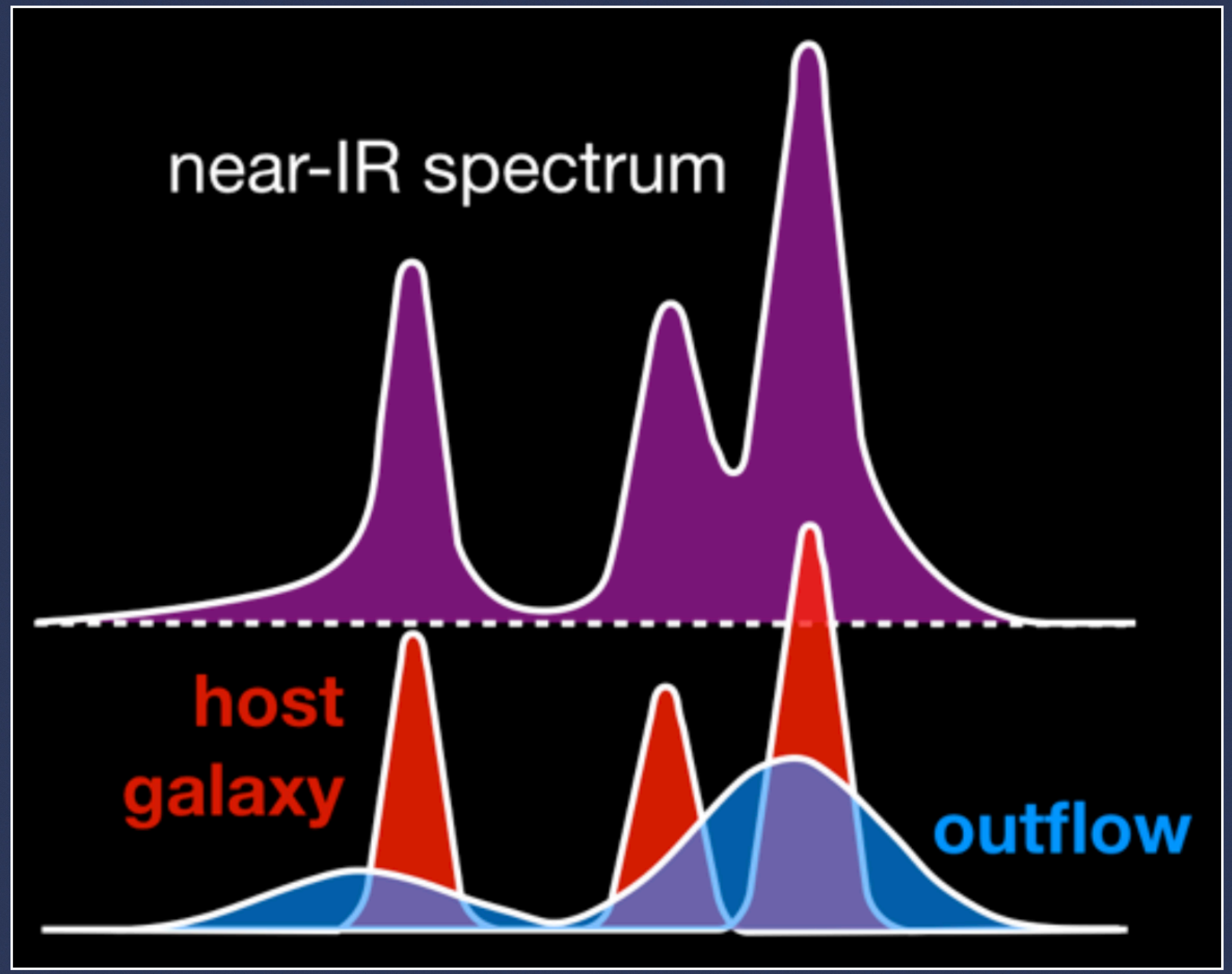

3) Studying individual targets in detail essential to determine how energy couples with gas = determines impact of feedback

4) Global galaxy properties and larger scale environment influenced by the cumulative output of multiple accretion episodes.

# Assessing the impact of quasar-driven outflows on galaxy properties

QSO FEED quasar feedback project

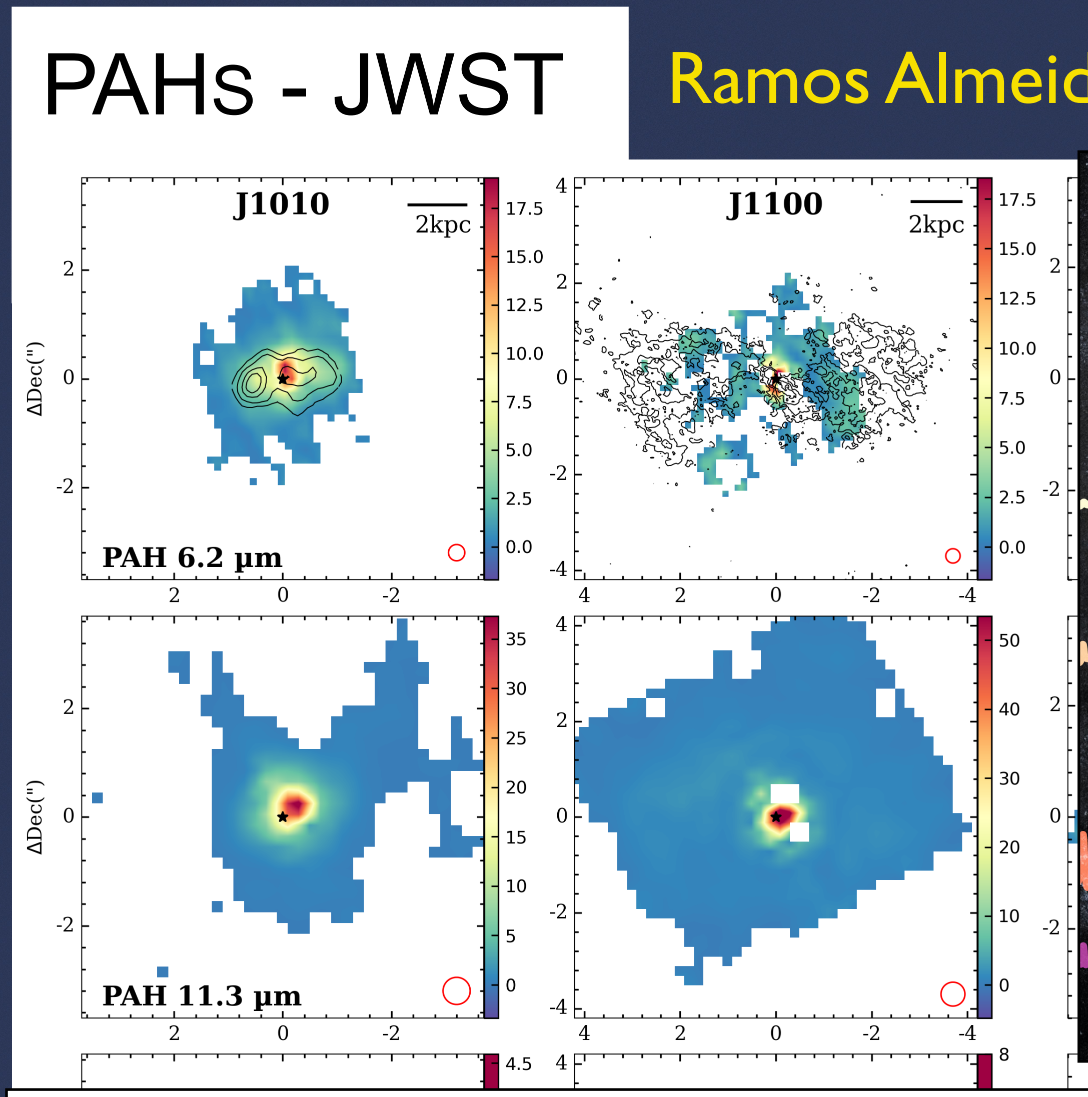


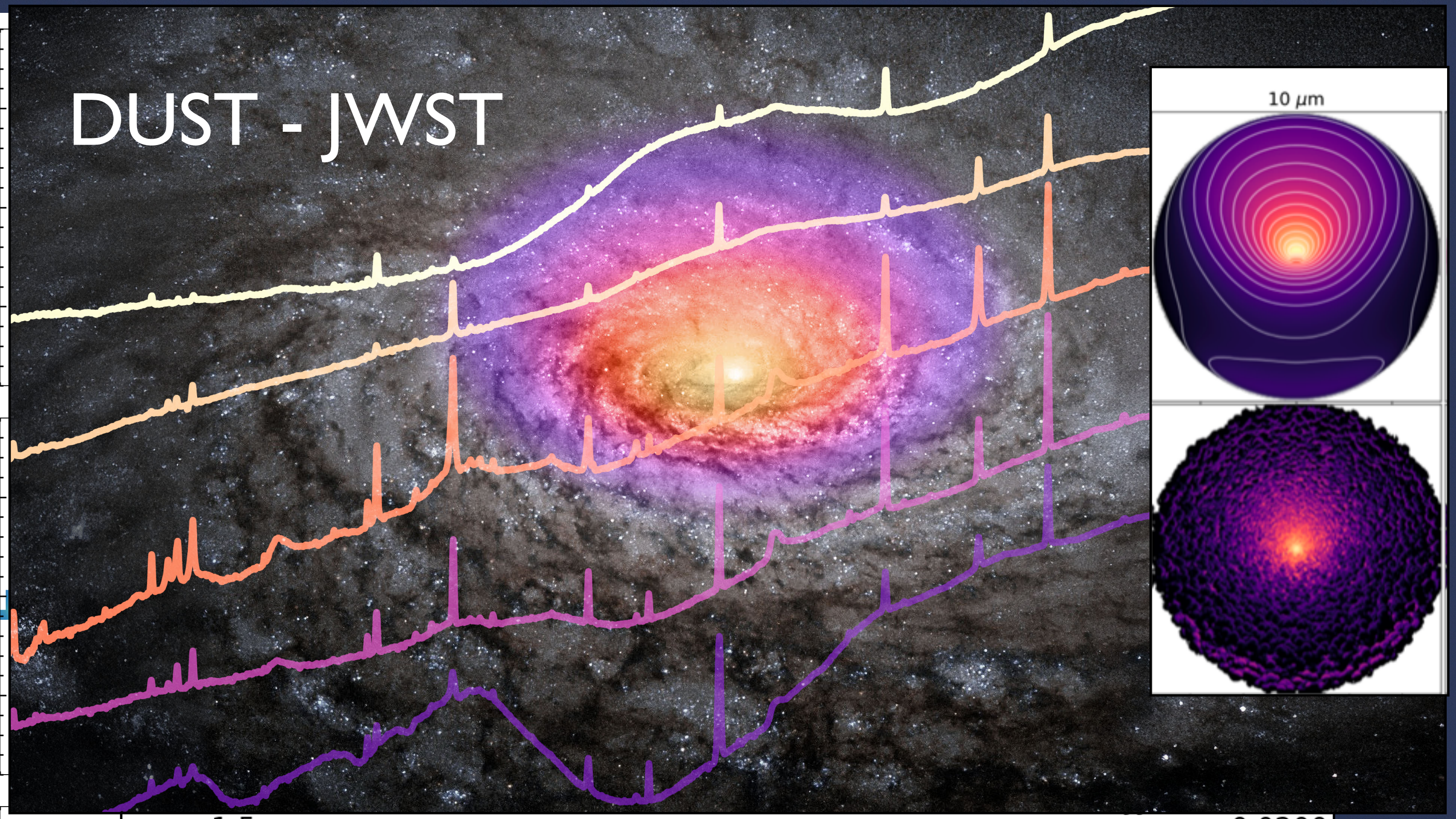

Ramos Almeida+17,19; Speranza+22, 24; Cezar+in prep.

IMPACT

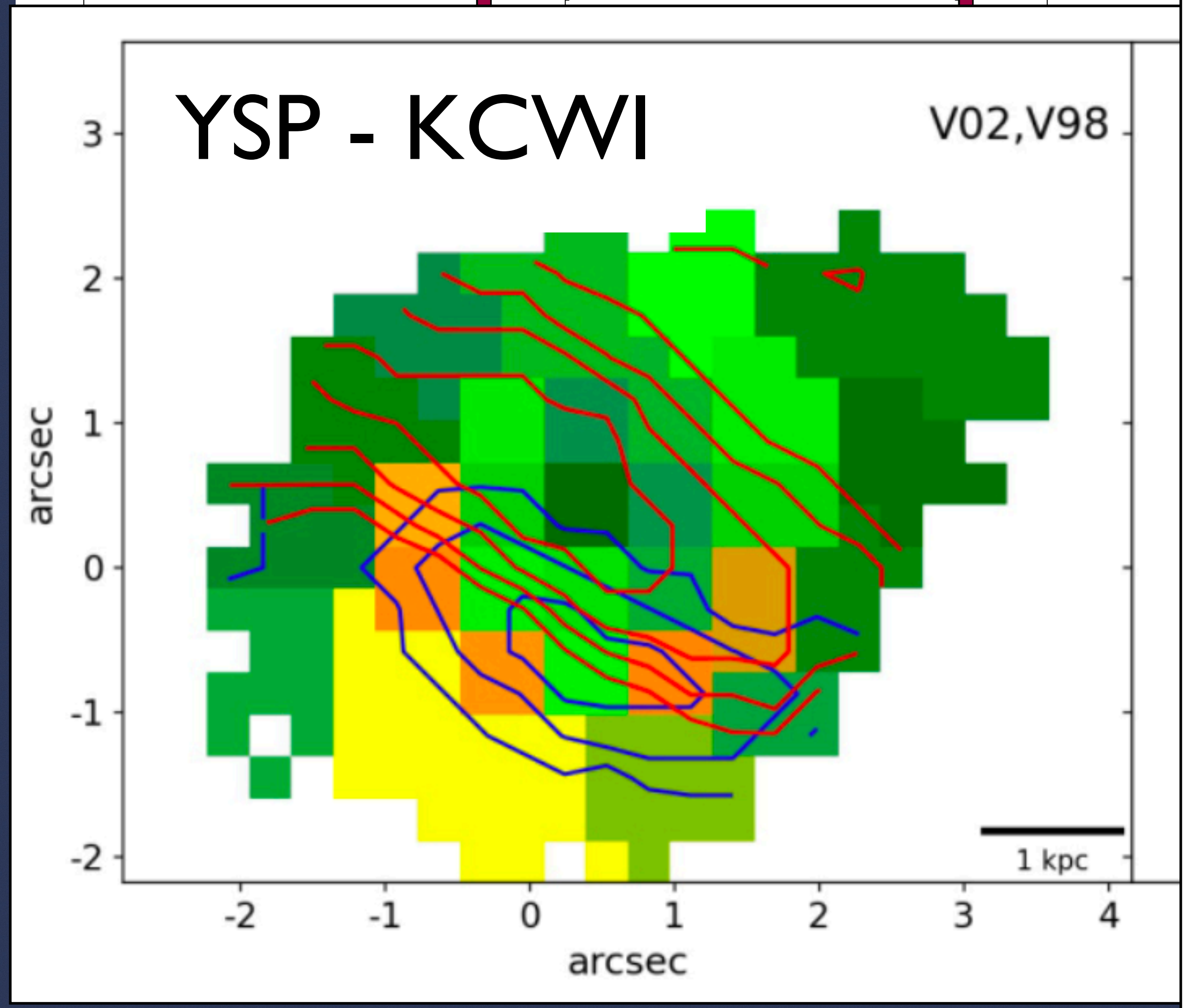
IMPACT



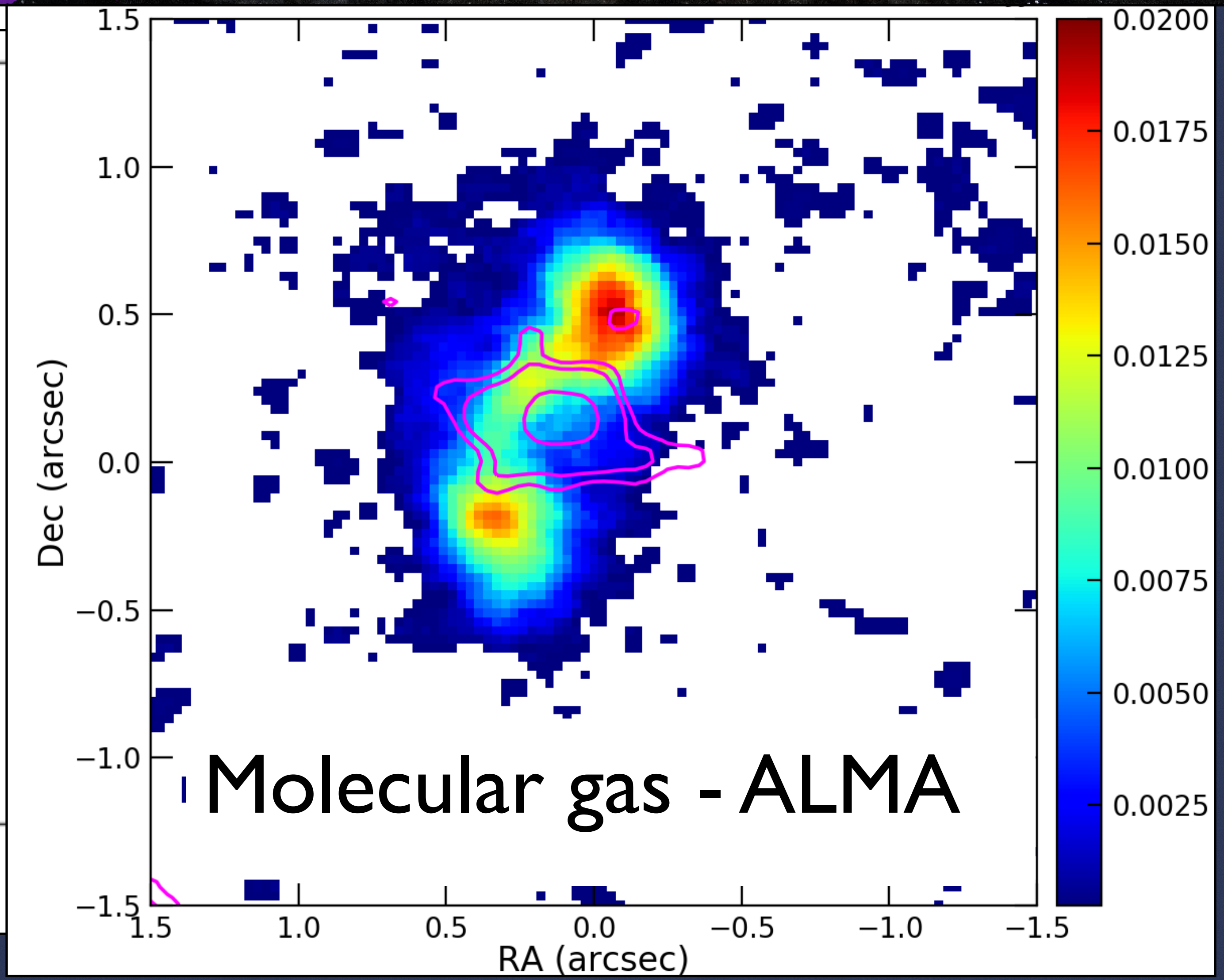

Ramos Almeida+23, 25




Ramos Almeida+in prep.




Bessiere & Ramos Almeida 22
Bessiere+24




Ramos Almeida+22; Audibert+23, 25; Holden+24; Zanchettin+25

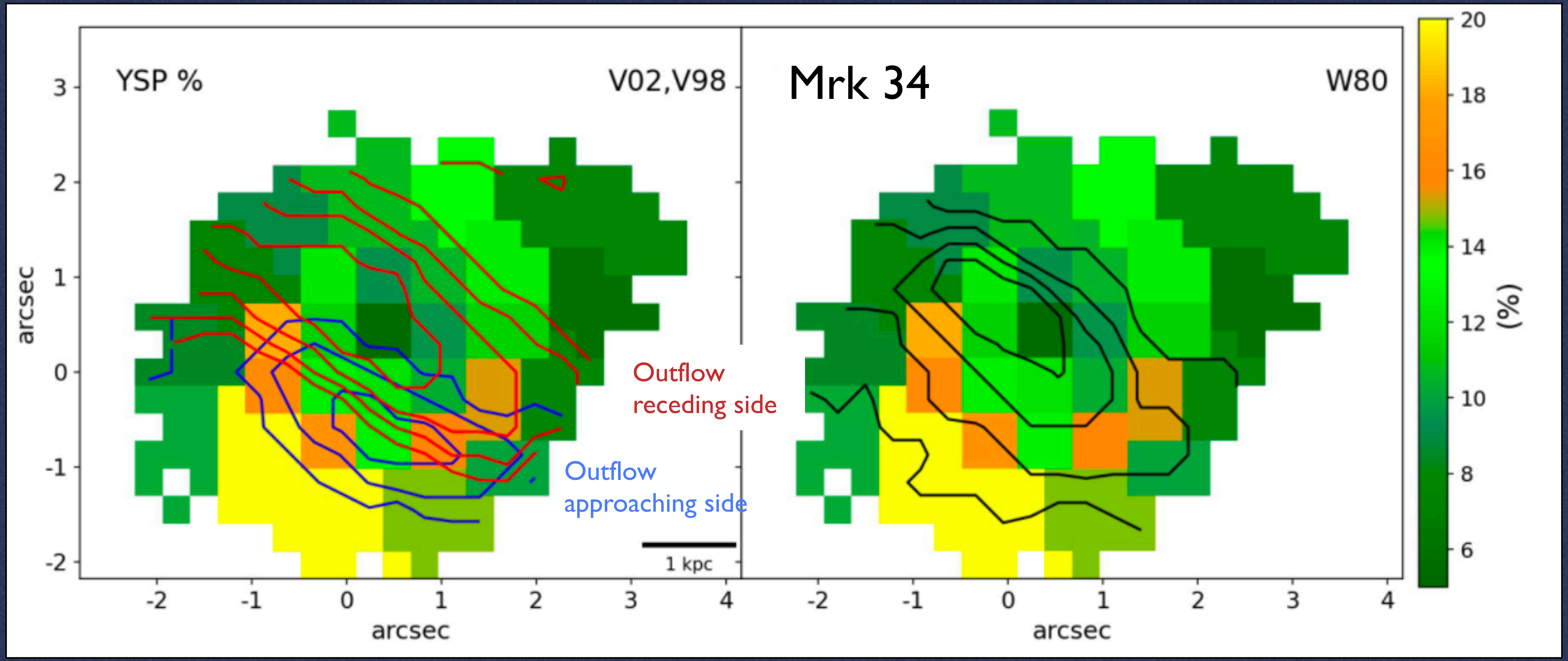

3 LOCALISED & TRANSIENT *impact on gas & SF*

# Impact of AGN-driven outflows on young stellar populations

Patricia Bessiere

YSP ages 1<Myr<2 at ~0.9 kpc SE from the center. Outflow dynamical timescale ~1 Myr.

