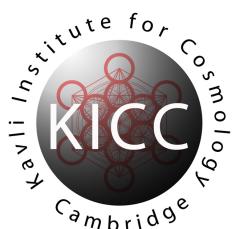
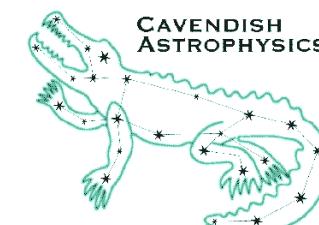


Observational evidence for AGN feedback throughout the cosmic epochs

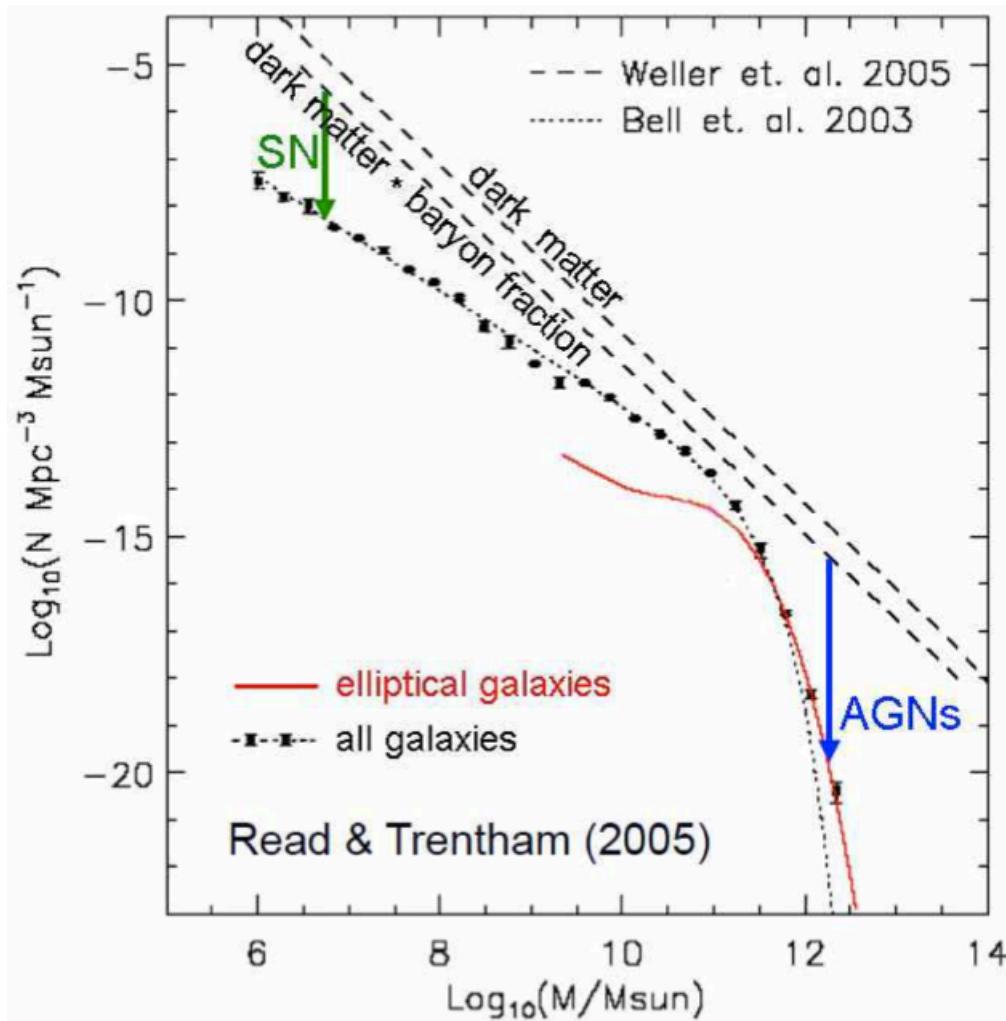
Roberto Maiolino



UNIVERSITY OF
CAMBRIDGE



The need for (negative) feedback

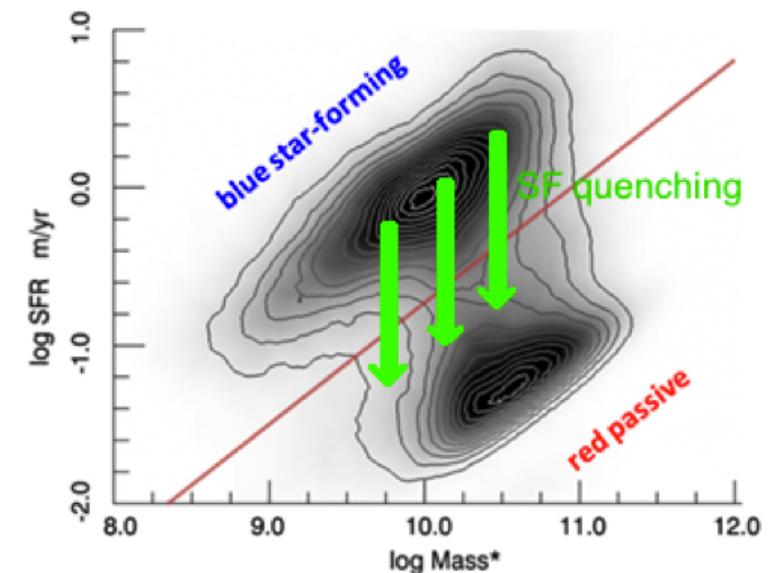


Theoretical expectations:

SNe + stellar radiation feedback:
removes baryons from galaxies
and reduce SF efficiency
in low mass galaxies