AGN-driven winds promoting and preventing star formation on different sides of the galaxy: complex wind-galaxy interplay. Energy injection higher in NW (Trindade Falcão+2021).




Bessiere & Ramos Almeida 2022

Also Cresci+15a,b; Carniani+16; Shin+19; Perna+20; Xu+24

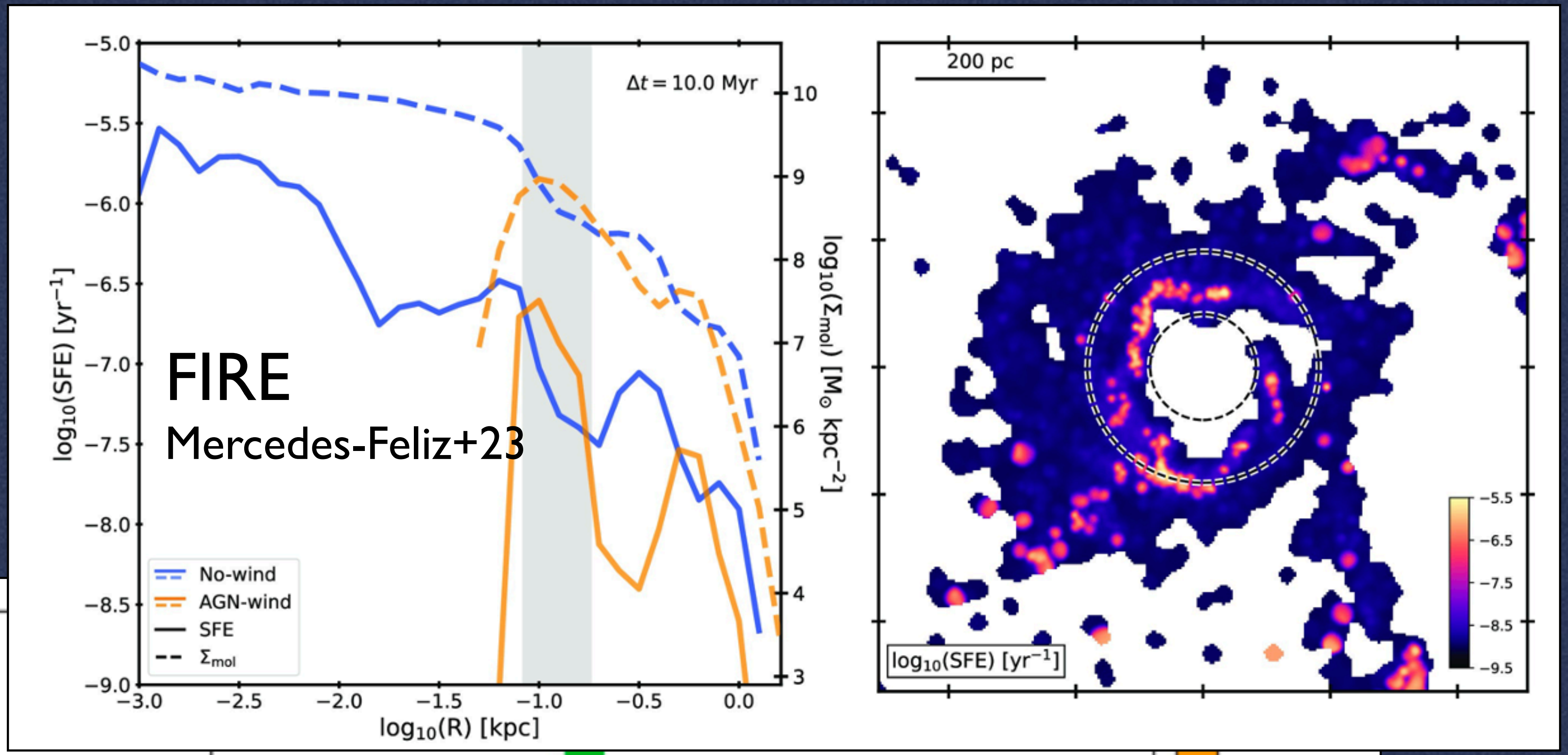
quasar feedback project

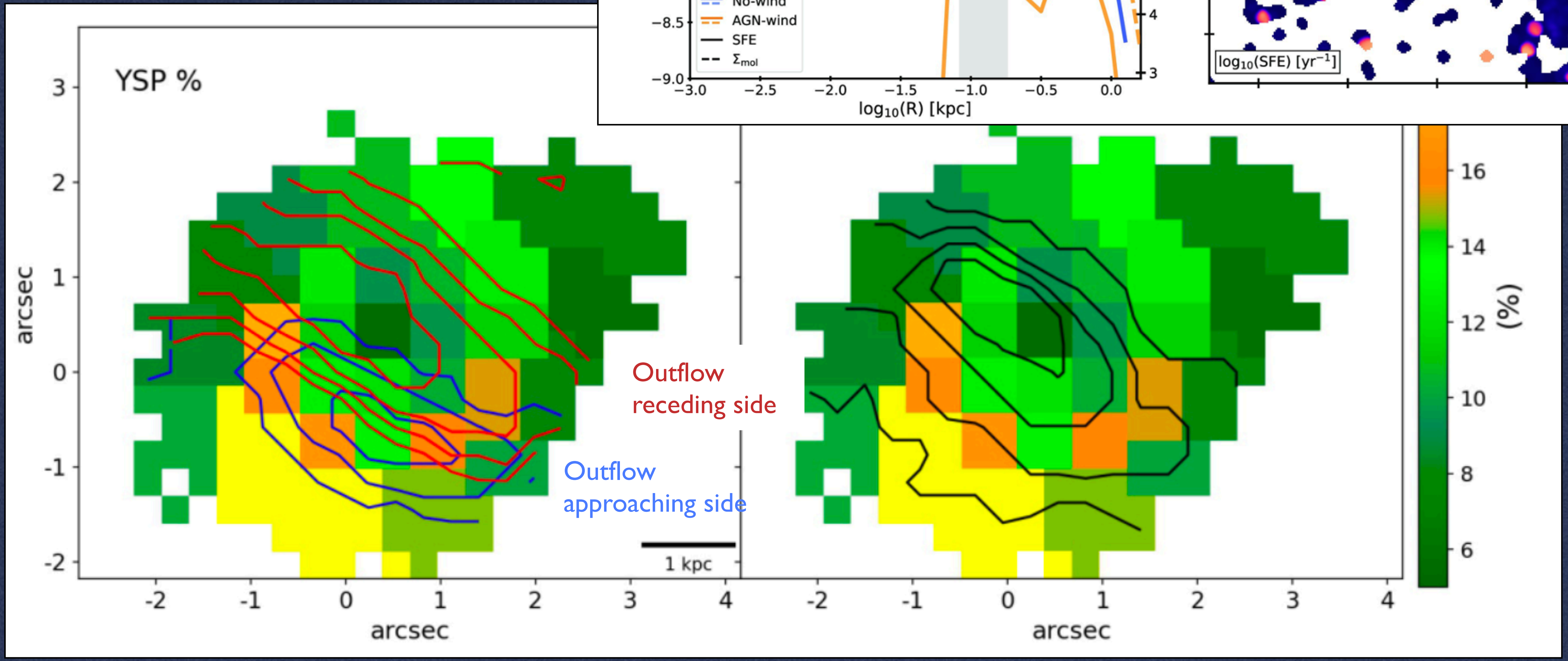

3 & LOCALISED TRANSIENT *impact on gas & SF*

Patricia Bessiere

# Impact of AGN-driven outflows on young stellar populations

Localized positive feedback
Global negative feedback




Bessiere & Ramos Almeida 2022

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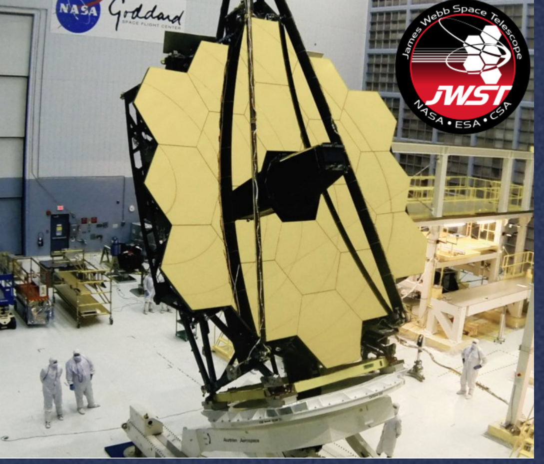
QSO FEED quasar feedback project

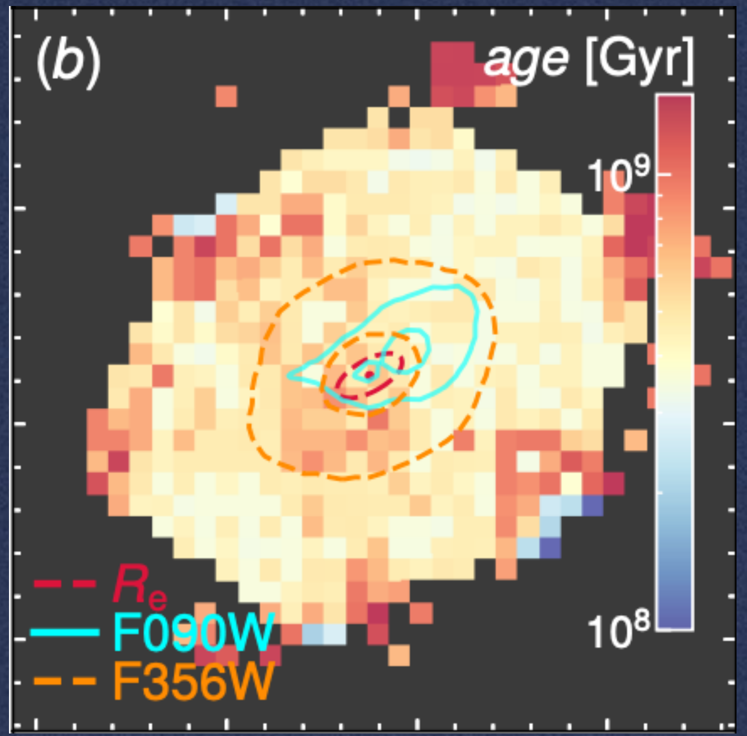


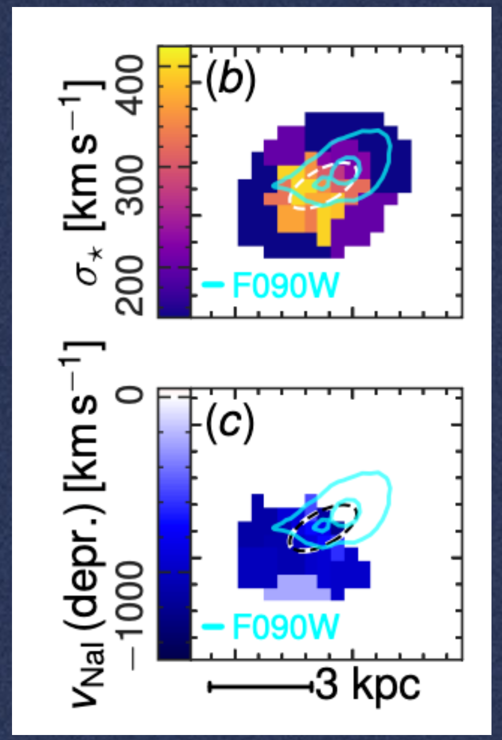
# Impact of AGN-driven outflows on young stellar populations

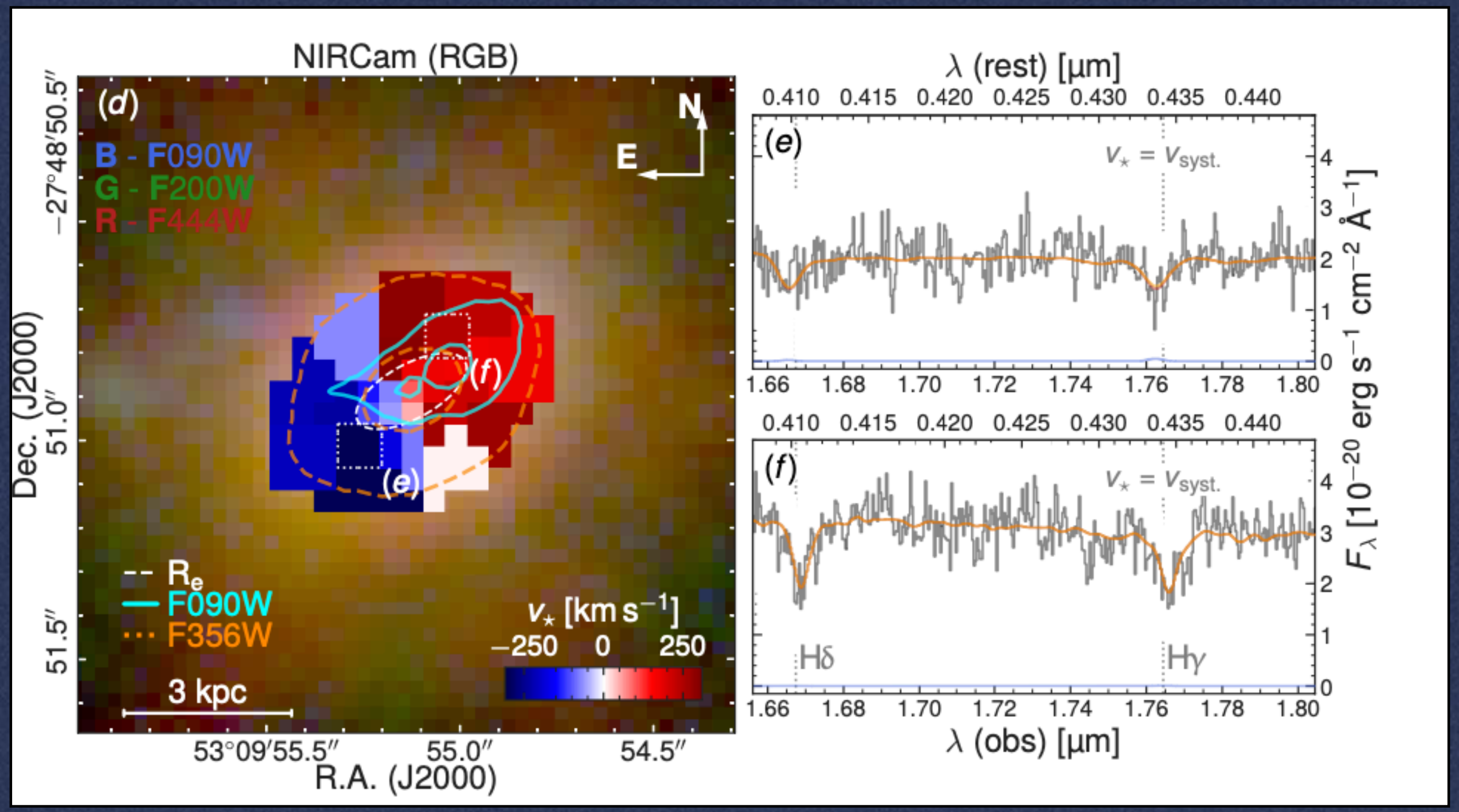
z=3, 0.2 arcsec
JWST/NIRSpec

z=0.1, 1.1 arcsec
seeing limited

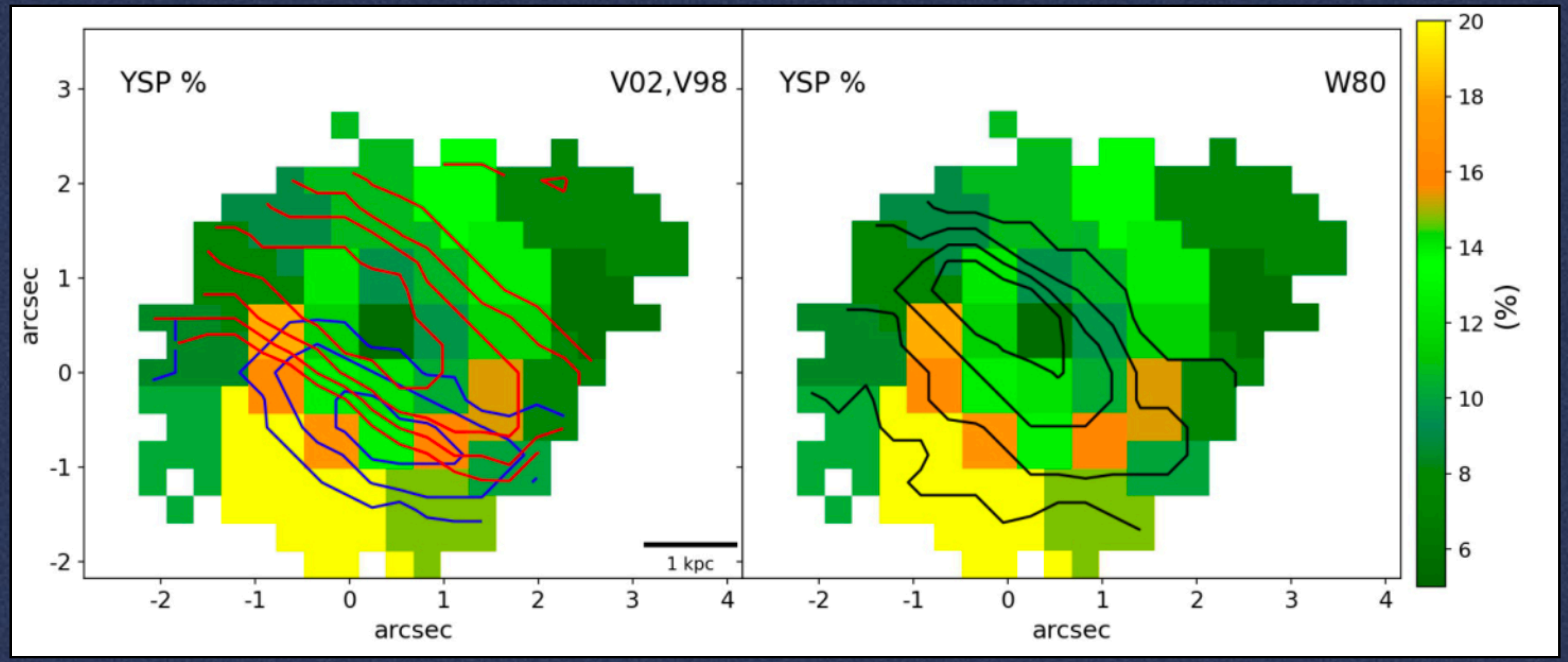
D'Eugenio+24

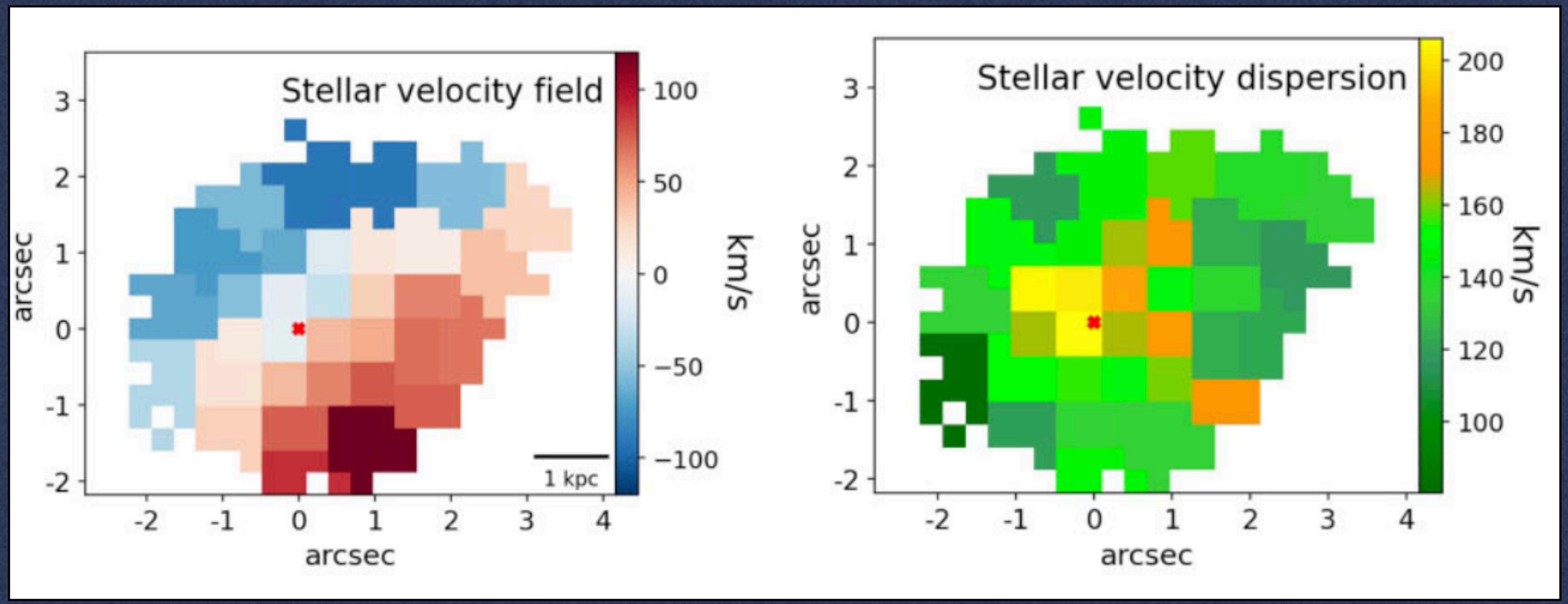



Bessiere & RA+22

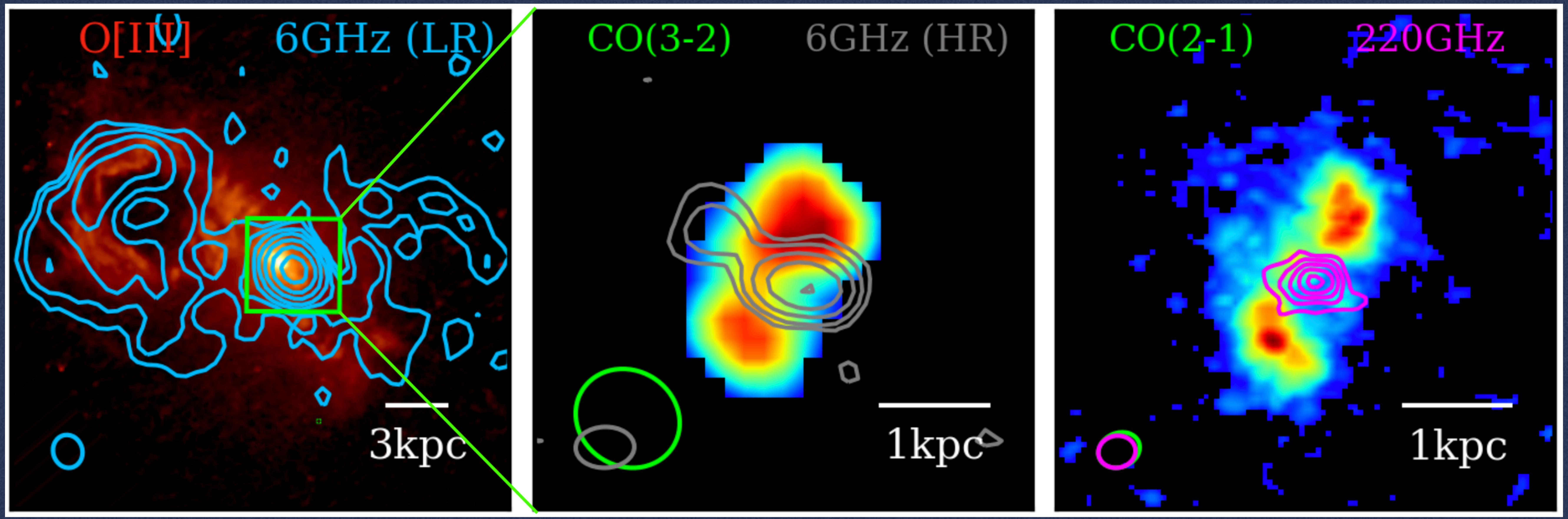



# Impact of jet-driven outflows on molecular gas properties

Anelise Audibert

The Teacup: radio-quiet QSO2 with a compact (~0.8 kpc) low-power (~$10^{43}$ erg/s) radio jet subtending a small angle (~20 deg) with the molecular gas disc and launching a molecular outflow.

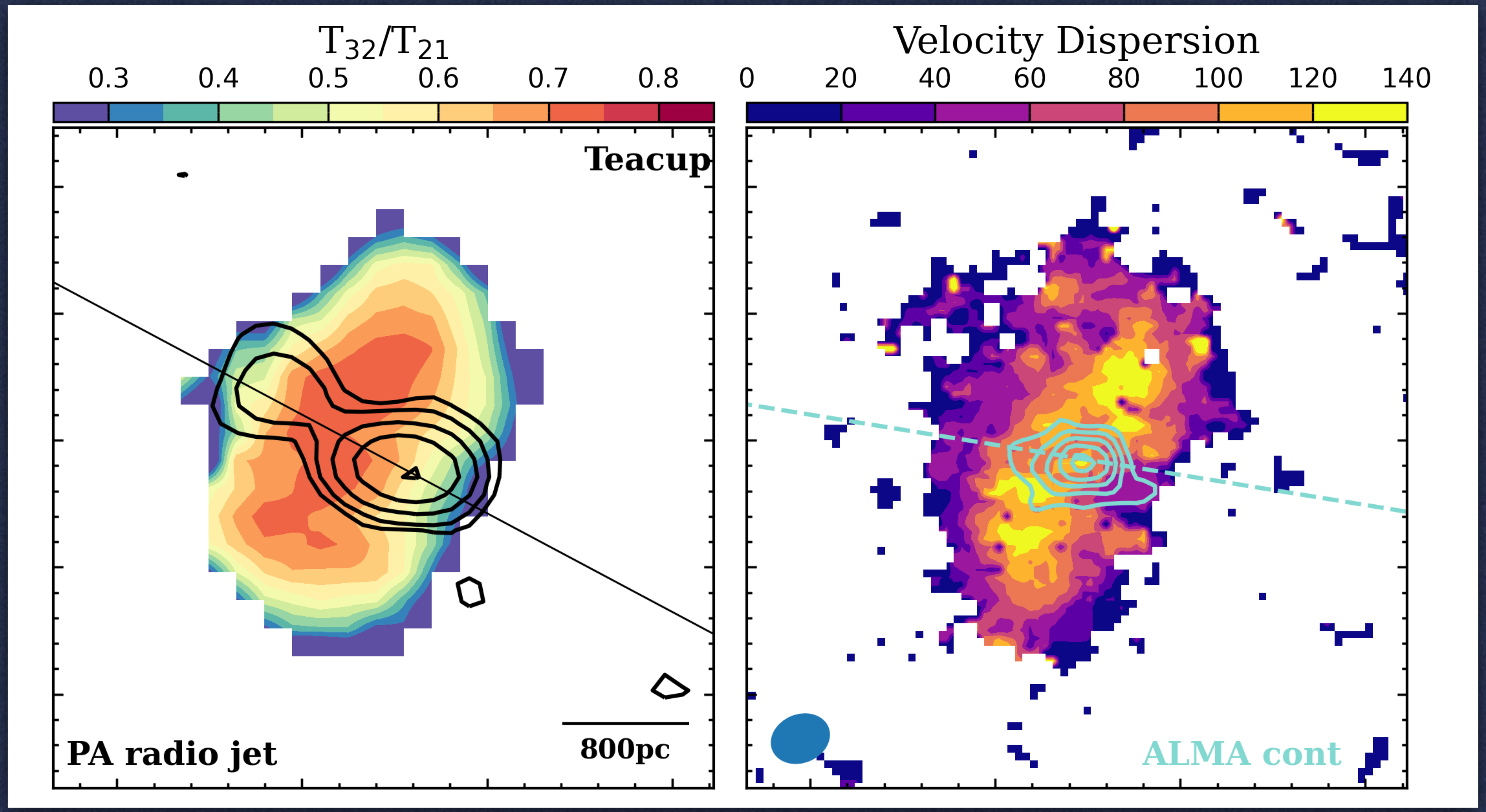



Audibert+23 (see also Harrison+15; Ramos Almeida+17; Lansbury+18; Venturi+23 for detailed studies of Teacup).


# Impact of jet-driven outflows on molecular gas properties

Anelise Audibert

- Enhancement CO(3-2)/CO(2-1) ratio
- Typical values spirals and disks $T_{32}/T_{21} \lesssim 0.5$
- Different gas excitation or optical thickness in the outflowing regions
- Hot dense gas ($T_{ex}$~50K), excited by the cocoon of shocked gas




Audibert+23

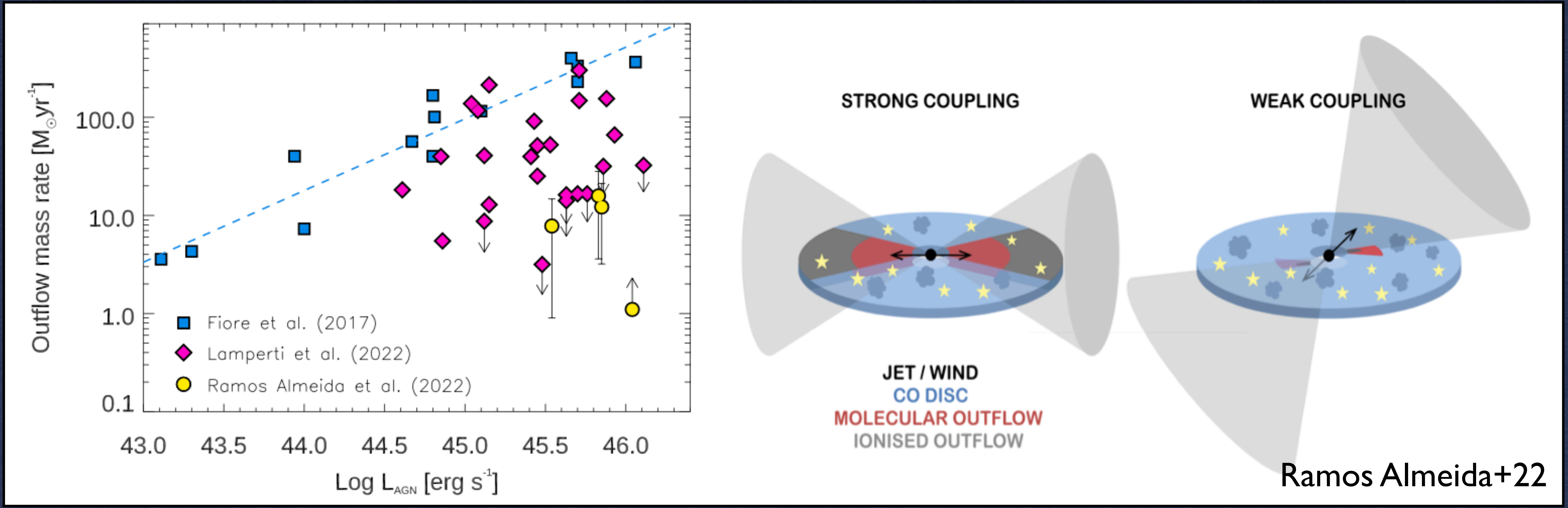
Examples of jets driving molecular outflows:
Morganti15; Oosterloo+19; García-Burillo+19; Girdhar+22; Murthy+22

First evidence of enhancement of velocity dispersion and gas excitation perpendicular to the radio jet.

Enhanced velocity dispersion perpendicular to jet in ionized gas:
Couto+17; Balmaverde+19, 22; Venturi+21,23; Ulivi+24


# Molecular gas outflows

- Outflow mass rate does not depend only on $L_{bol}$, other factors as jet power, jet/ionized outflow orientation, amount & geometry of dense gas key to produce massive molecular outflows (Ramos Almeida+22; Lamperti+22; Audibert+25).



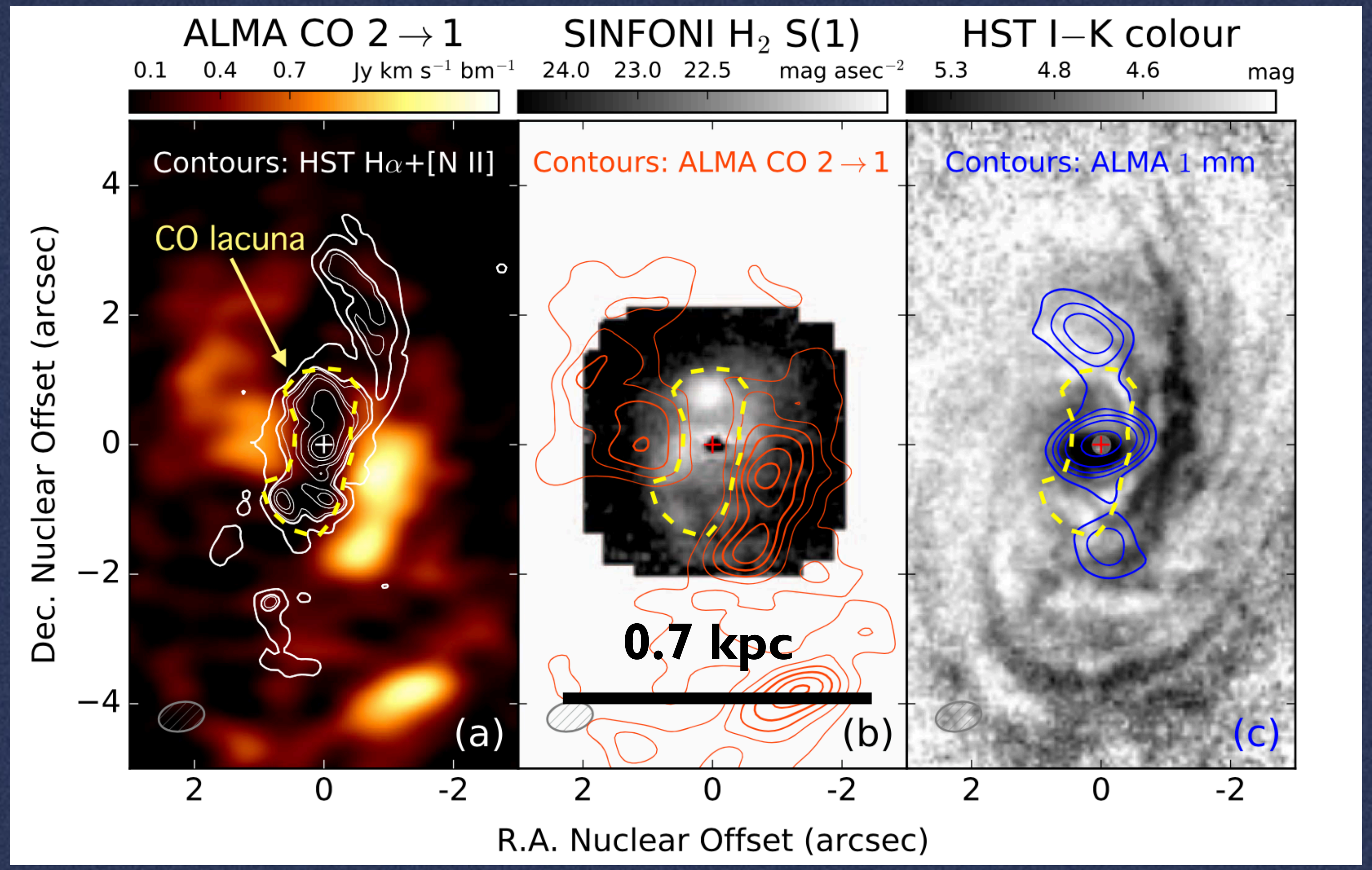
Ramos Almeida+22

- Observations of representative samples of AGN of different luminosities, hosted in galaxies with diverse properties, needed to quantify the relevance of these factors on the coupling.


3 LOCALISED & TRANSIENT *impact on gas & SF*

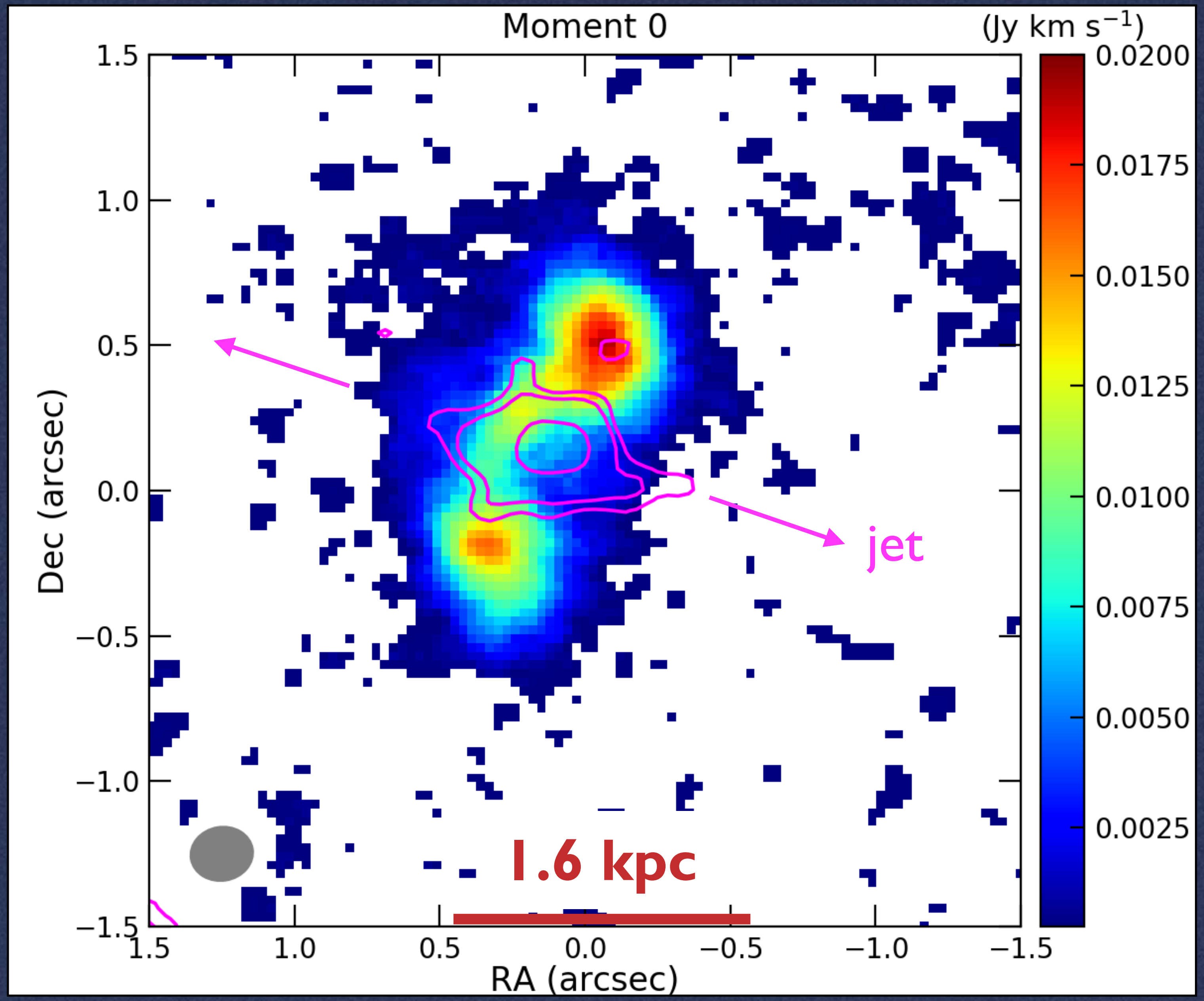
# Imprint of AGN feedback on nuclear scales

NGC 2110; Seyfert 2, log $L_{bol}$~44.3 erg/s

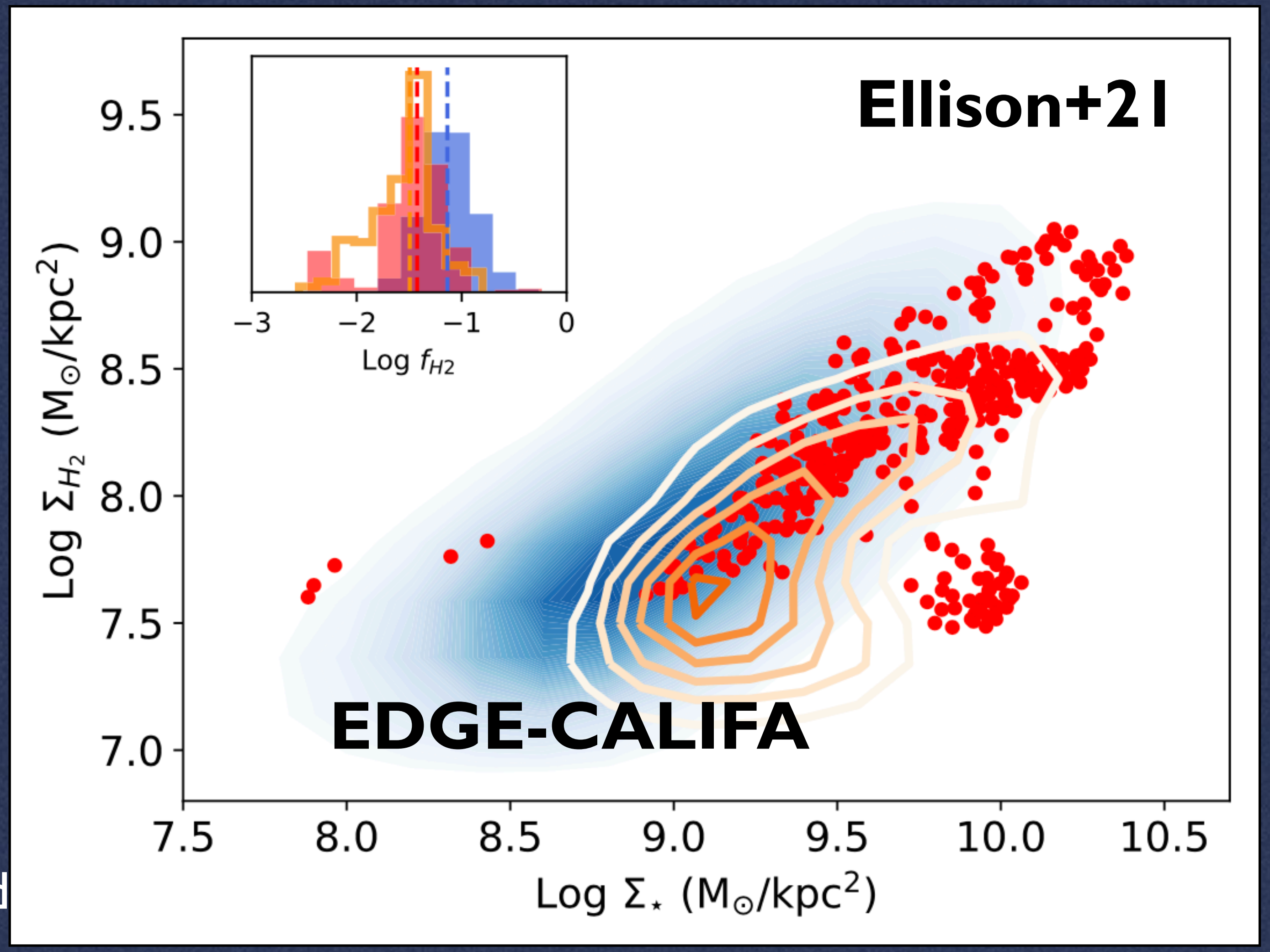



**Rosario+19**

The Teacup; QSO2, log $L_{bol}$~45.8 erg/s




**Ramos Almeida+22; Audibert+23**

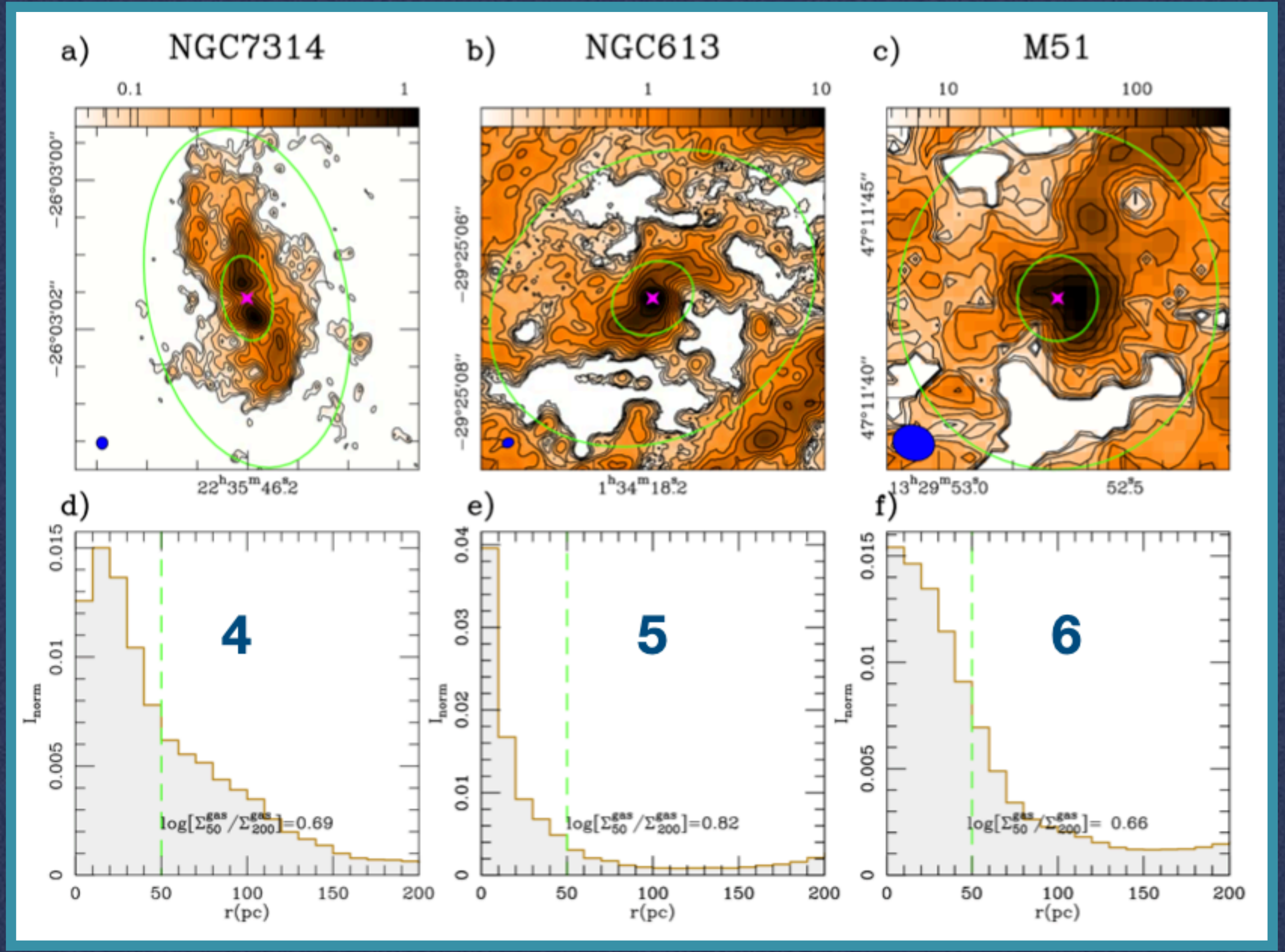



AGN feedback creating molecular gas cavities from scales of tens of pc to kpc-scales (García-Burillo+19,21; Feruglio+20; Zanchettin+21; García-Bernete+21; Ruffa+22).