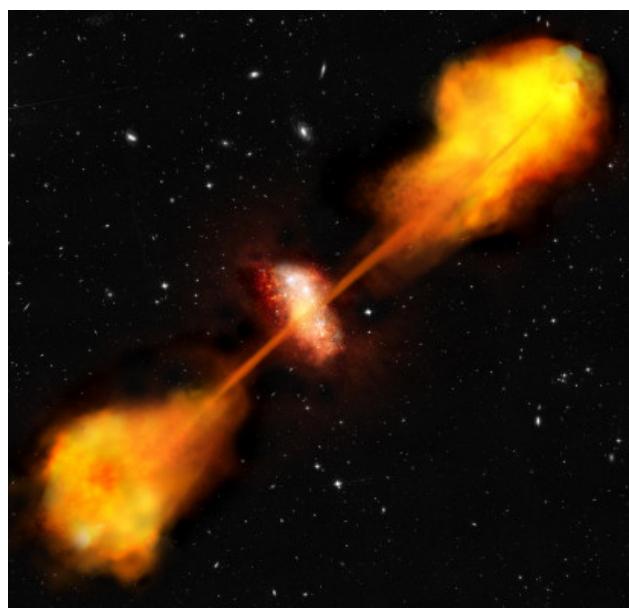
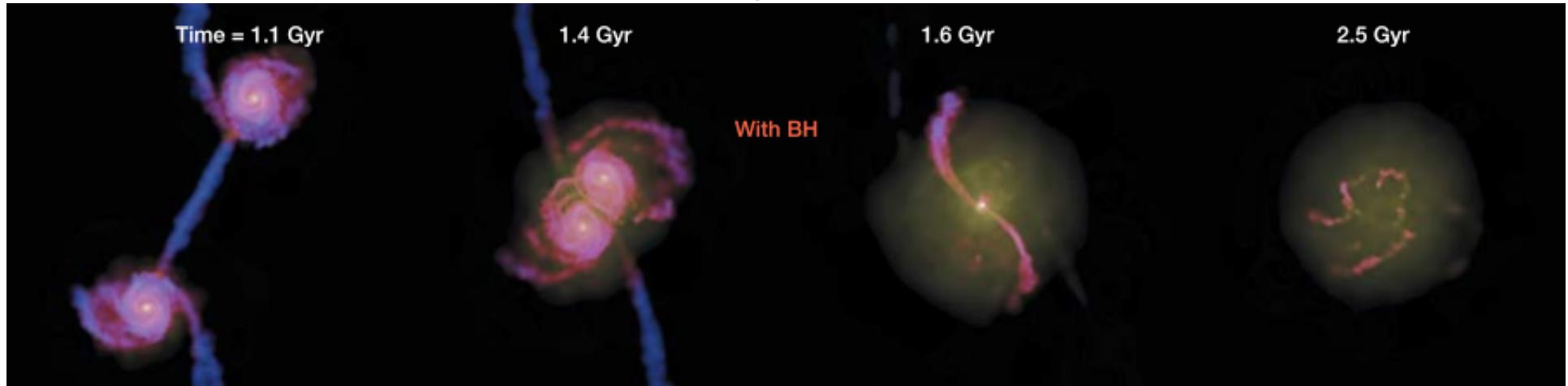
AGN feedback:

- prevents overgrowth of massive galaxies (and of BHs)
- invoked for the $M_{\text{BH}}-M_{\text{star}}$ relation
- explains red-and-dead properties of local ellipticals



AGN feedback (rough) scenario

Invoked by most models to quench star formation in massive galaxies and to keep them “dead”



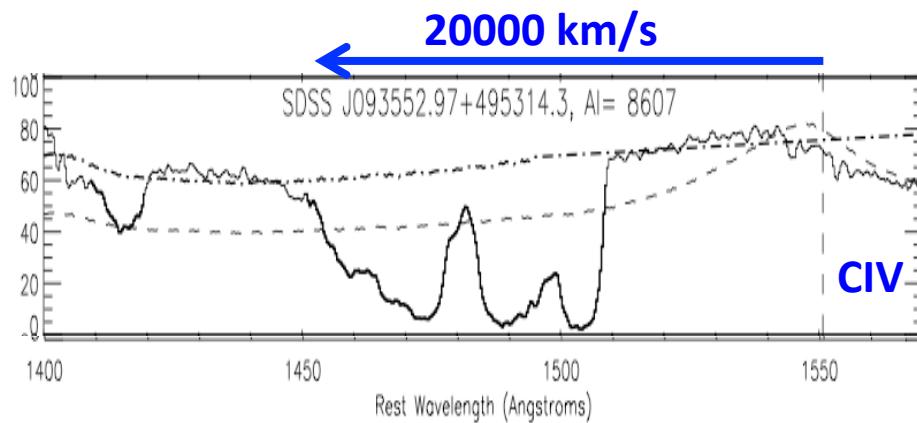
Quasar mode

Radio (maintenance)
mode

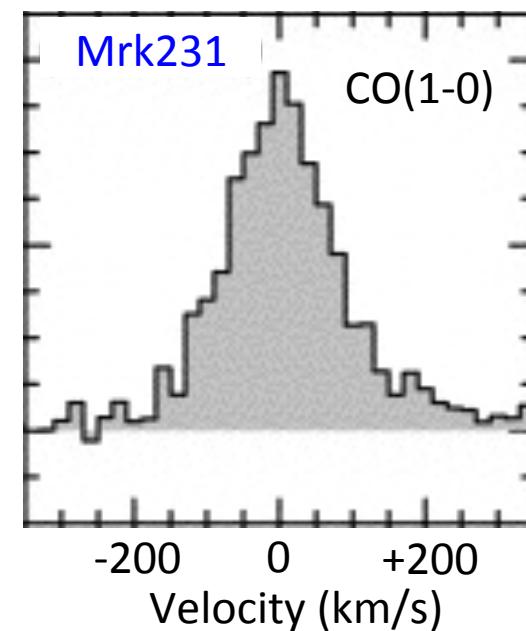
Silk & Rees 1998, Granato+04, Di Matteo+05, Bower+06, Croton+06, Springel+08, King+05,10, Zubovas & King'11, Menci+06,08, Narayanan+06,08, Hopkins+08,+10,