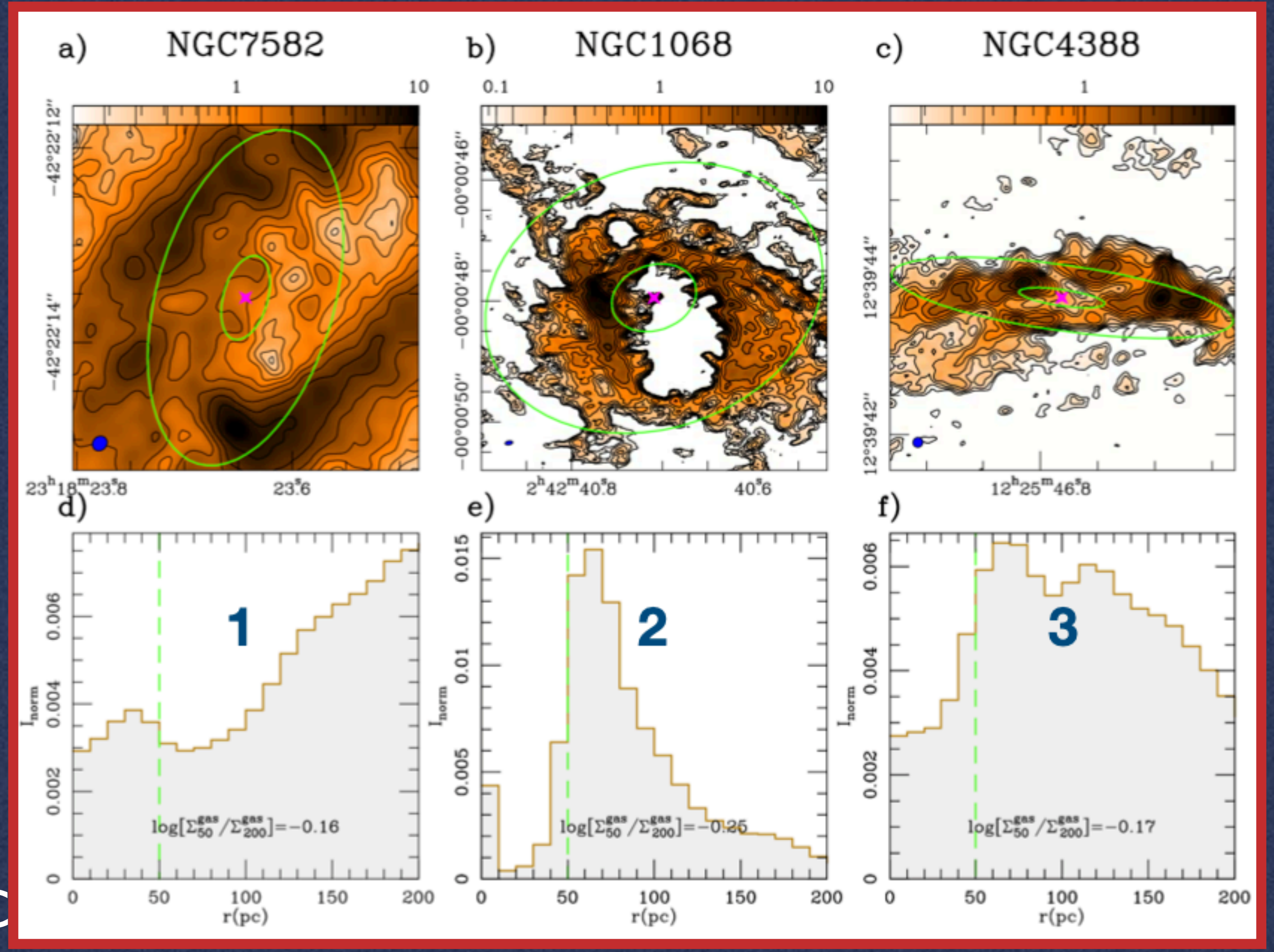
3 LOCALISED & TRANSIENT *impact on gas & SF*

# Imprint of AGN feedback on pc-scales

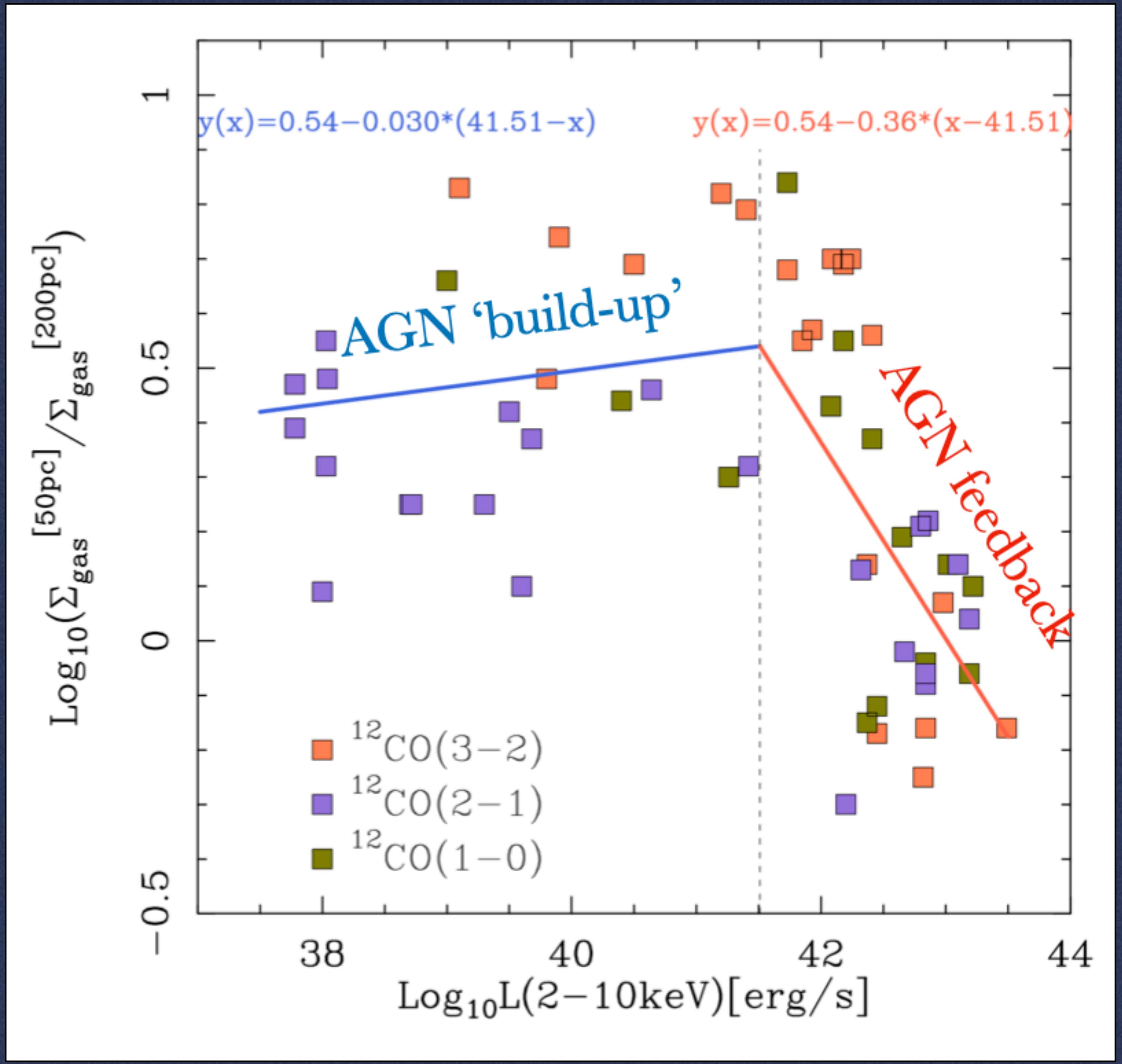

## AGN 'build-up'




## AGN feedback

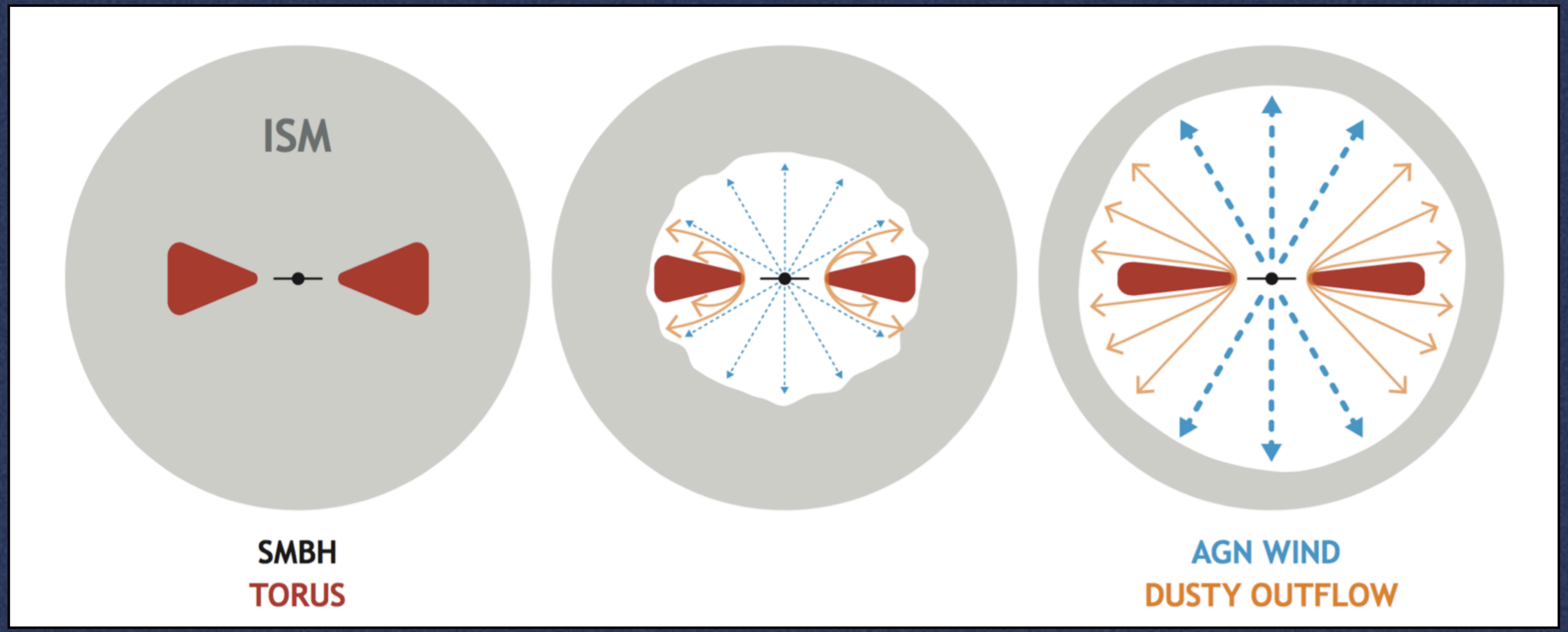


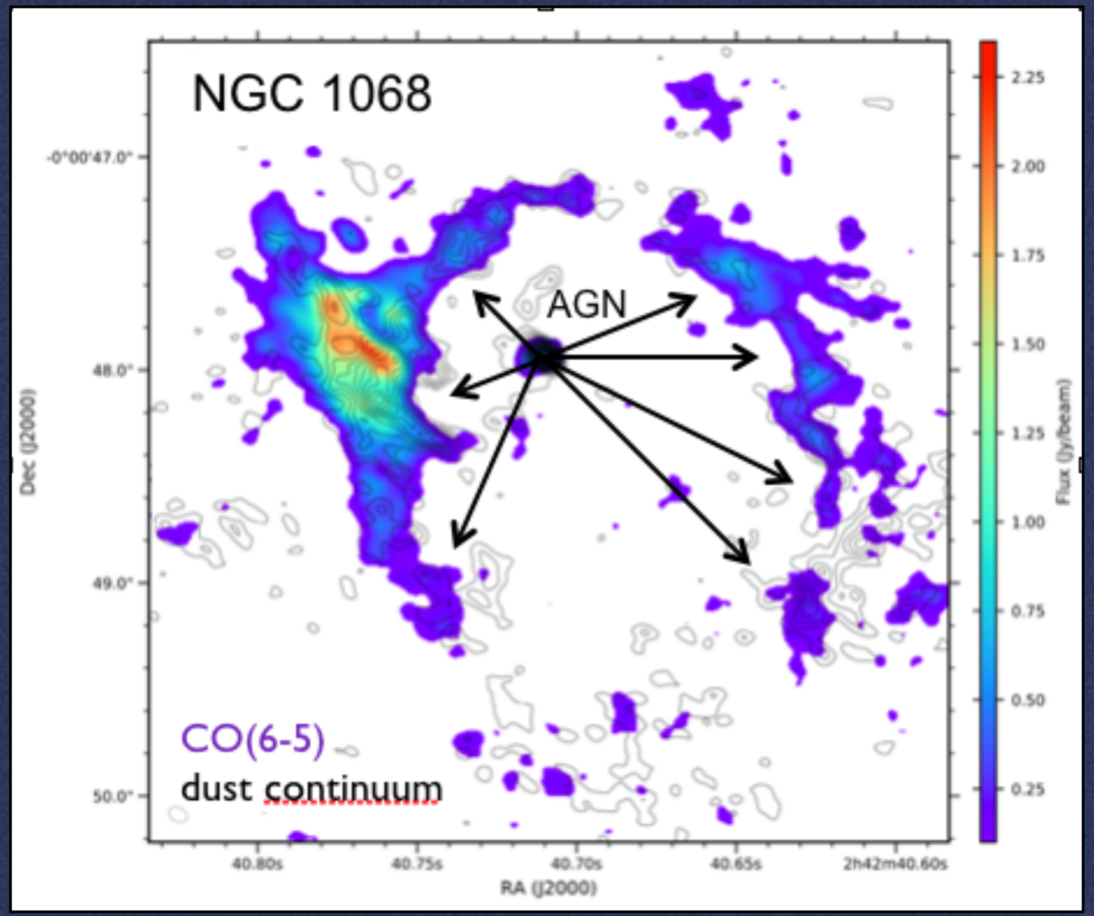

## 75 AGN from the ALMA archive with CO




**García-Burillo+21,24 spiral galaxies in GATOS**
**Elford+24 for spheroidal galaxias in WISDOM**

AGN luminosity / Eddington ratio



# Impact of AGN feedback on galaxy scales

Comparison between SFRs, gas fractions and star formation efficiencies of AGN and matched control samples of non-active galaxies (Vito+14; Brusa+16; 18; Husemann+17; Kakkad+17; Perna+18; Rosario+18; Scholtz+18; Herrera-Camus+19; Kirkpatrick+19; Spingola+20; Circosta+21; Bischetti+21; Koss+21; Valentino+21; Ramos Almeida+22; Salvestrini+22; Bertola+24; Mountrichas+24).

No consensus!!

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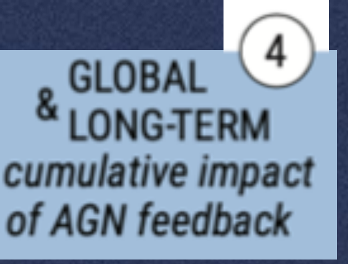
No consensus!!

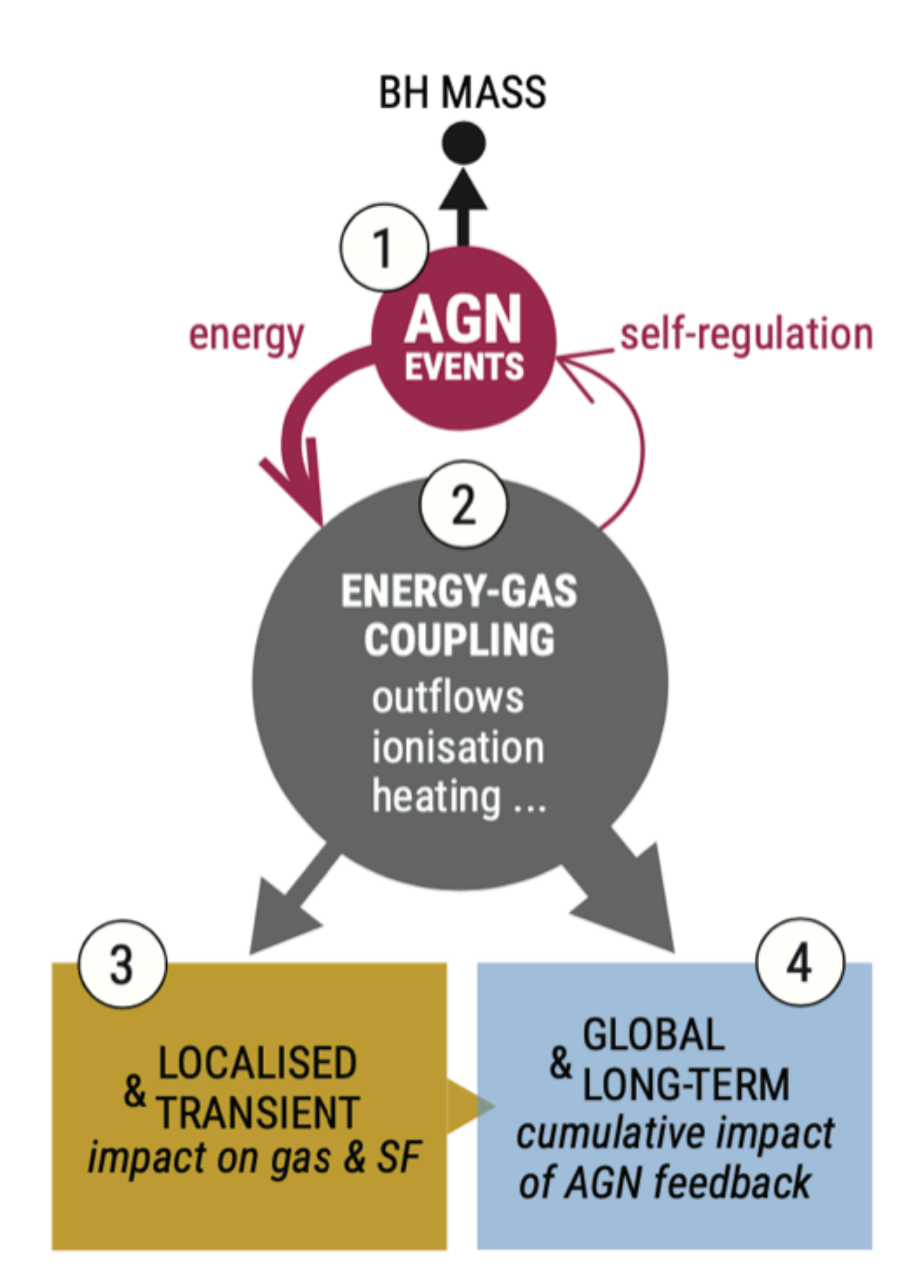
Comparison between global galaxy properties and outflow properties and/or AGN luminosity (Stanley+15, 17; Balmaverde+16; Woo+17; Kim+22; Hervella-Seoane+23; Bessiere+24).

No clear correlation

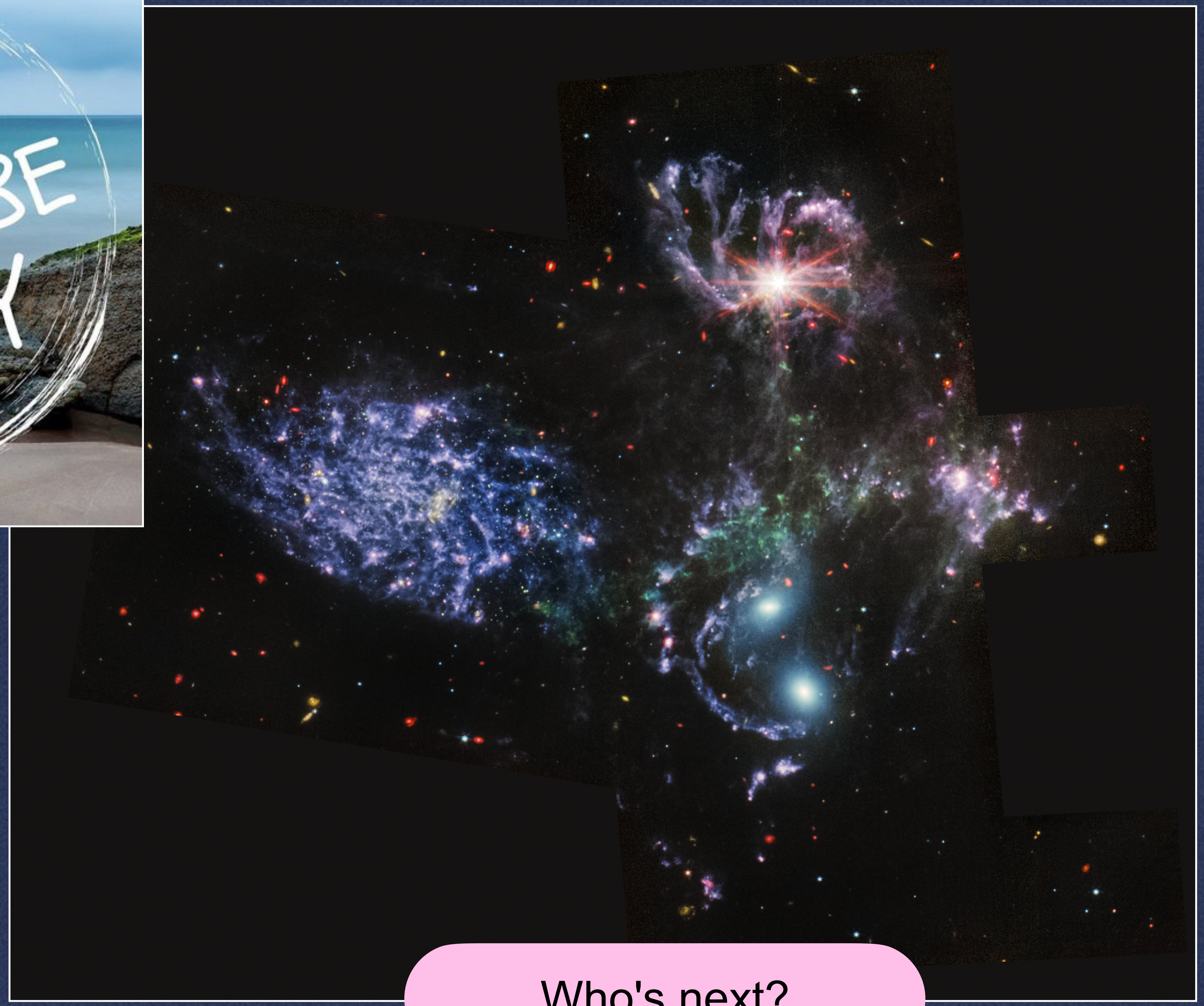



# Impact of AGN feedback on galaxy scales

AGN are events and not objects that persist in time. Therefore, it may be difficult to directly relate a single accretion episode to a significant, global impact on galaxy properties.