Observational evidence for “quasar-mode” feedback: early misconceptions

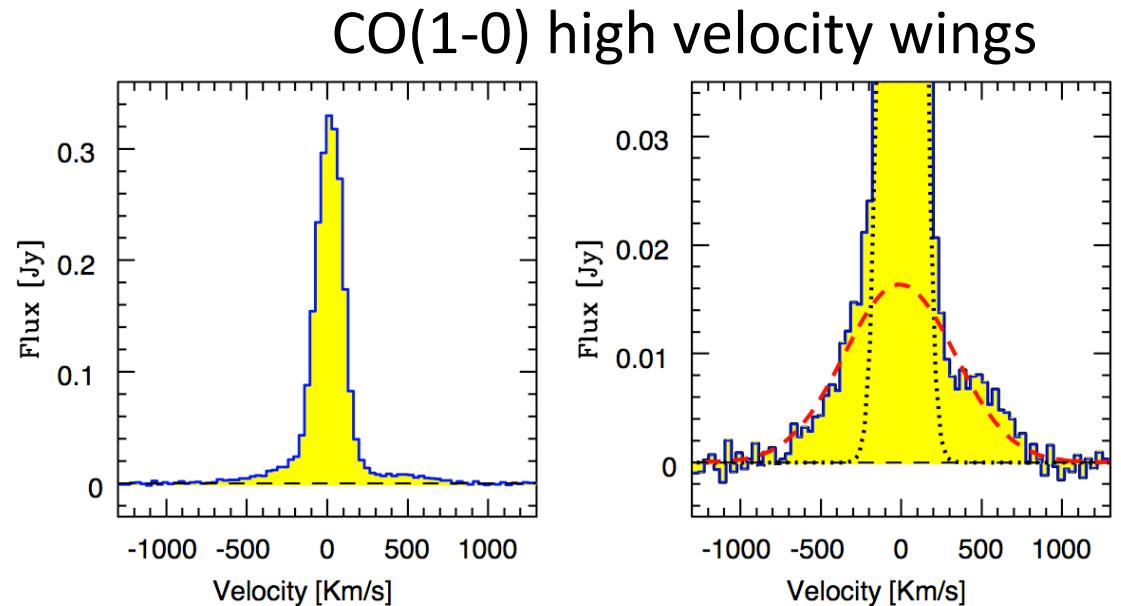
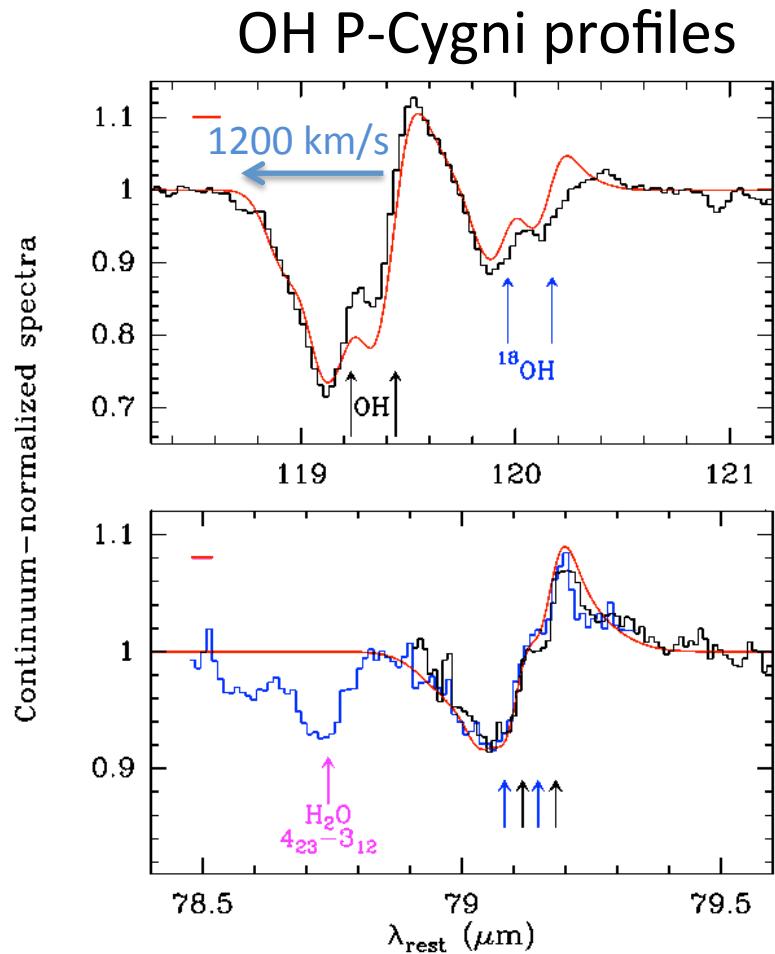
“Broad Absorption Line (BAL) winds are nuclear
→ not affecting the galaxy on large scales”



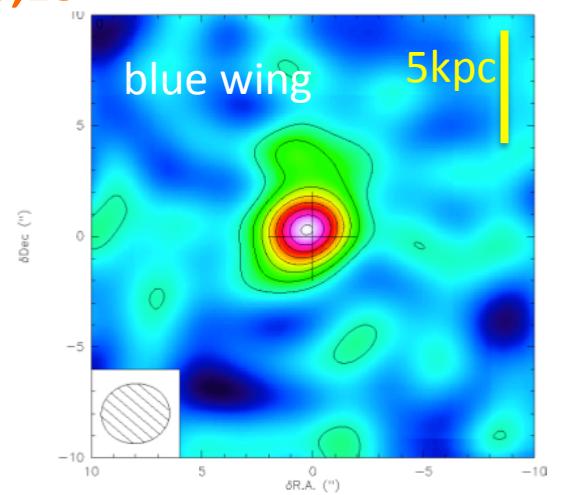
“(molecular) gas in quasar hosts is in regular rotation, quiescent unaffected by the quasar”



First evidence of quasar-mode feedback in local quasars achieved only recently

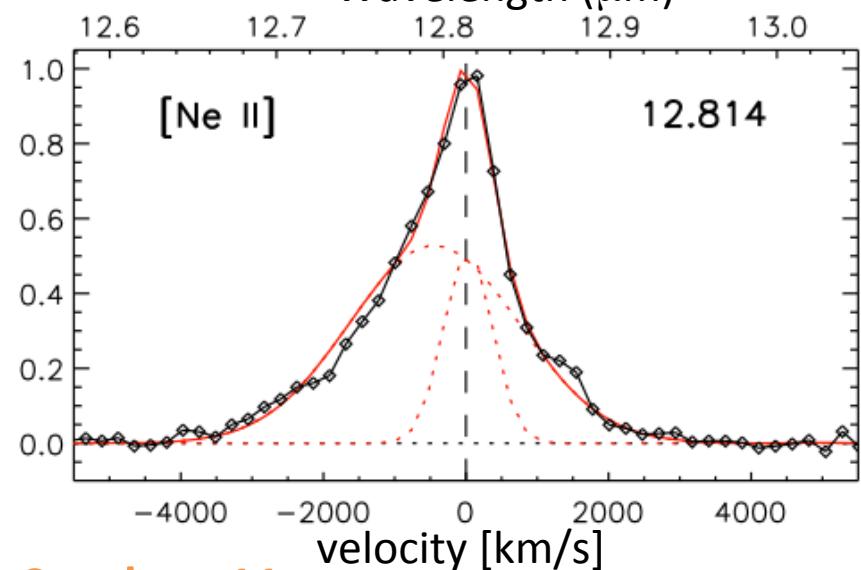
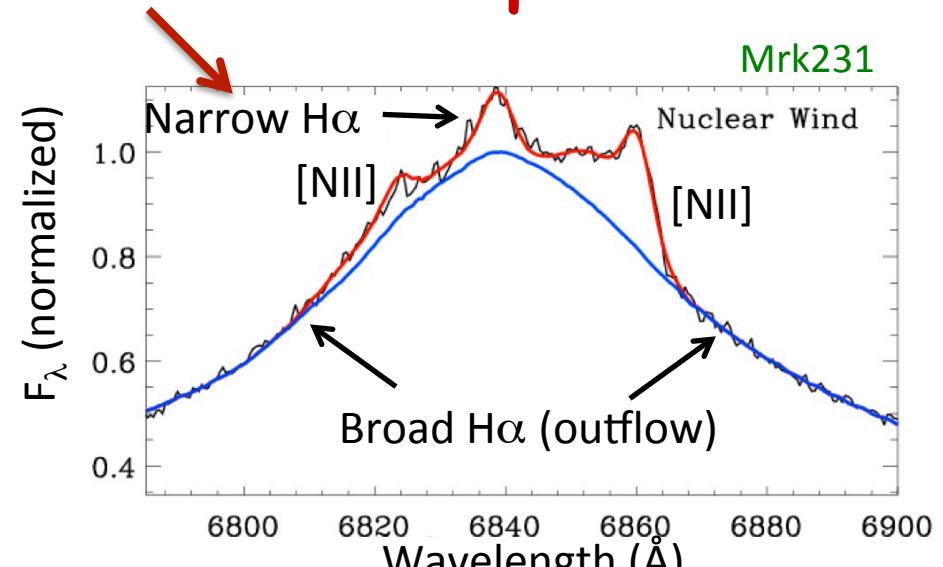
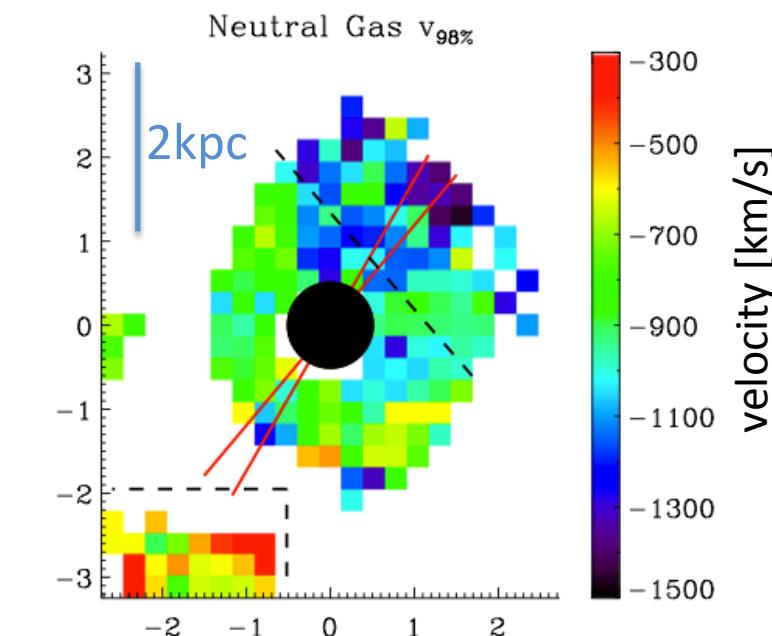
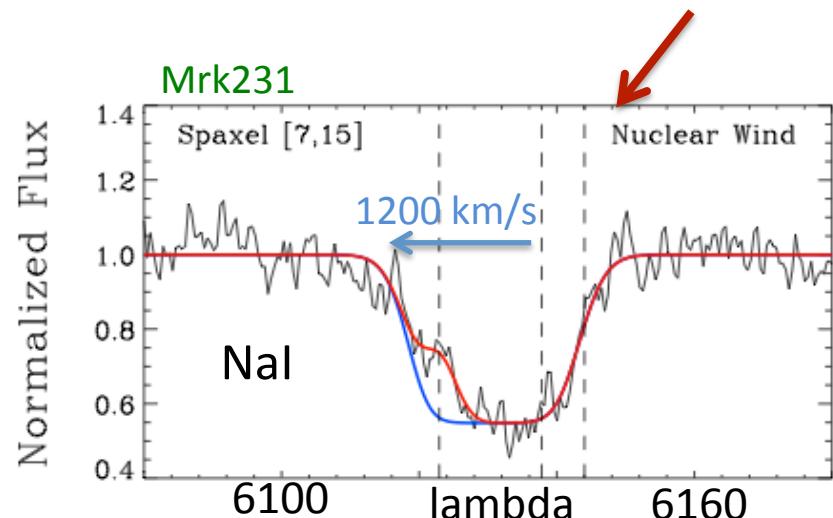