Who's next?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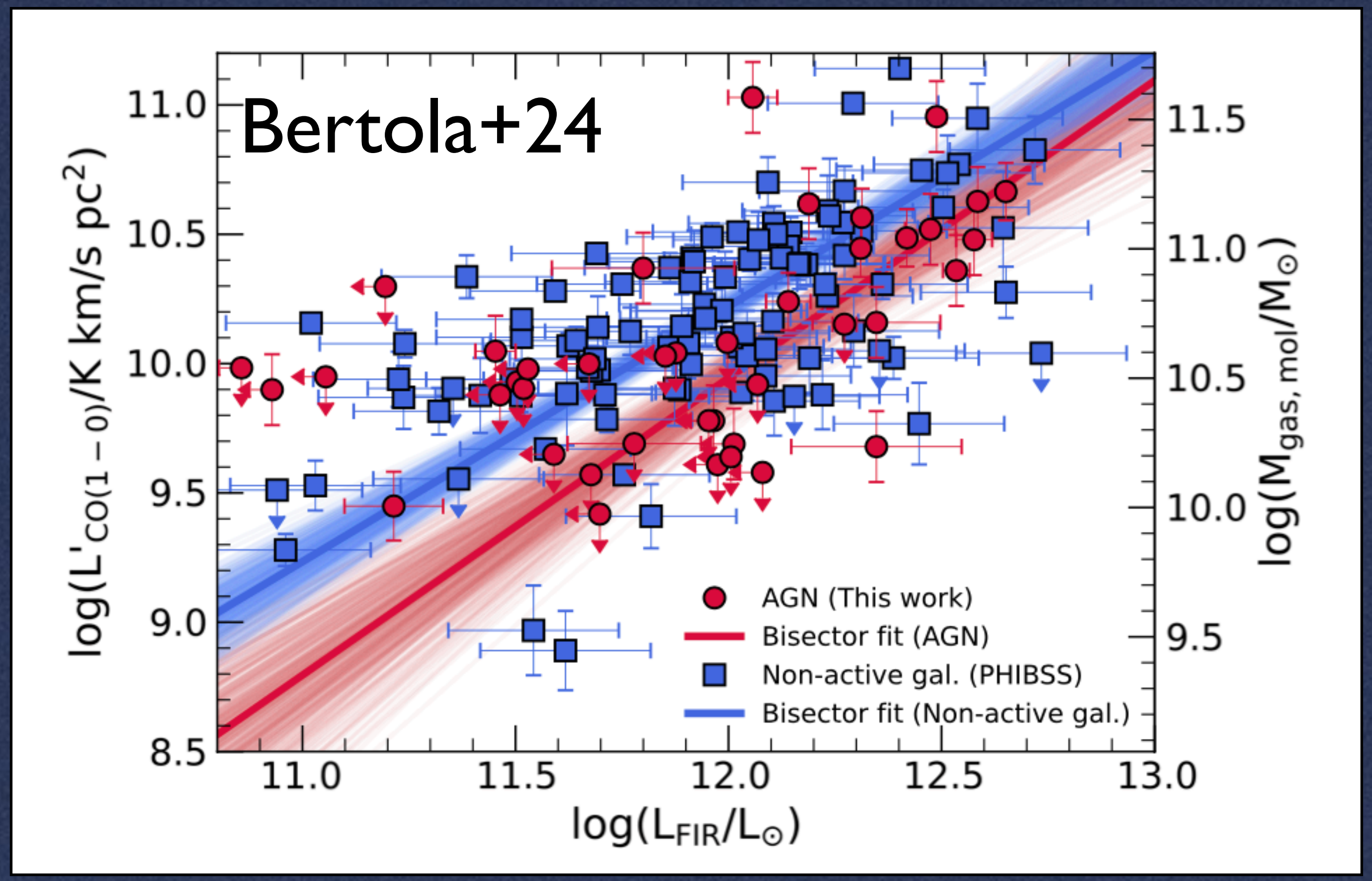
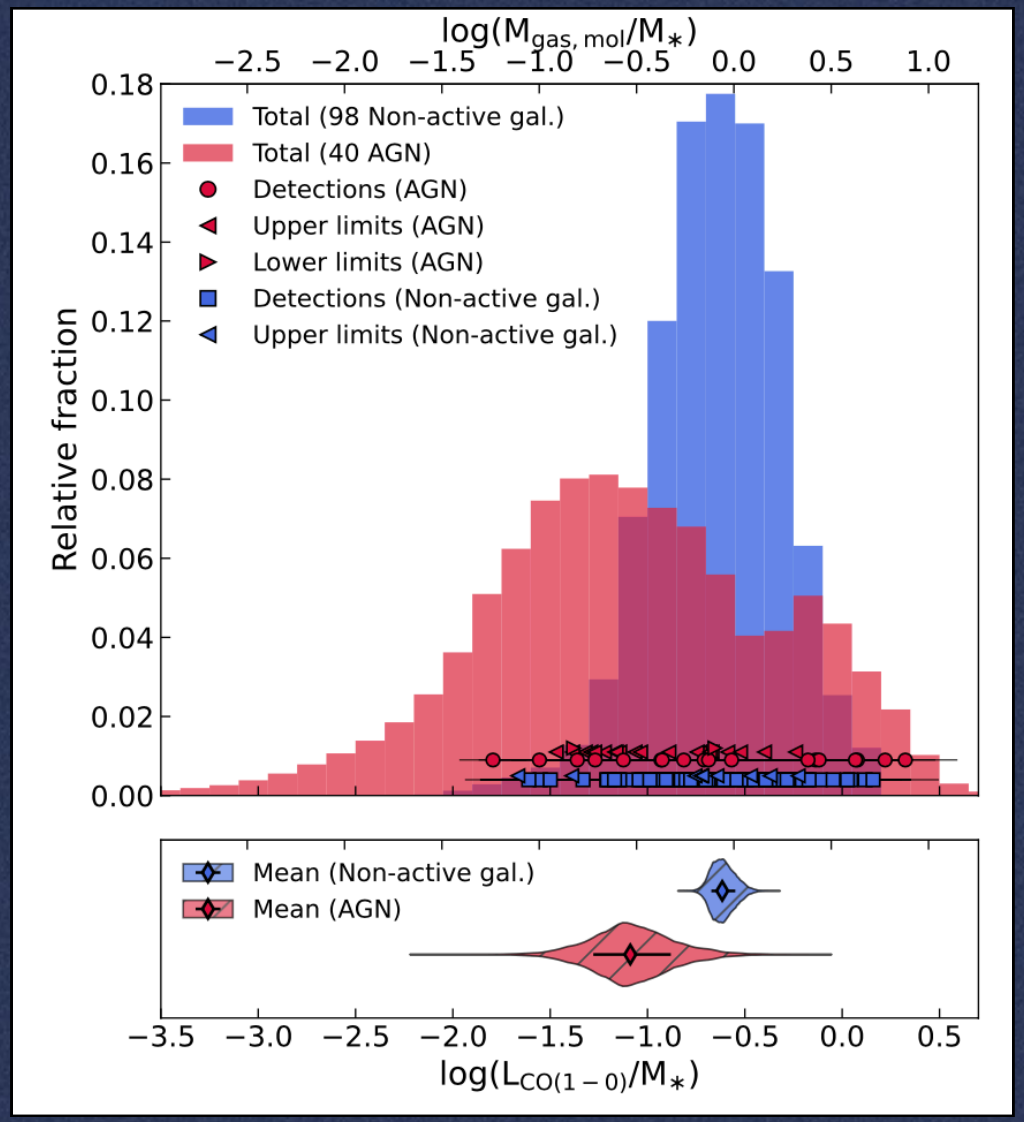
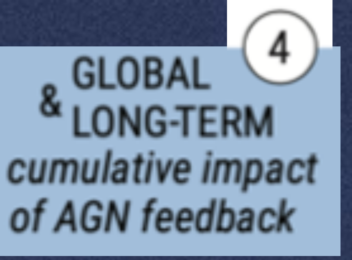


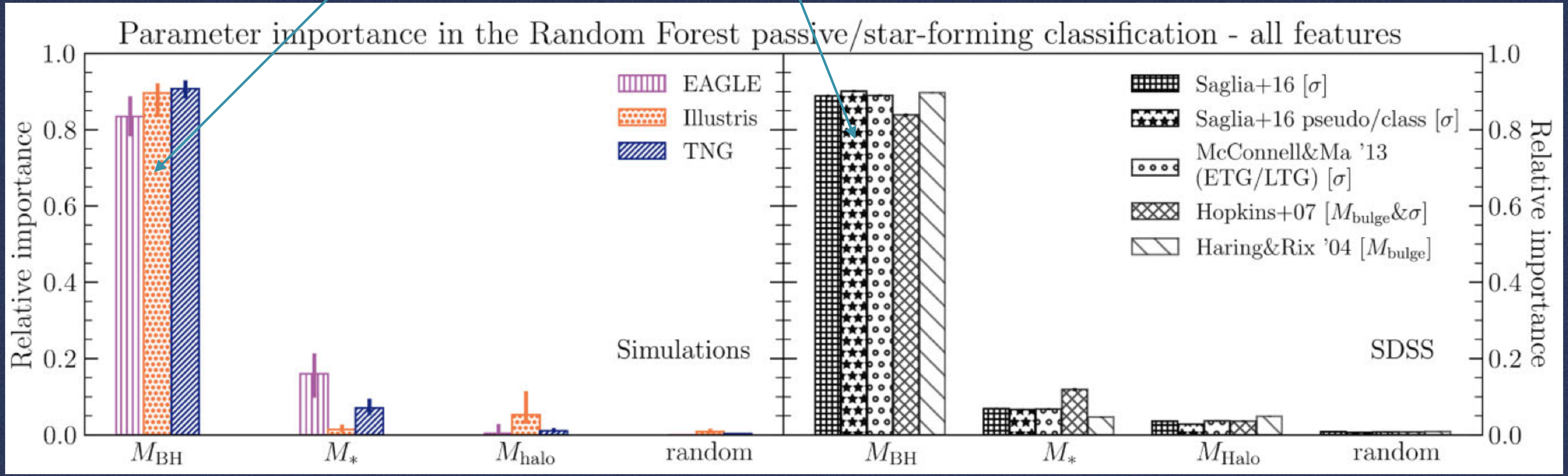

- At cosmic noon (z~1-3) there is some evidence for cold molecular gas depletion in AGN hosts (Perna+18; Circosta+21; Bertola+24). AGN feedback more effective removing gas or heating the ambient medium.




# Impact of AGN feedback on galaxy scales

The integrated power output of the AGN, rather than instantaneous activity, causes galaxies to quench (Terrazas+16; Martín-Navarro+18,21; Piotrowska+22; Bluck+23; Bessiere+24).

Black hole mass primary driver of quenching




Bluck+16; 20a,b; Piotrowska+22

# Impact of AGN feedback on galaxy scales

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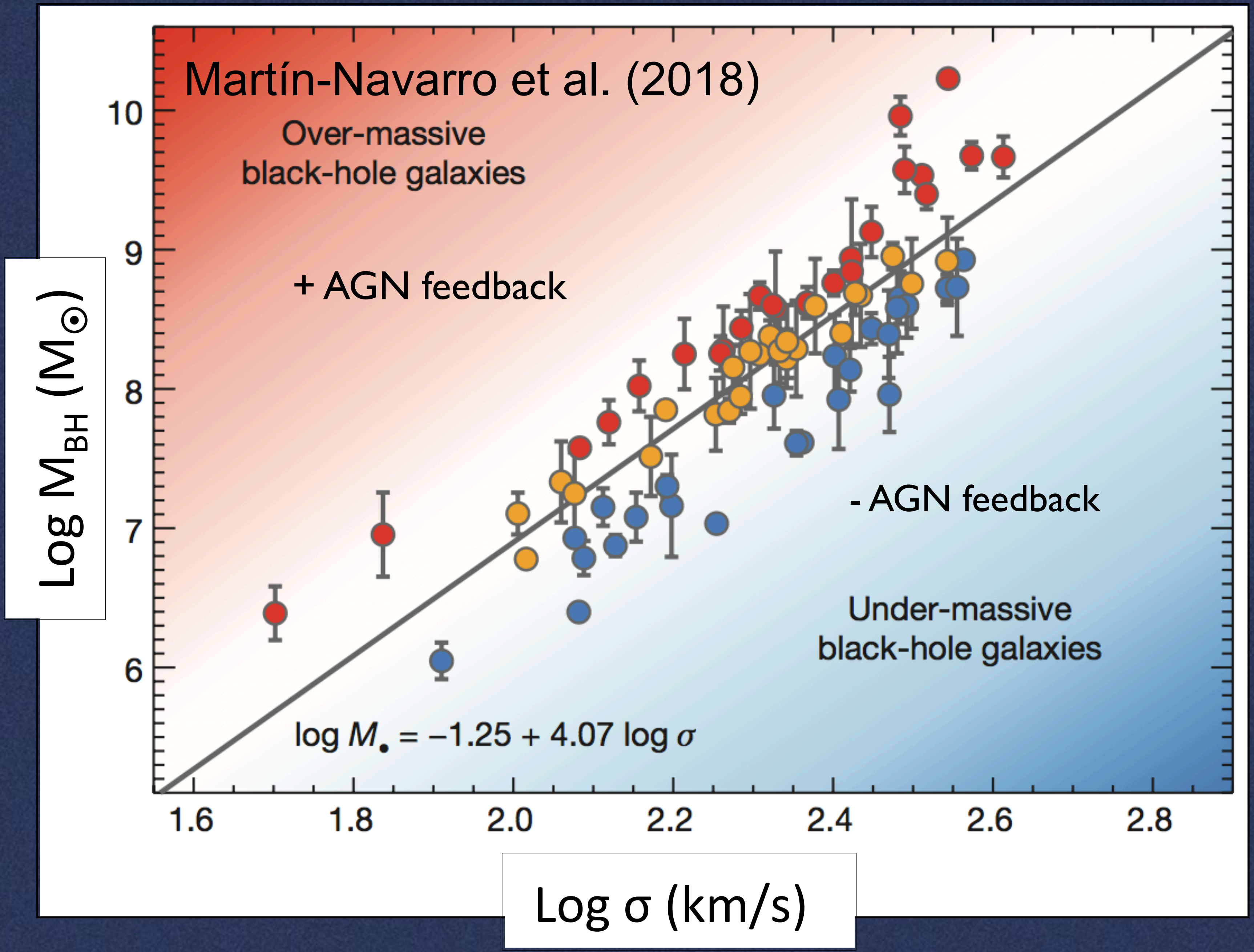


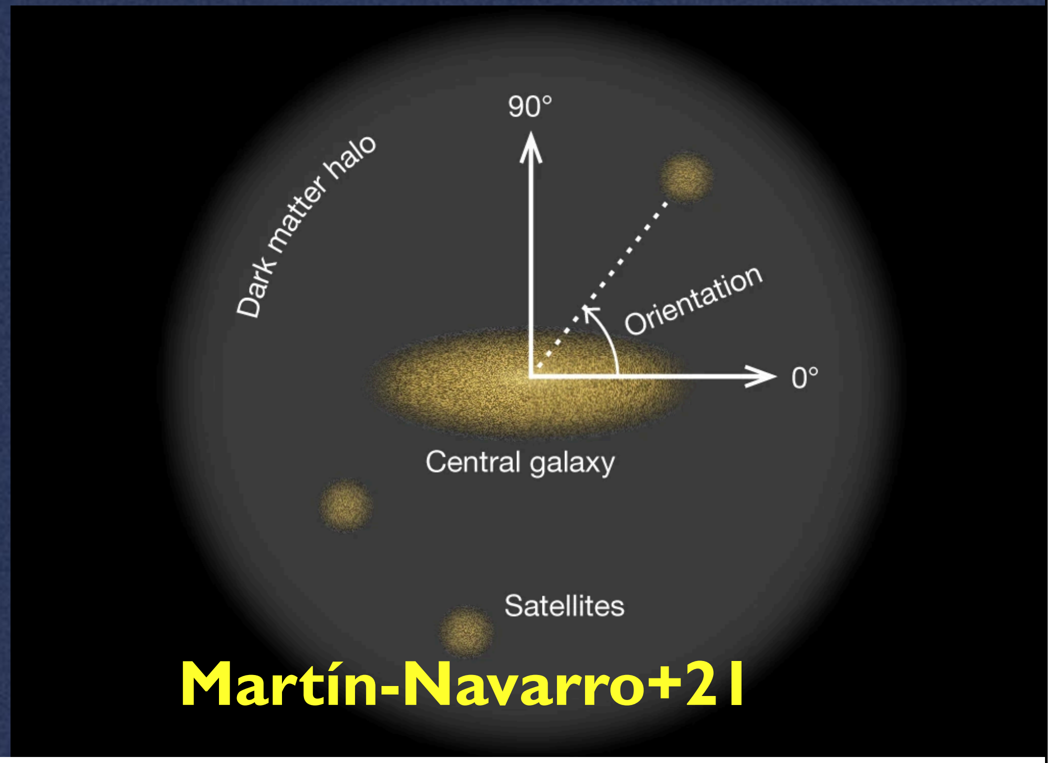
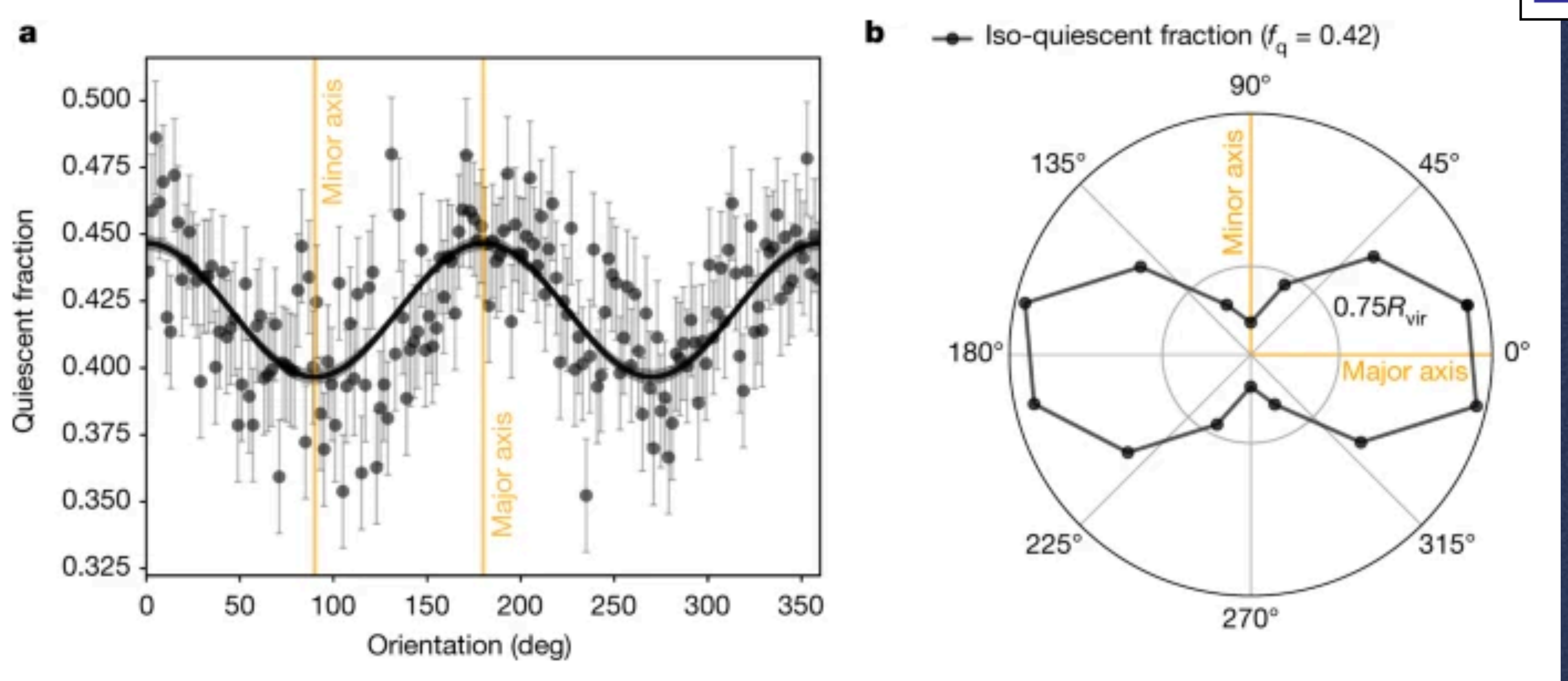
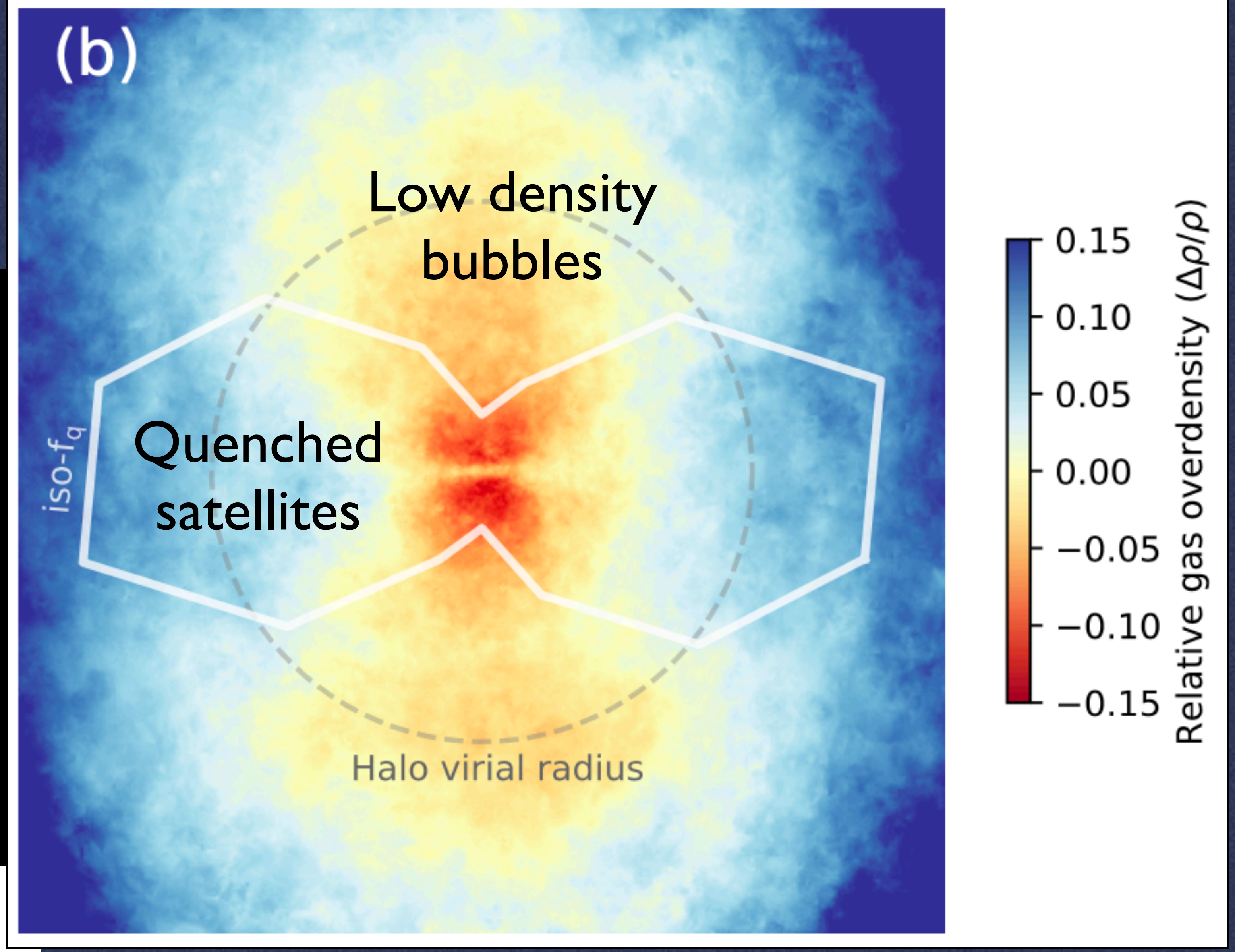




Fig. 2: Anisotropic distribution of quiescent satellite galaxies in SDSS.