Fischer+10 Feruglio+10,13
Sturm+11



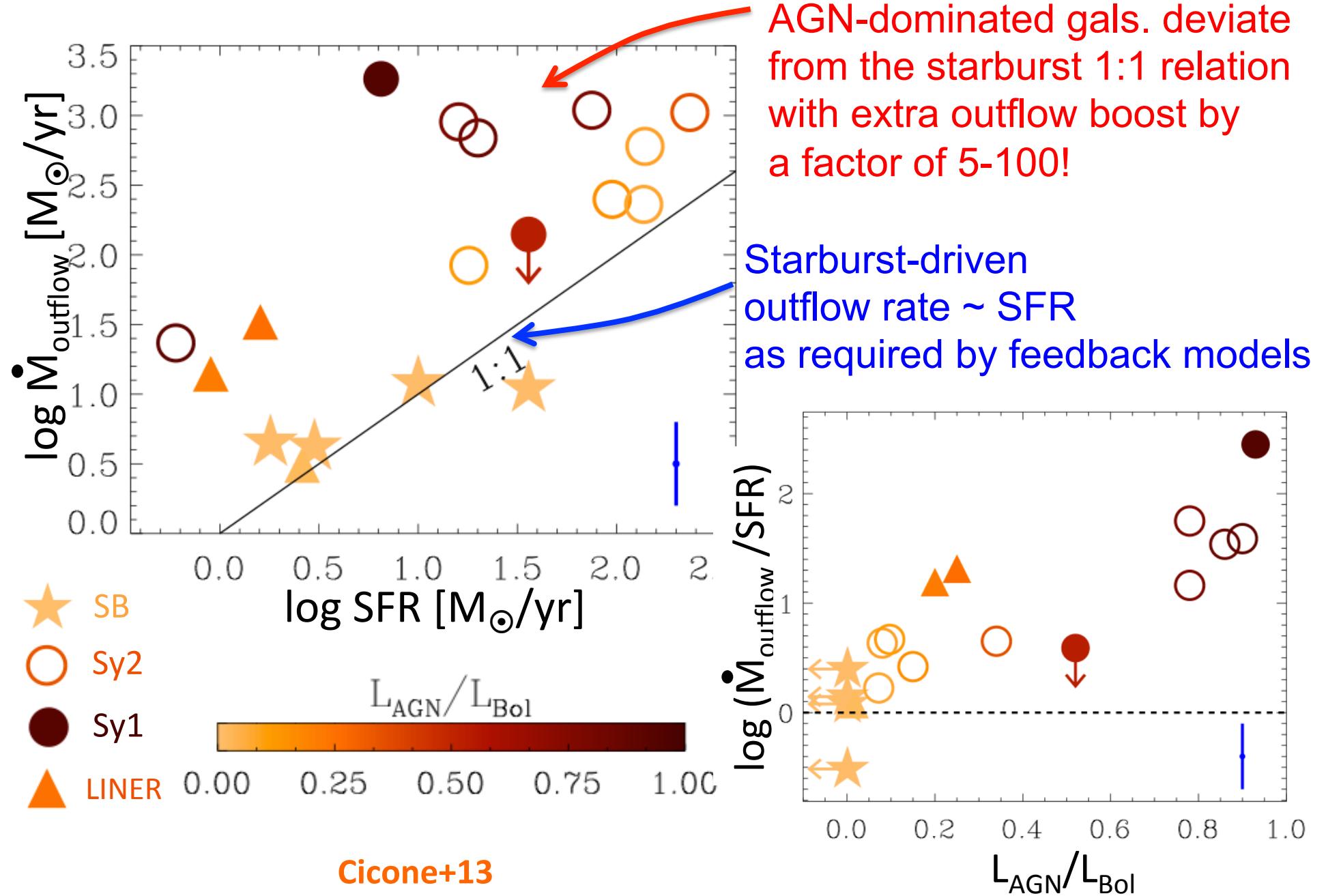
Massive molecular outflows ($1000 M_\odot/\text{yr}$)
Extended on kpc scales

Massive outflows detected also in the atomic neutral and ionized component



Rupke+11,13, Spoon+11, Greene+11, Muller-Sanchez+11

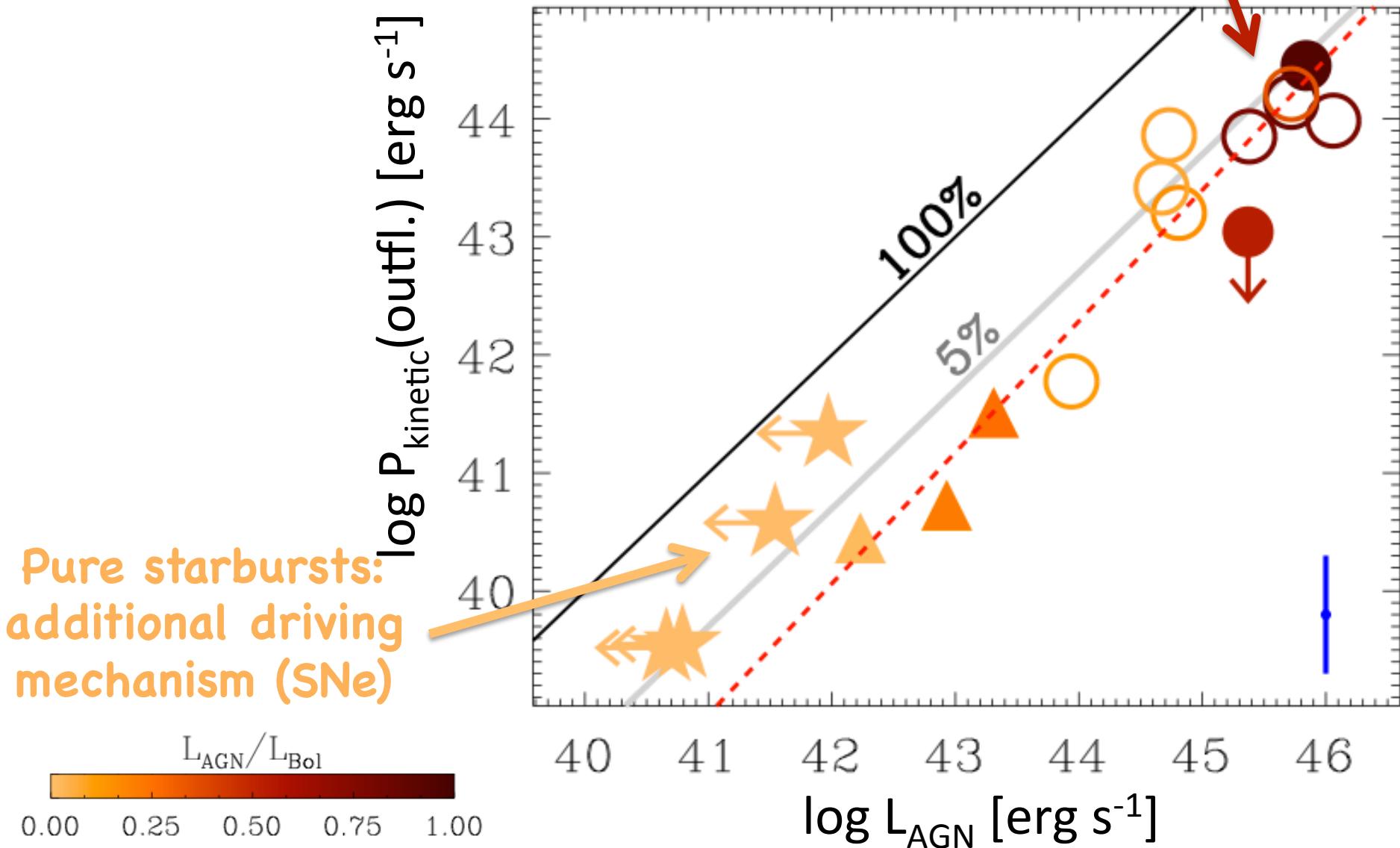
More CO observations (IRAM, Carma,...+ALMA ongoing)



Outflow kinetic power (in powerful AGNs)

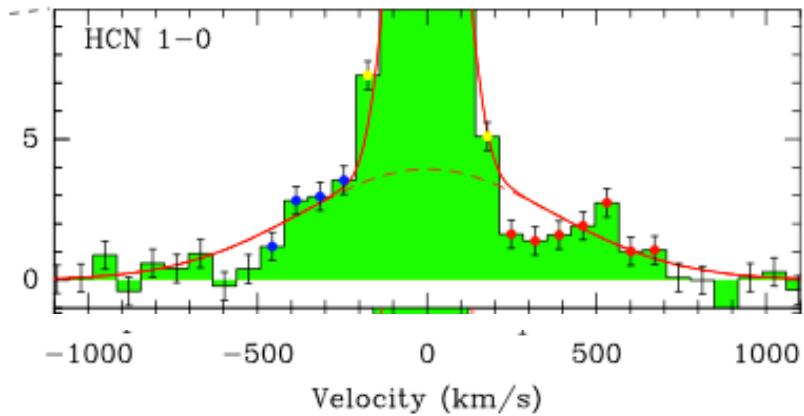
$P_K \sim 0.05 L_{\text{AGN}}$

as predicted by models (King's talk)



Investigating the physics gas of quasar-driven outflows

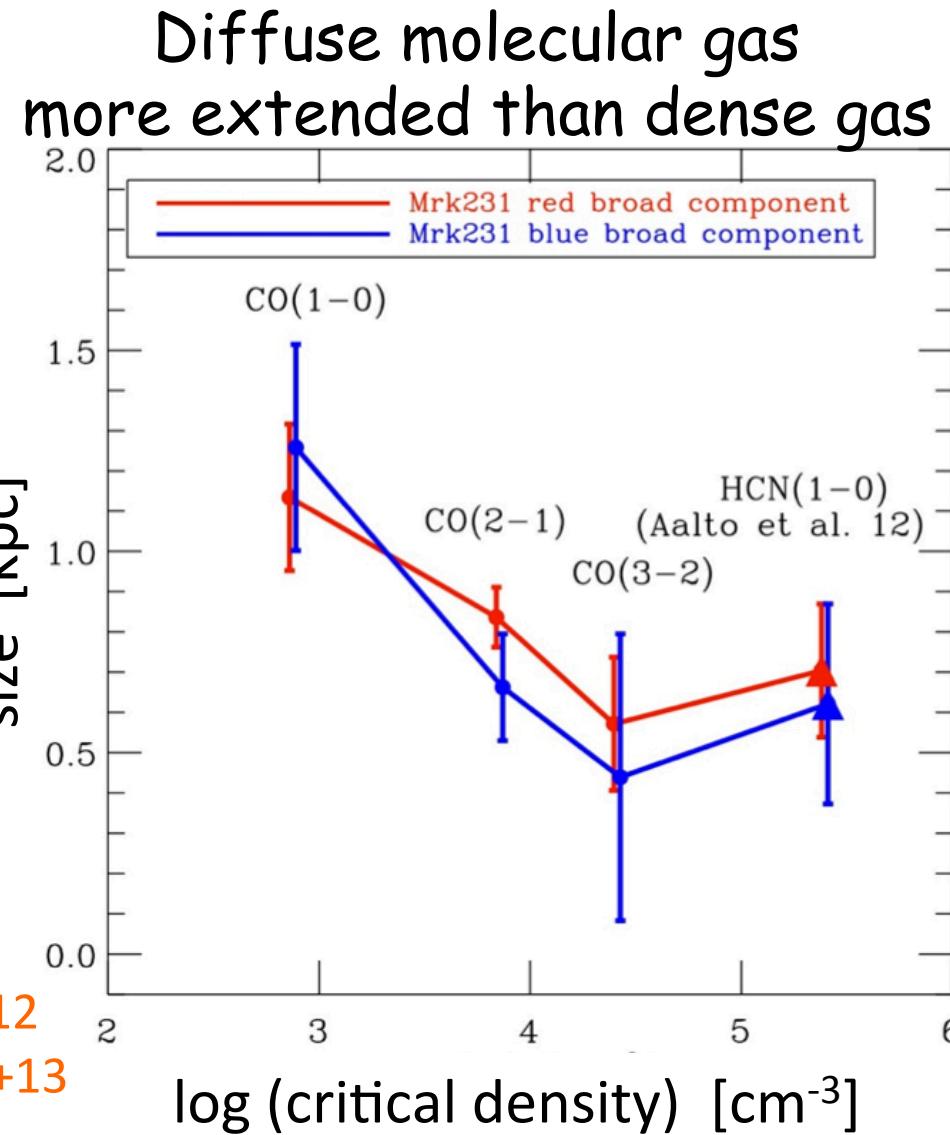
HCN wings:
very dense gas in the outflow