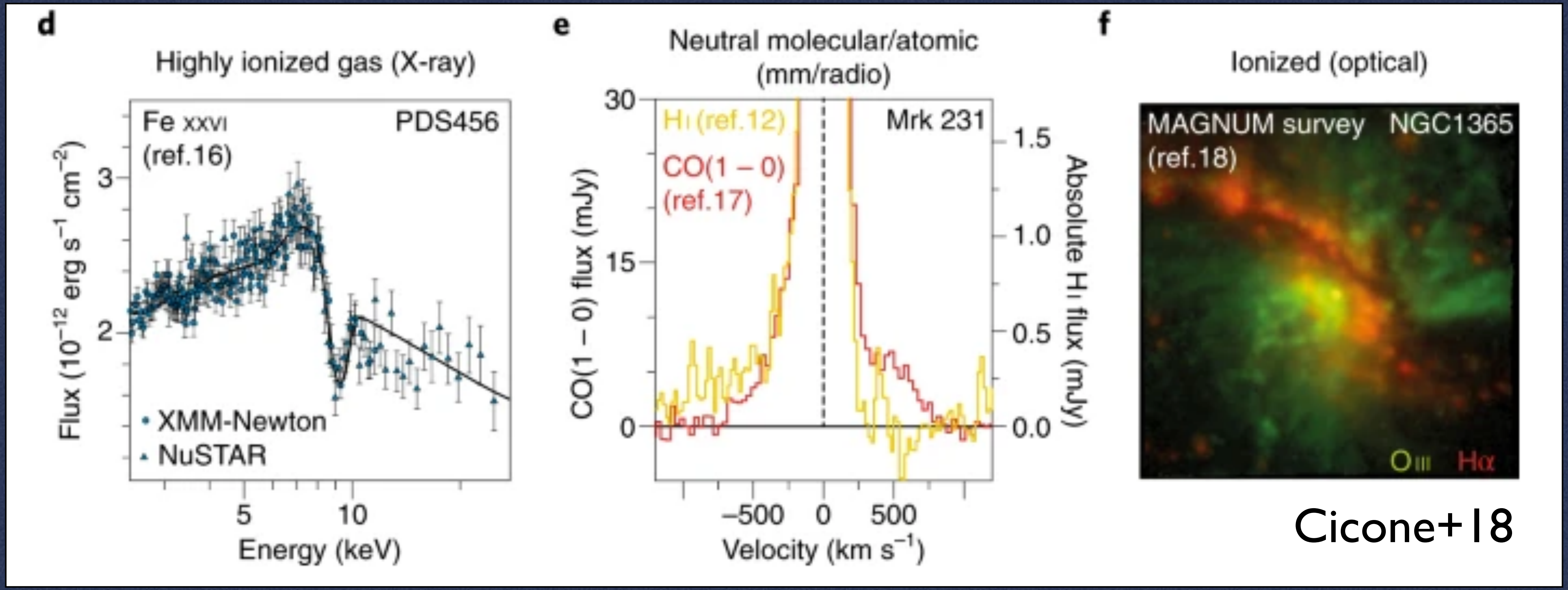

Outflows clearing out the circumgalactic medium along minor axis, reducing ram pressure and thus preserving star formation.

Similar behavior shown by TNG50 simulations.

# AGN-driven outflows

Any gas that is not just photoionised, excited and/or shocked by the AGN, but also kinematically disturbed by it (Davies+20; Harrison & Ramos Almeida 24).

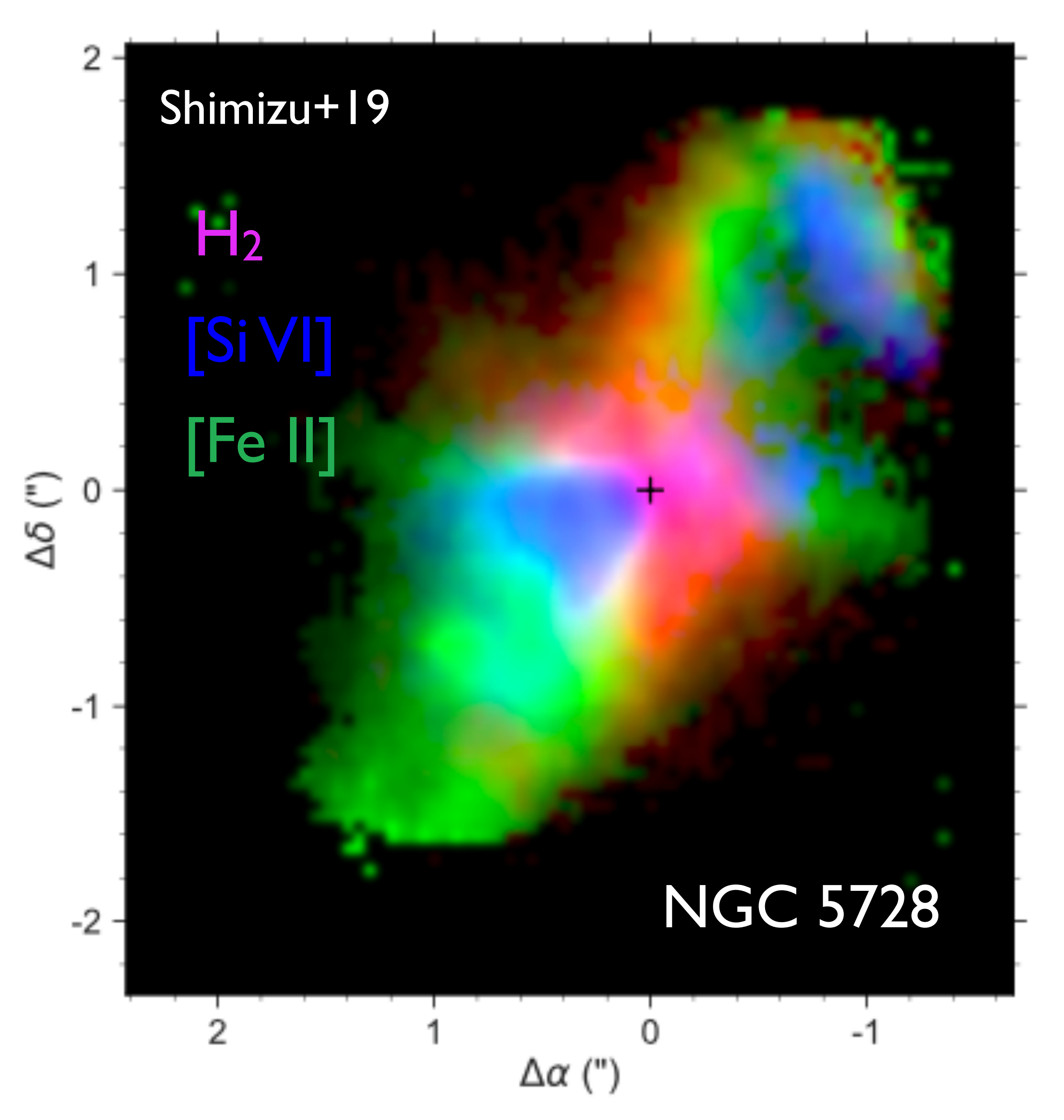
Gas kinematically disturbed by a variety of possible driving mechanisms including accretion disc winds, radiation pressure, and jets.

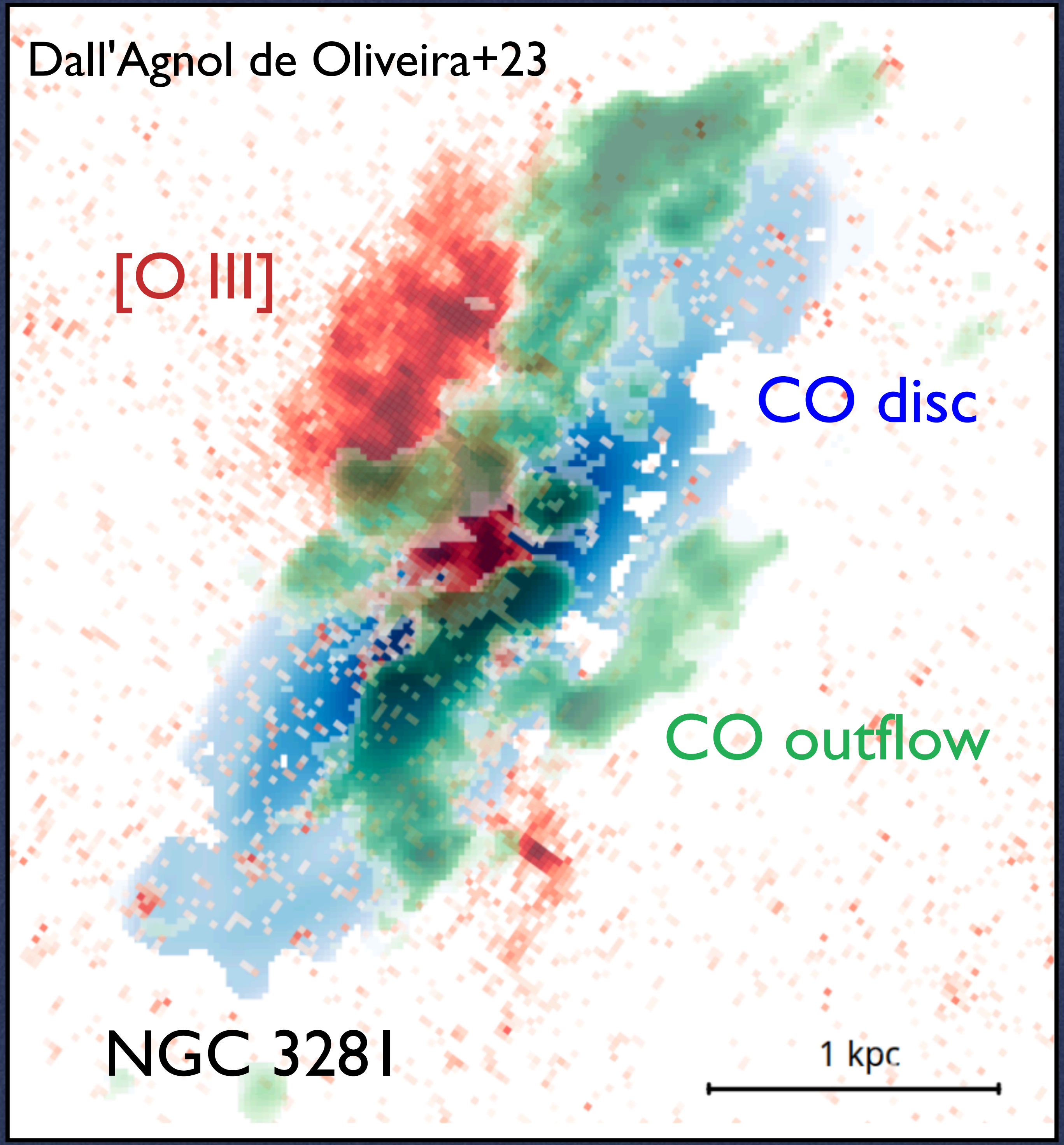


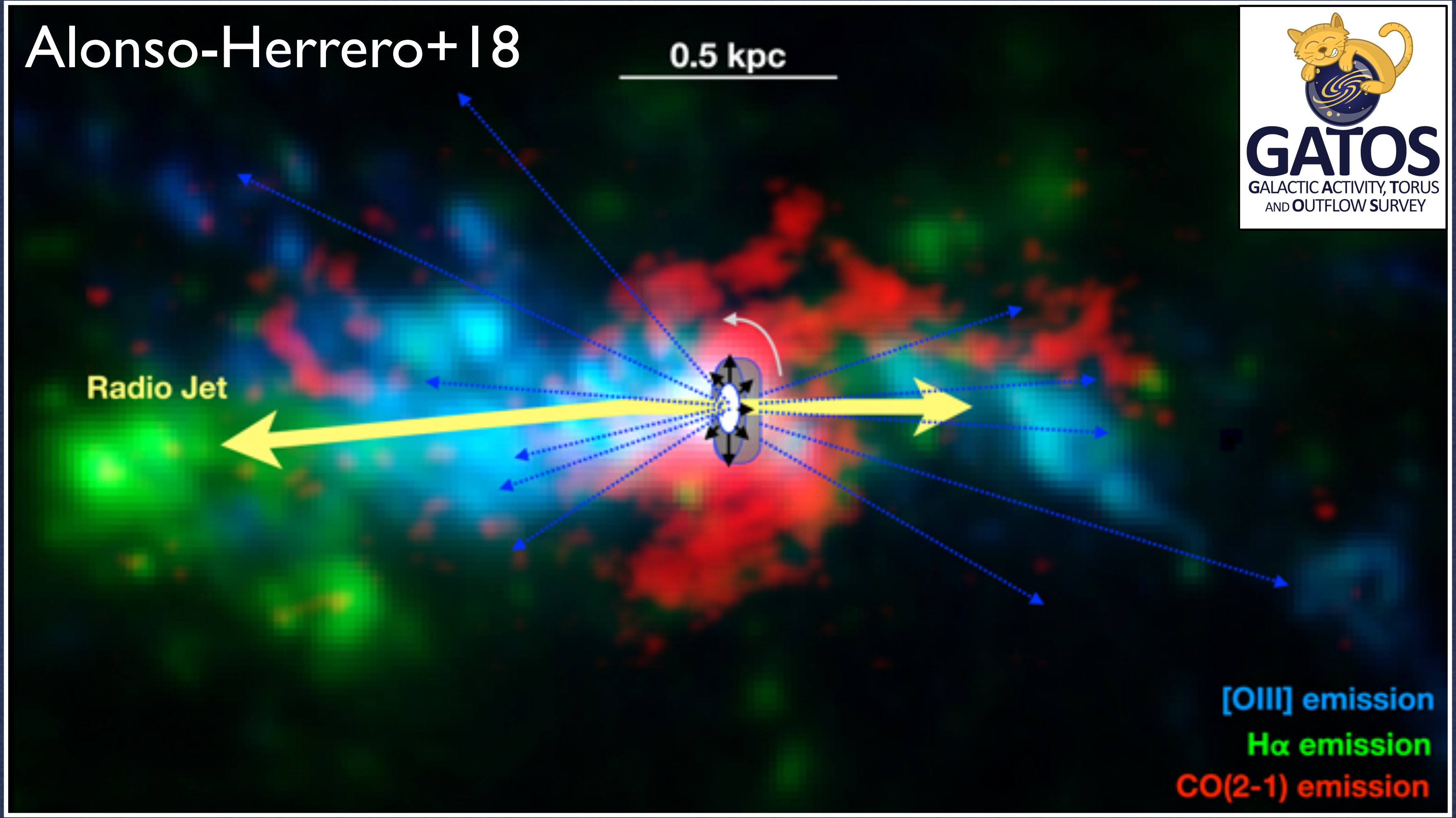

Cicone+18

## Multi-phase gas outflows

Single-phase estimates of outflow properties provide an incomplete view of the AGN feedback phenomenon (Cicone+18).



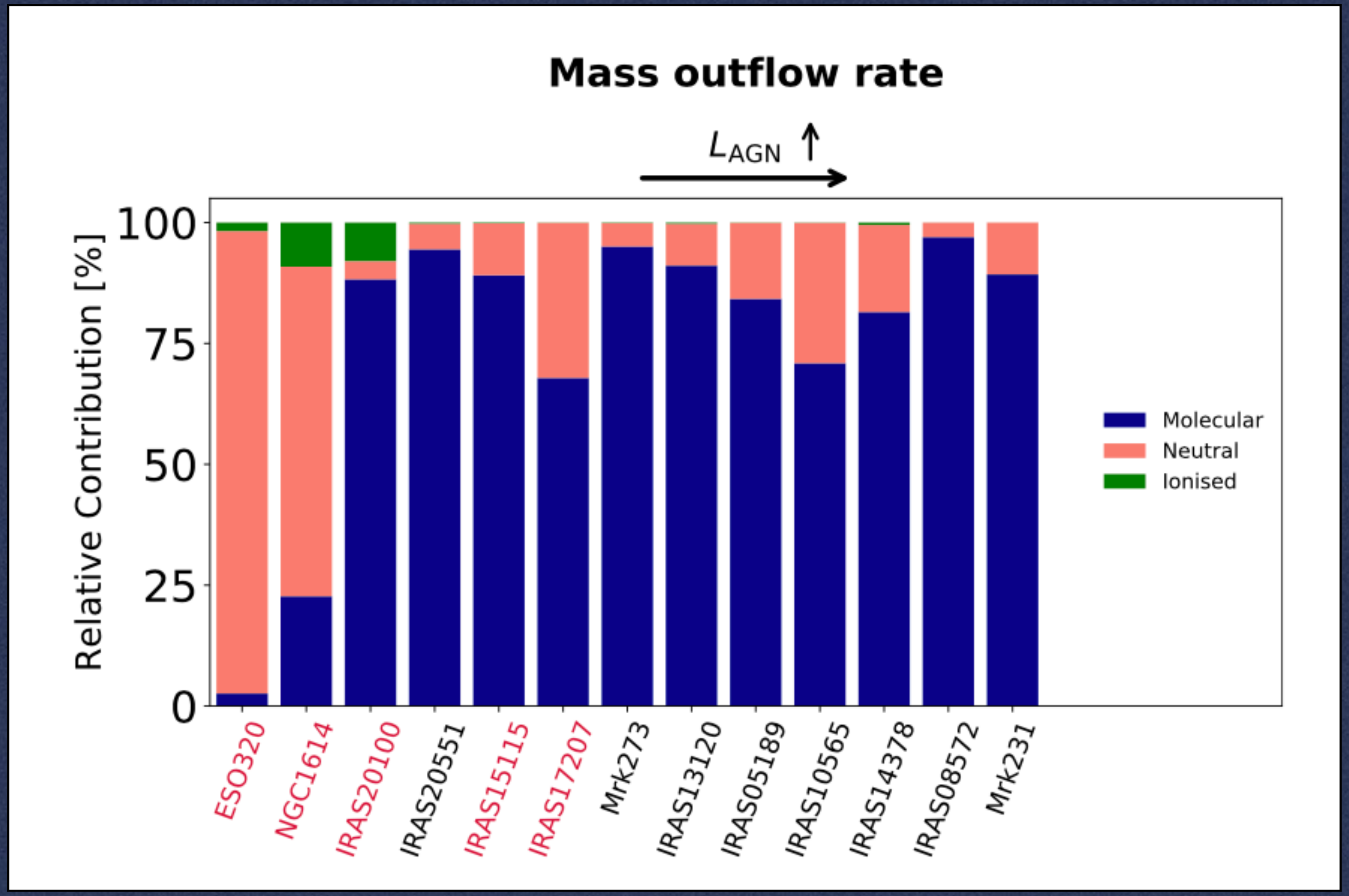



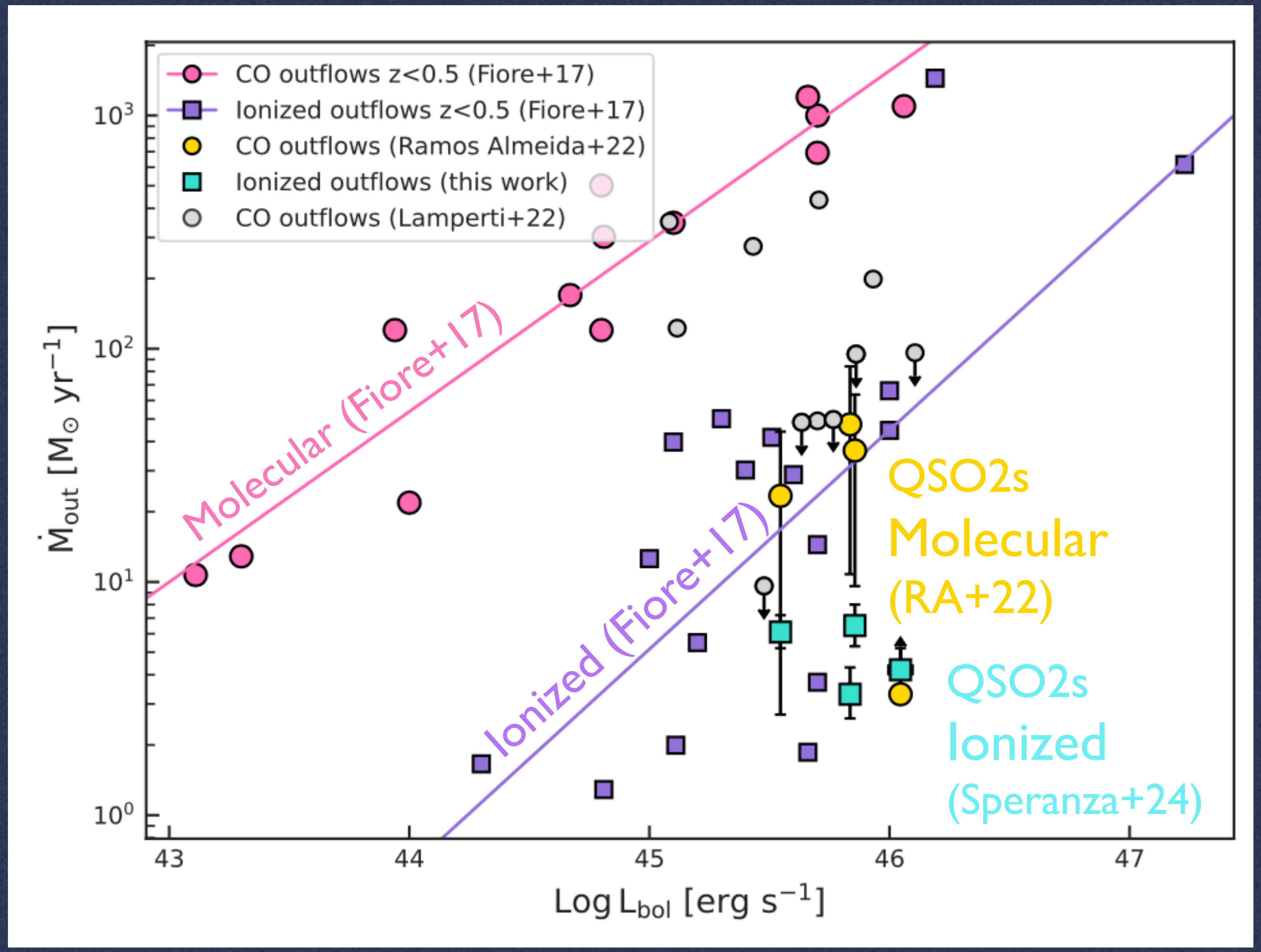
# AGN-driven outflows

Giovanna Speranza

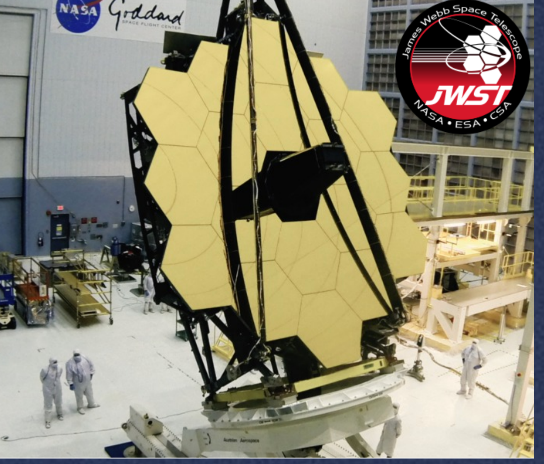
- Molecular gas phase dominant in terms of mass (Fiore+17; Cicone+18; Fluetsch+21; Speranza+24; Vayner+21).




Fluetsch+21

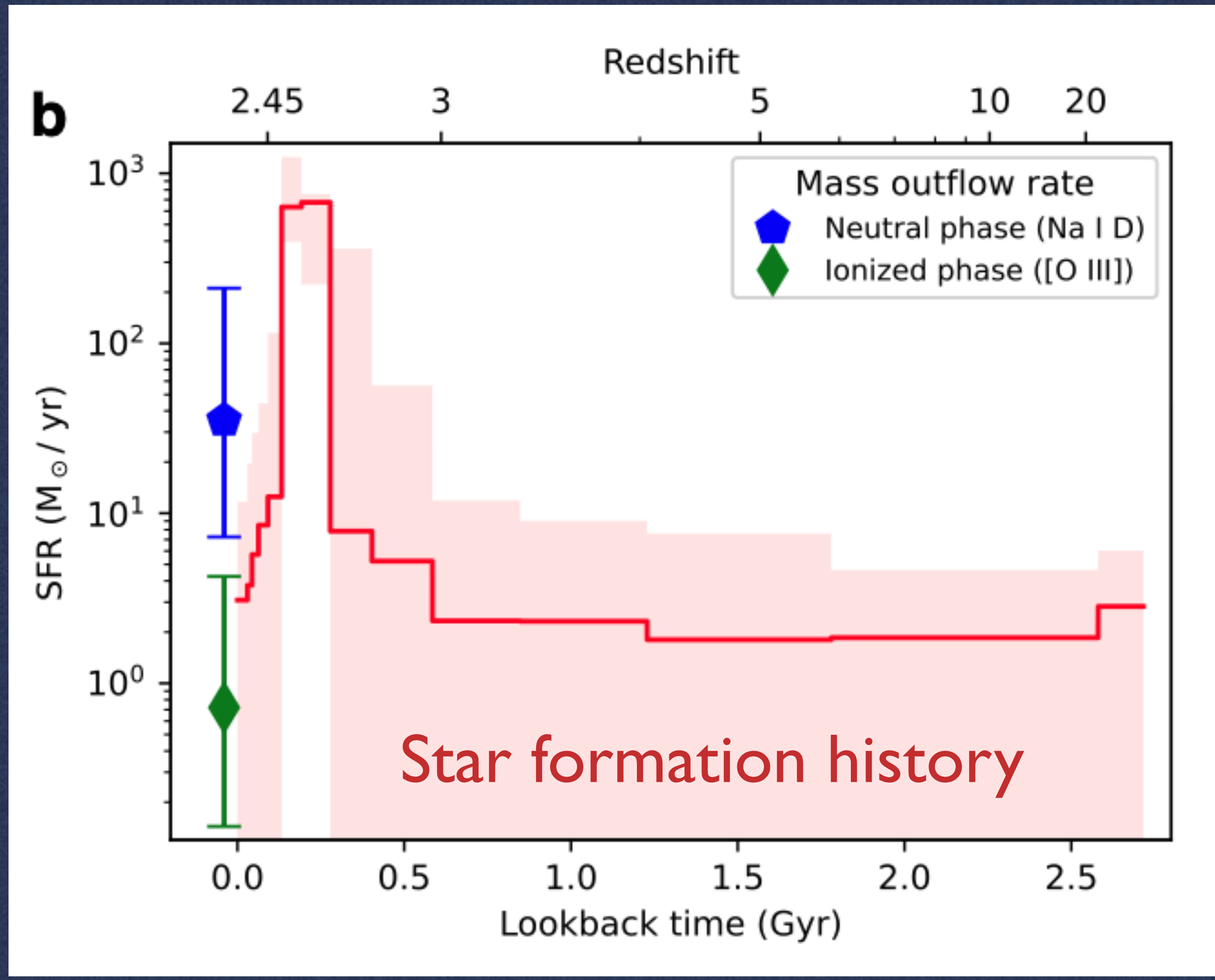



Speranza+24

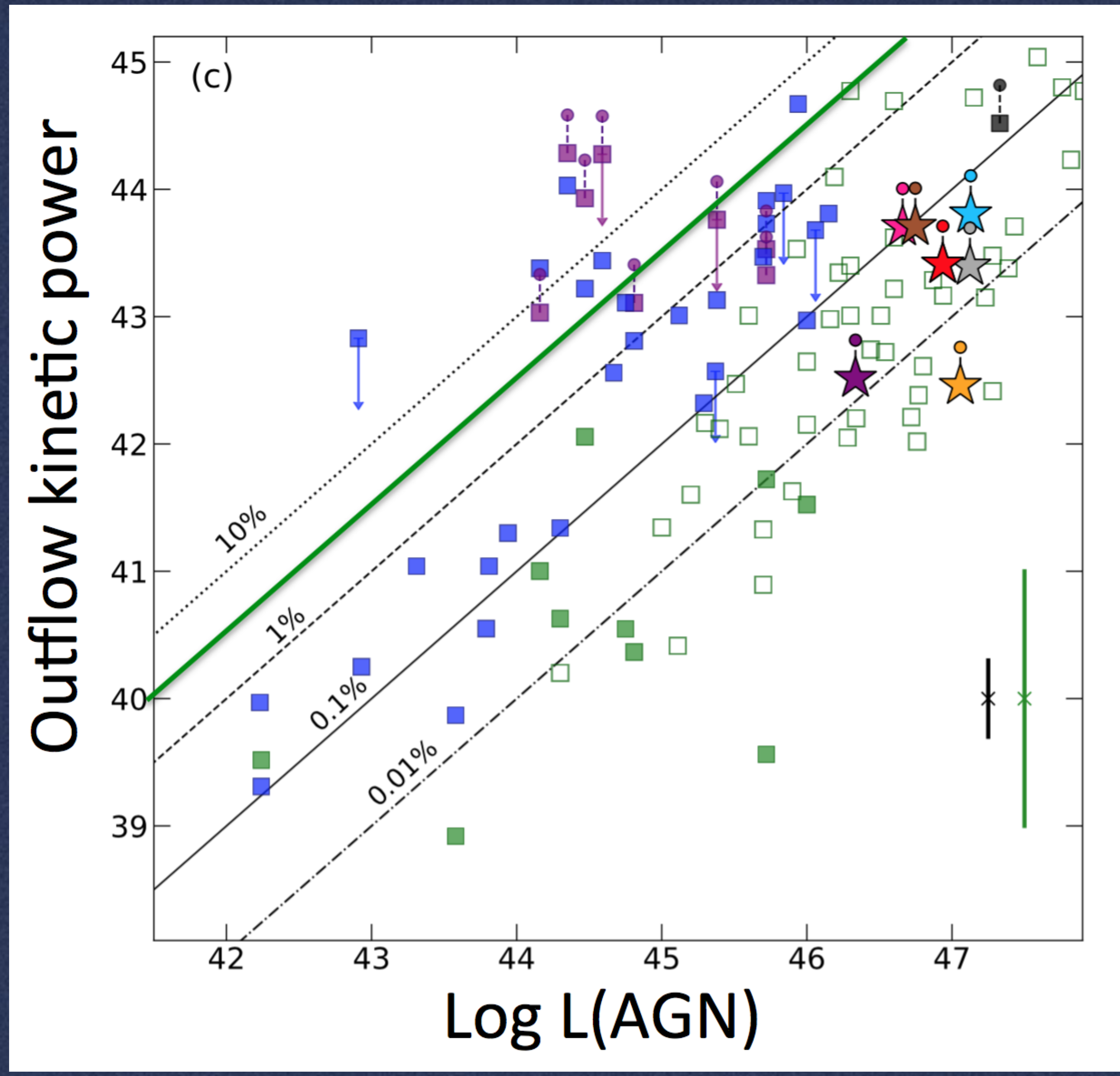


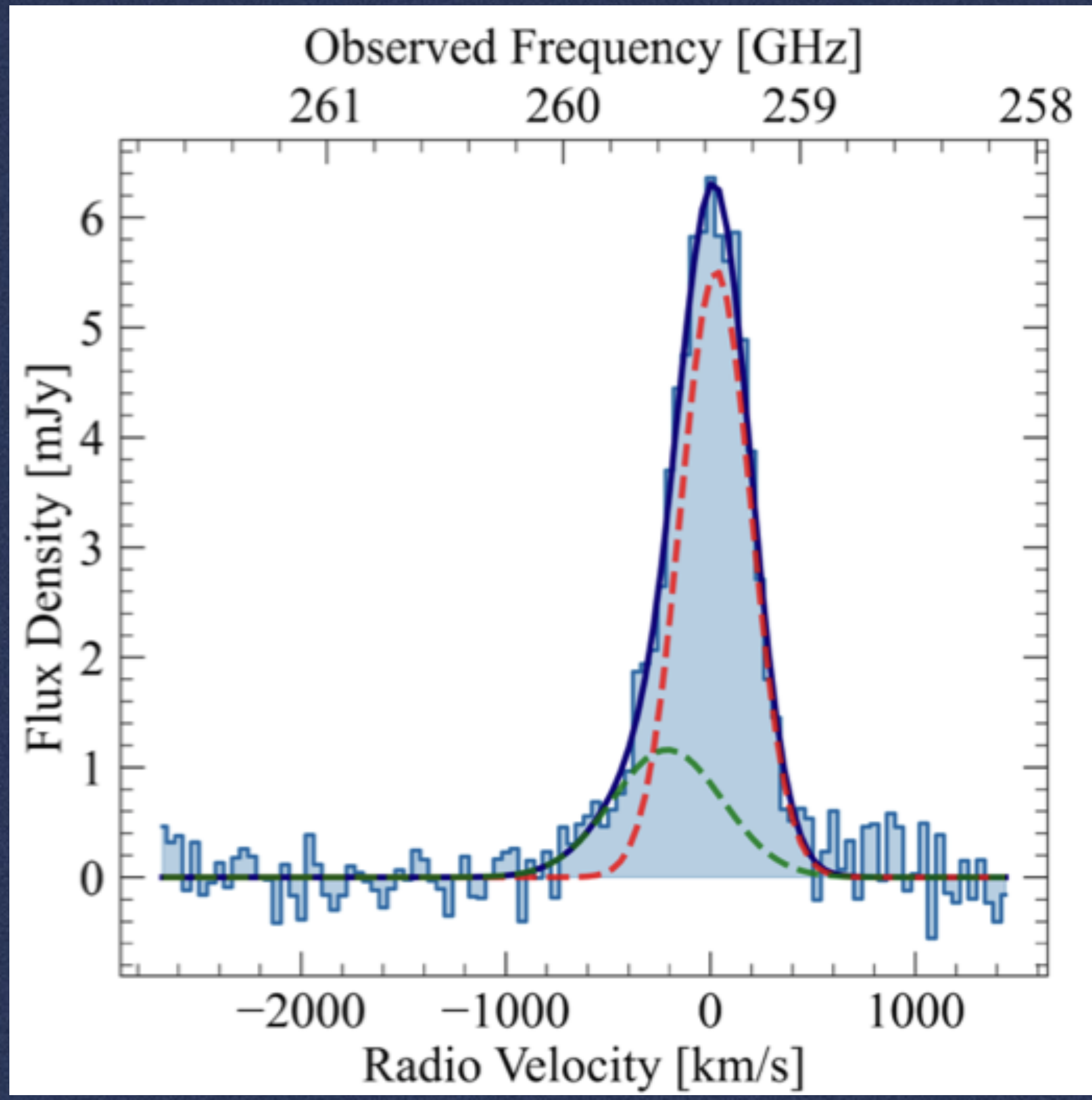
# Neutral outflows more relevant at higher redshift?

Belli+24



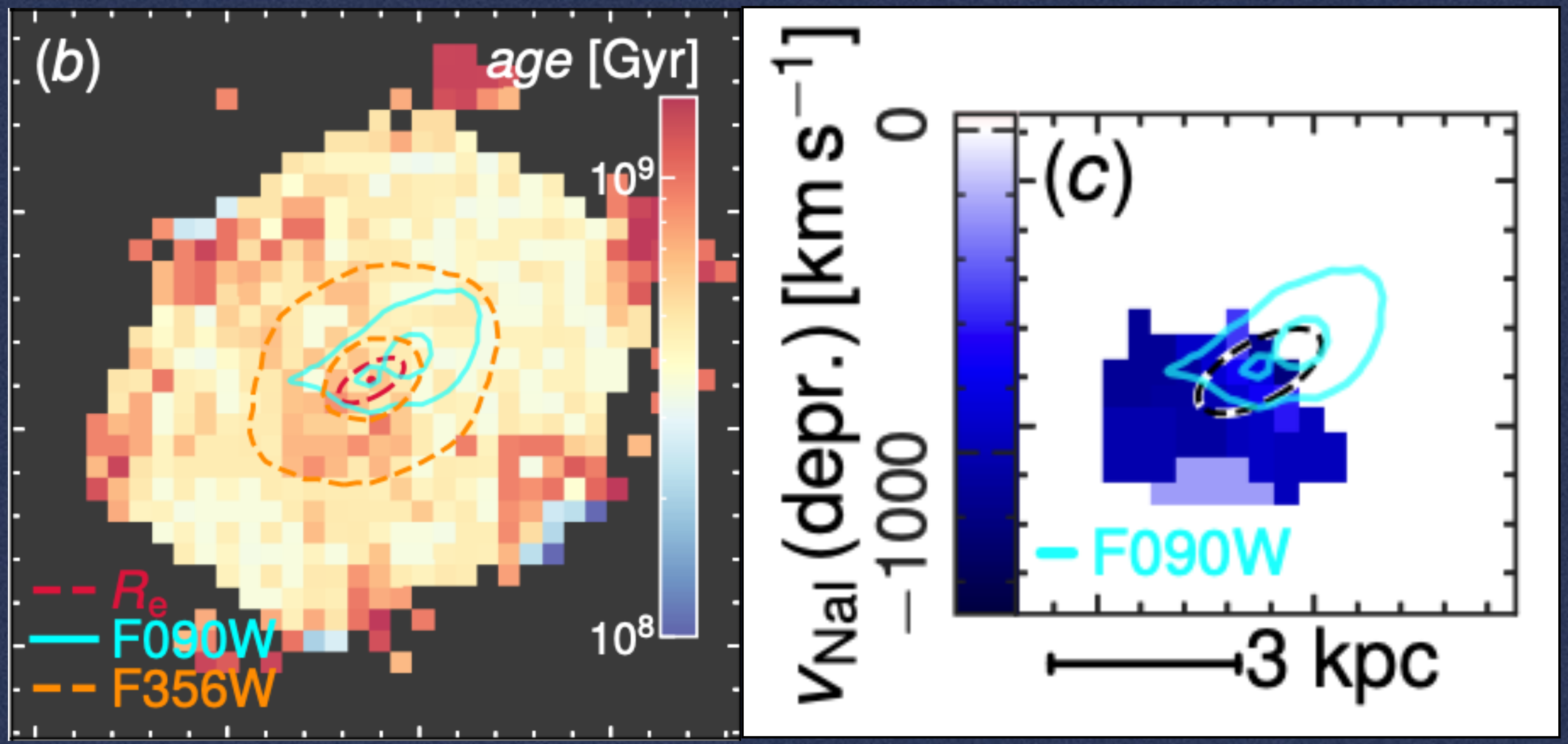

Molecular outflows in high-z (z~6) quasars detected (and not detected) with ALMA.