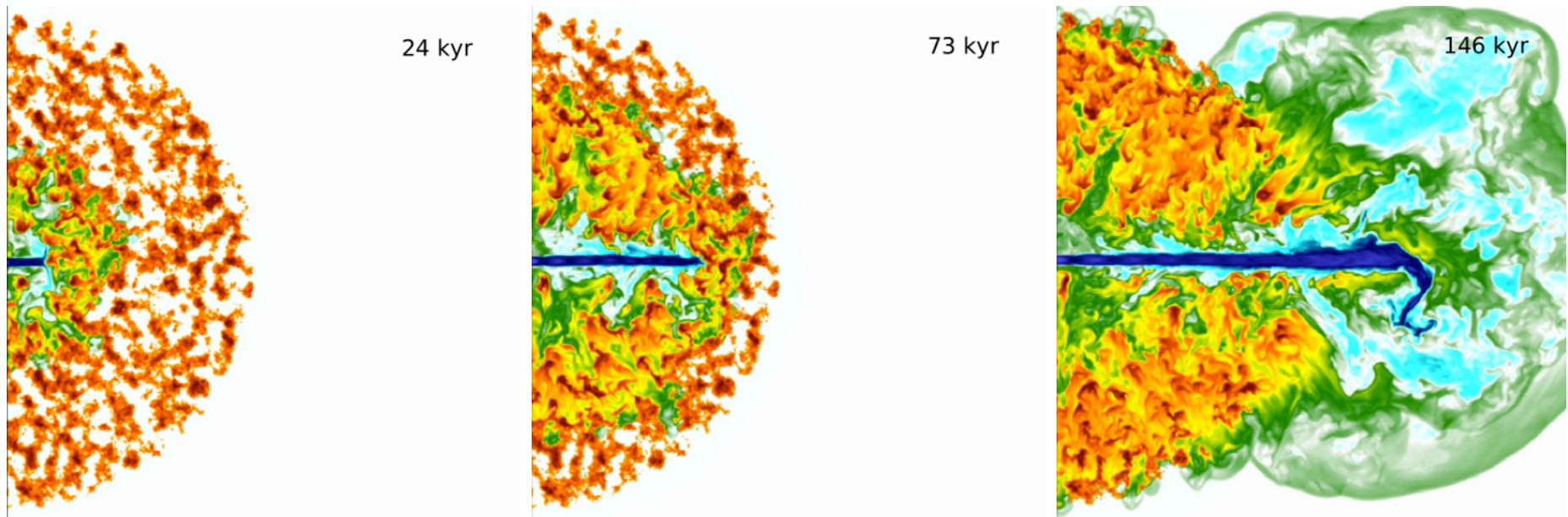
clouds with $n \sim 10^6 \text{ cm}^{-3}$ at $v \sim 700 \text{ km/s}$

Aalto+12

Cicone+12
Feruglio+13



“Quasar-feedback” phase driven by jets?

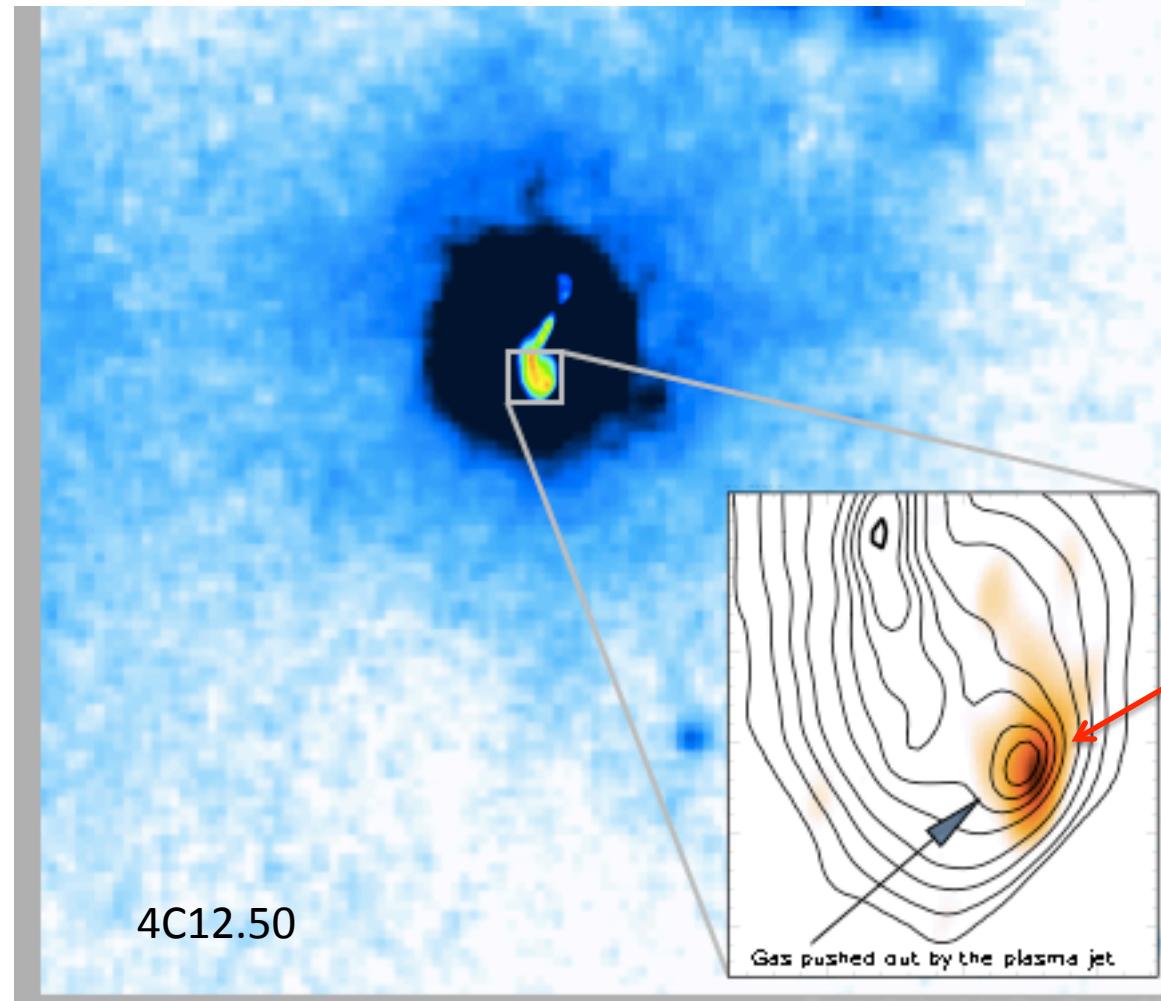


Wagner & Bicknell 2011, 2012

SCIENCE (today)