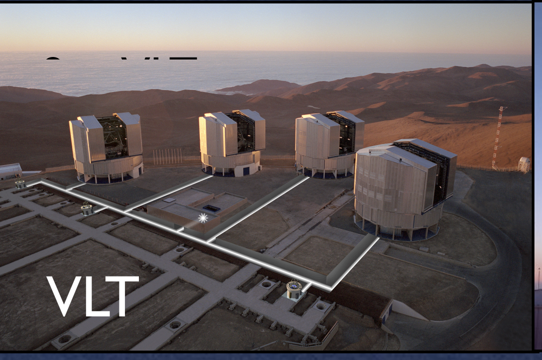




Maiolino+12; Bischetti+19; Stanley+19; Stacey+22

Decarli+18; Novak+20; Tripodi+24




D'Eugenio+24



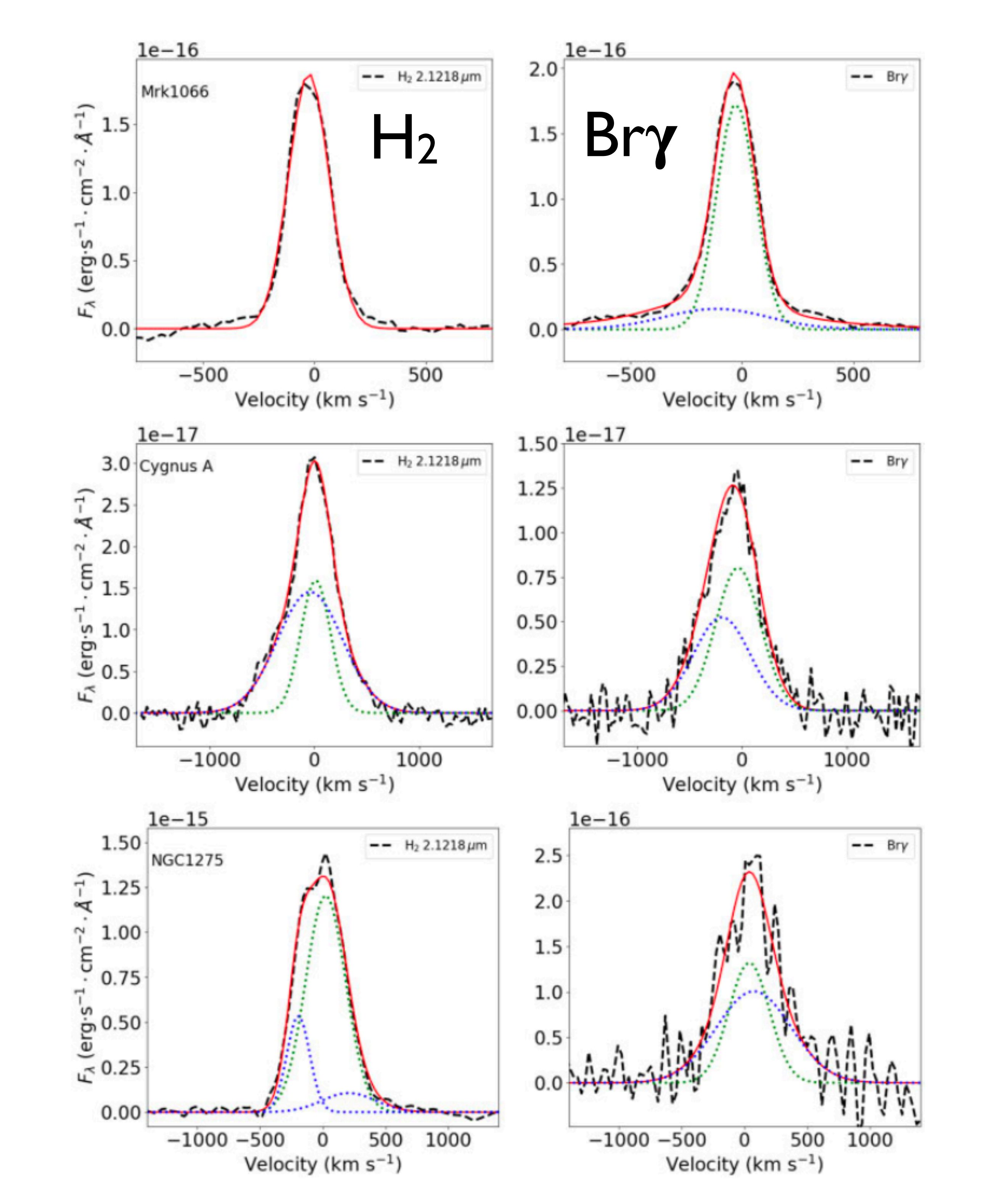


# The elusive warm molecular outflows

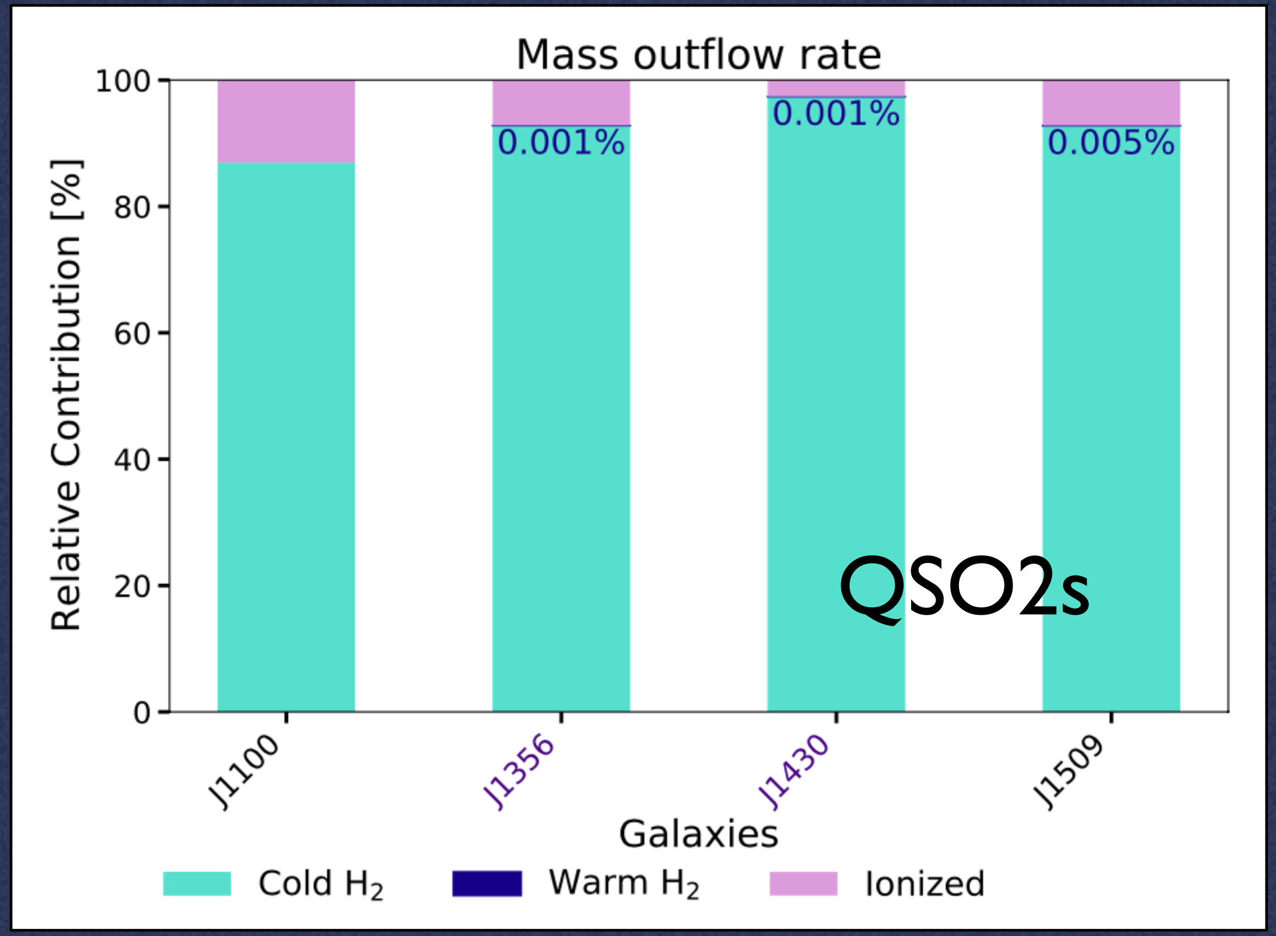
Maria Vittoria Zanchettin

Difficult to detect because of the tiny gas fraction that the near-infrared $H_2$ represents (Ramos Almeida+17, 19, 25; Speranza+22; Riffel+23; Zanchettin+24).

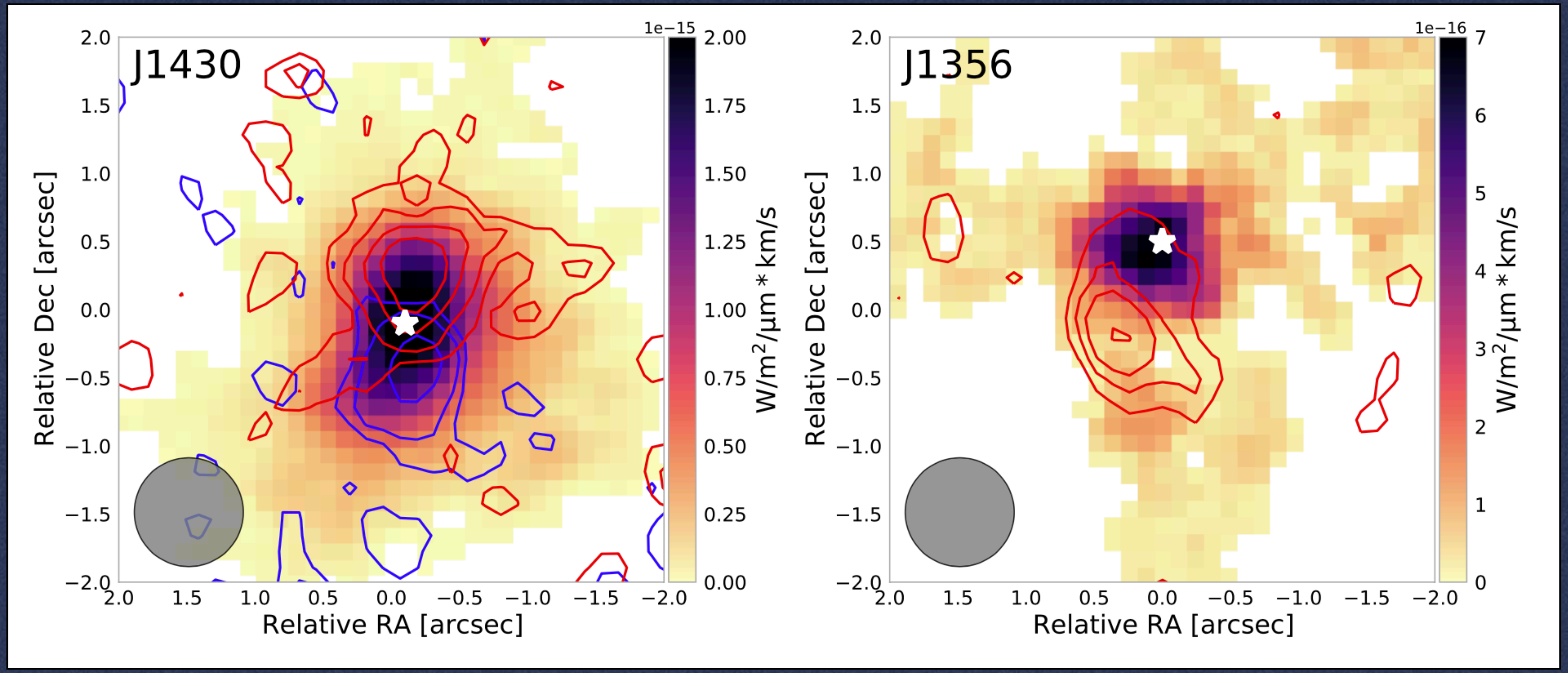
Riffel+23

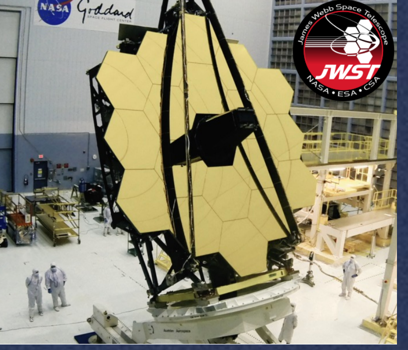



AGNIFS sample
33 local AGN - Brγ & $H_2$




Zanchettin+25





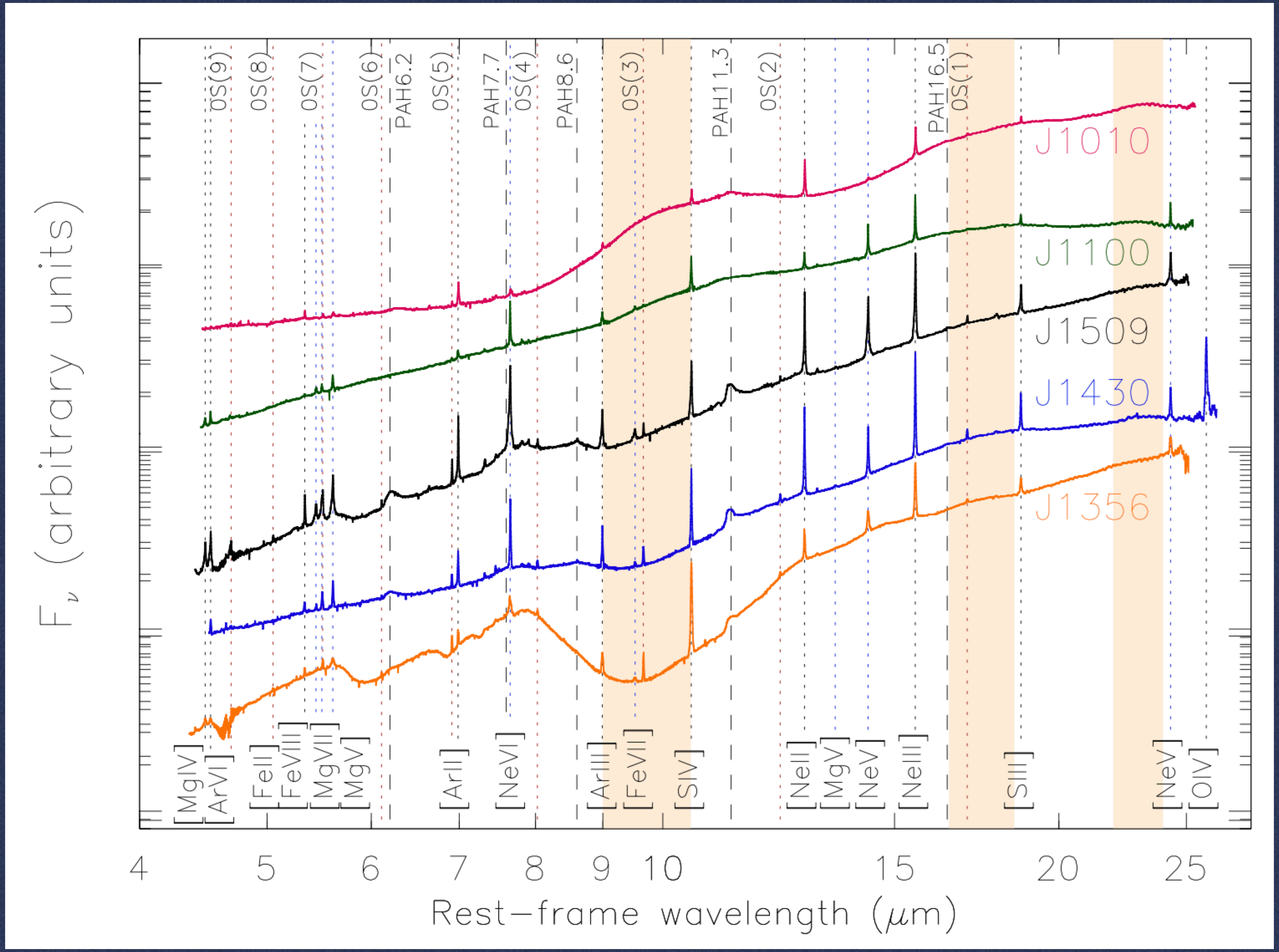
# The elusive warm molecular outflows

JWST/MIRI Cycle 2

proposal 3655, 30 hours

PI: C. Ramos Almeida

Difficult to detect because of the tiny gas fraction that the near-infrared $H_2$ represents (Ramos Almeida+17, 19, 25; Speranza+22; Riffel+23; Zanchettin+25).

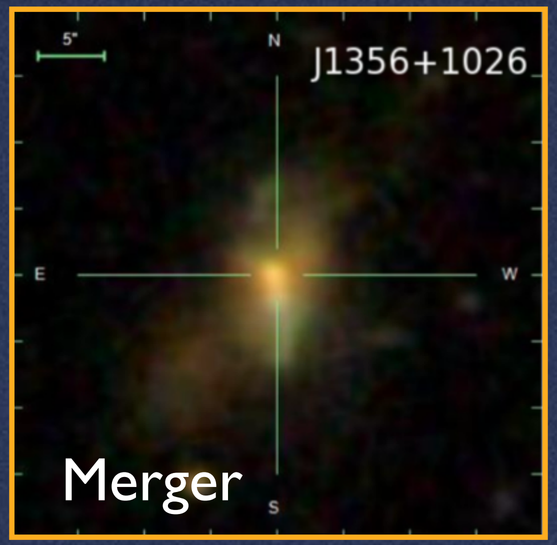


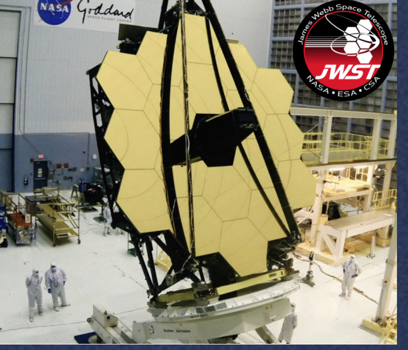

Warm-to-cold gas mass ratios of 1-2%

Ramos Almeida+25



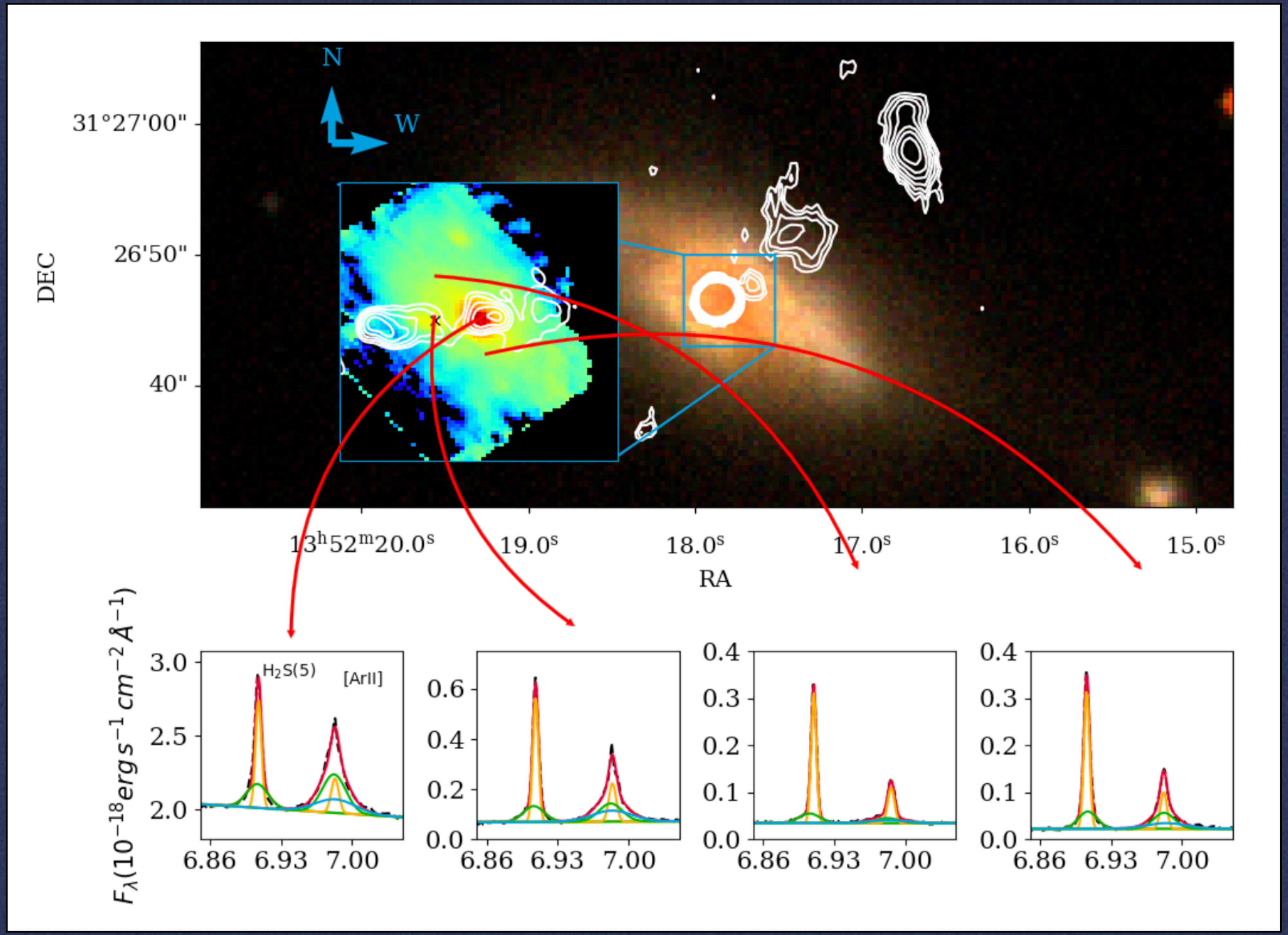




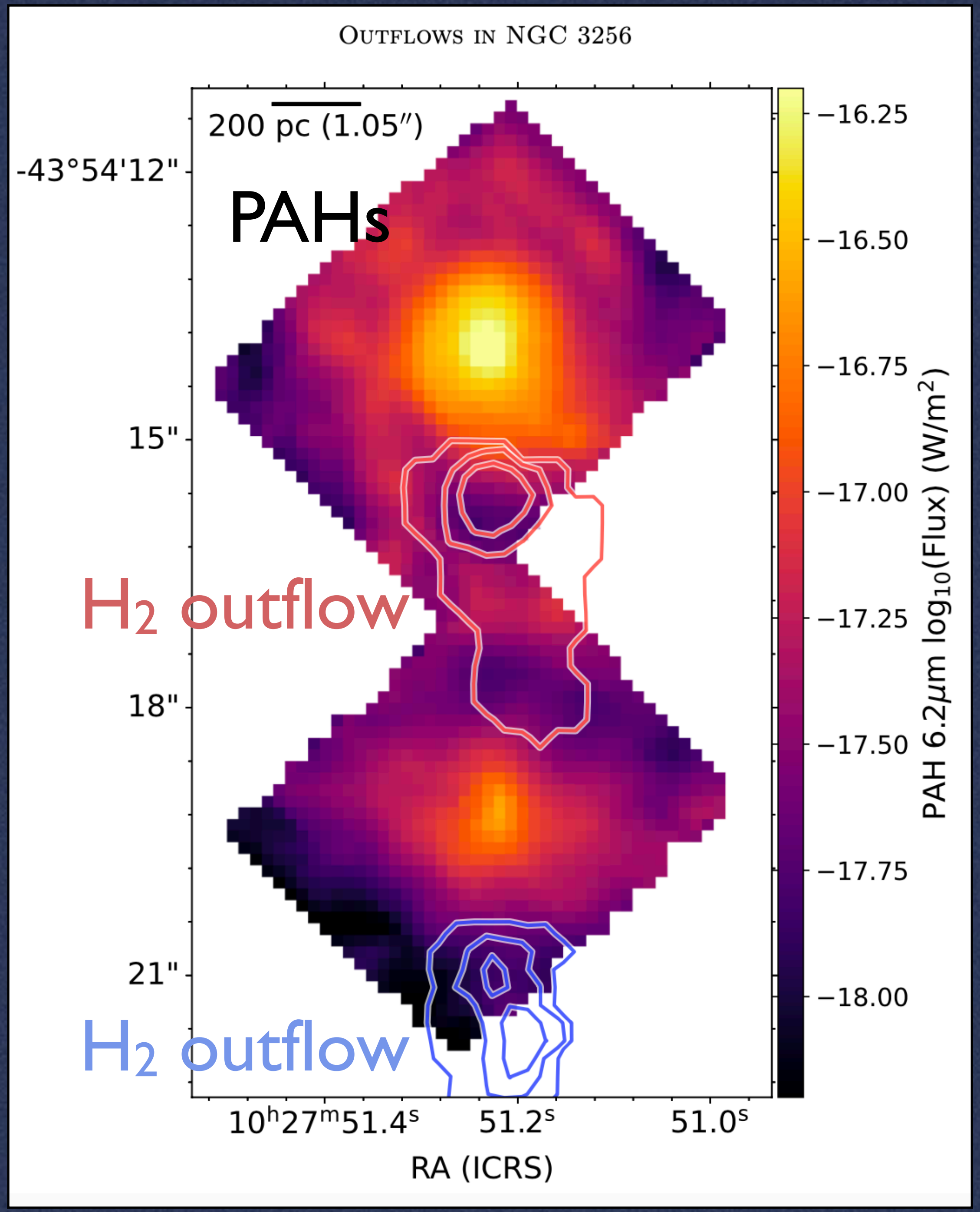


# Studying warm molecular outflows with MIRI

Evidence for jet-ISM interactions in the warm molecular gas (Pereira-Santaella+22; Costa-Souza+24).




Costa-Souza+24 UGC8782




Bohn+24 NGC3256

See also warm molecular outflows in jetted-AGN reported by Dasyra+11 (Spitzer/IRS); Davies & GATOS 24; Esparza-Arrendondo & GATOS 25 (JWST/MIRI).

# Take home messages

- There are no observations inconsistent with AGN feedback being crucial component of galaxy evolution theory for explaining properties of massive galaxies.
- AGN = events and not objects that persist in time. Difficult to directly relate a single accretion episode to a significant, global impact on galaxy properties.
- By studying currently active AGN with spatially-resolved observations, we can obtain crucial information on physics of localised feedback, essential to determine how energy couples with gas, and under which circumstances enhances or reduces star formation efficiency.
- Global galaxy properties are influenced by the cumulative output of multiple accretion episodes.
- Evidence of cumulative AGN impact on global galaxy properties better found in galaxy population as a whole. Important for testing/ruling out AGN feedback prescriptions implemented in simulations.
- For outflows to be relevant their energy has to couple to multi-phase gas, and coupling depends on several factors including AGN luminosity, jet-power, jet/wind orientation and ISM properties.



Plan de Recuperación, Transformación y Resiliencia
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