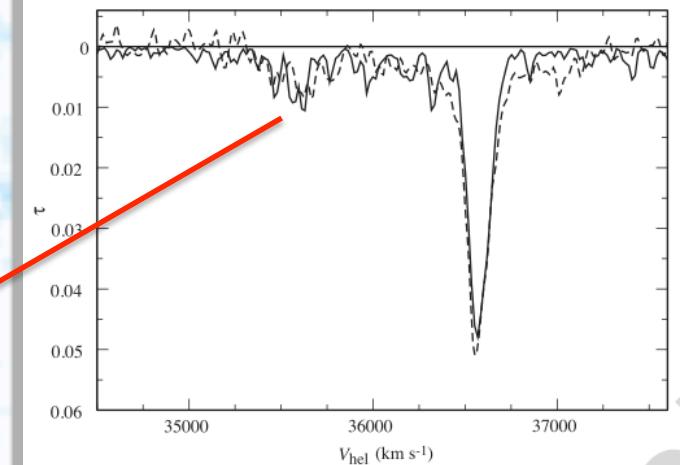
Radio Jets Clearing the Way Through a Galaxy: Watching Feedback in Action

Raffaella Morganti,^{1,2*} Judit Fogasy,³ Zsolt Paragi,⁴ Tom Oosterloo,^{1,2} Monica Orienti⁵



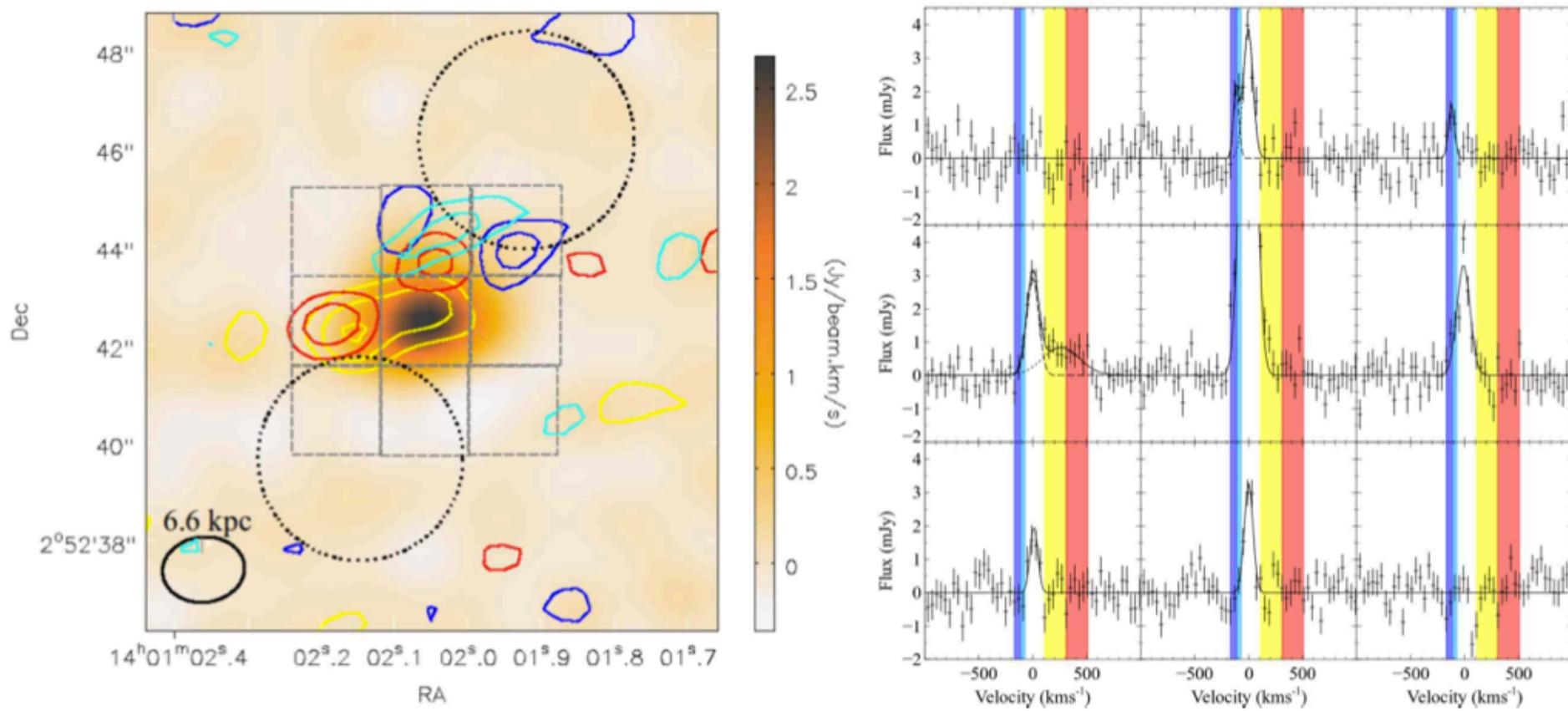
see also
Morganti+03,05, Emonts+03

blueshifted 21cm absorption



A TEN BILLION SOLAR MASS OUTFLOW OF MOLECULAR GAS LAUNCHED BY RADIO BUBBLES IN THE ABELL 1835 BRIGHTEST CLUSTER GALAXY

B. R. McNAMARA^{1,2,3} H.R. RUSSELL¹, P. E. J. NULSEN³ A. C. EDGE⁴, N. W. MURRAY⁷, R. A. MAIN¹, A. N. VANTYGHEM¹, F. COMBES⁵, A. C. FABIAN⁶, P. SALOME⁵, C.C. KIRKPATRICK¹, S. A. BAUM⁸, J. N. BREGMAN⁹, M. DONAHUE¹⁰, E. EGAMI¹¹, S. HAMER⁵, C. P. O'DEA⁸, J.B.R. OONK¹², G. TREMBLAY¹³, G.M. VOIT¹⁰



ALMA CO(1-0)

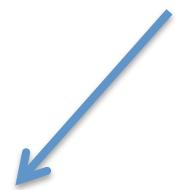
“Quasar mode”



Cleaning the galaxy



Keeping the galaxy clean



“Radio mode”

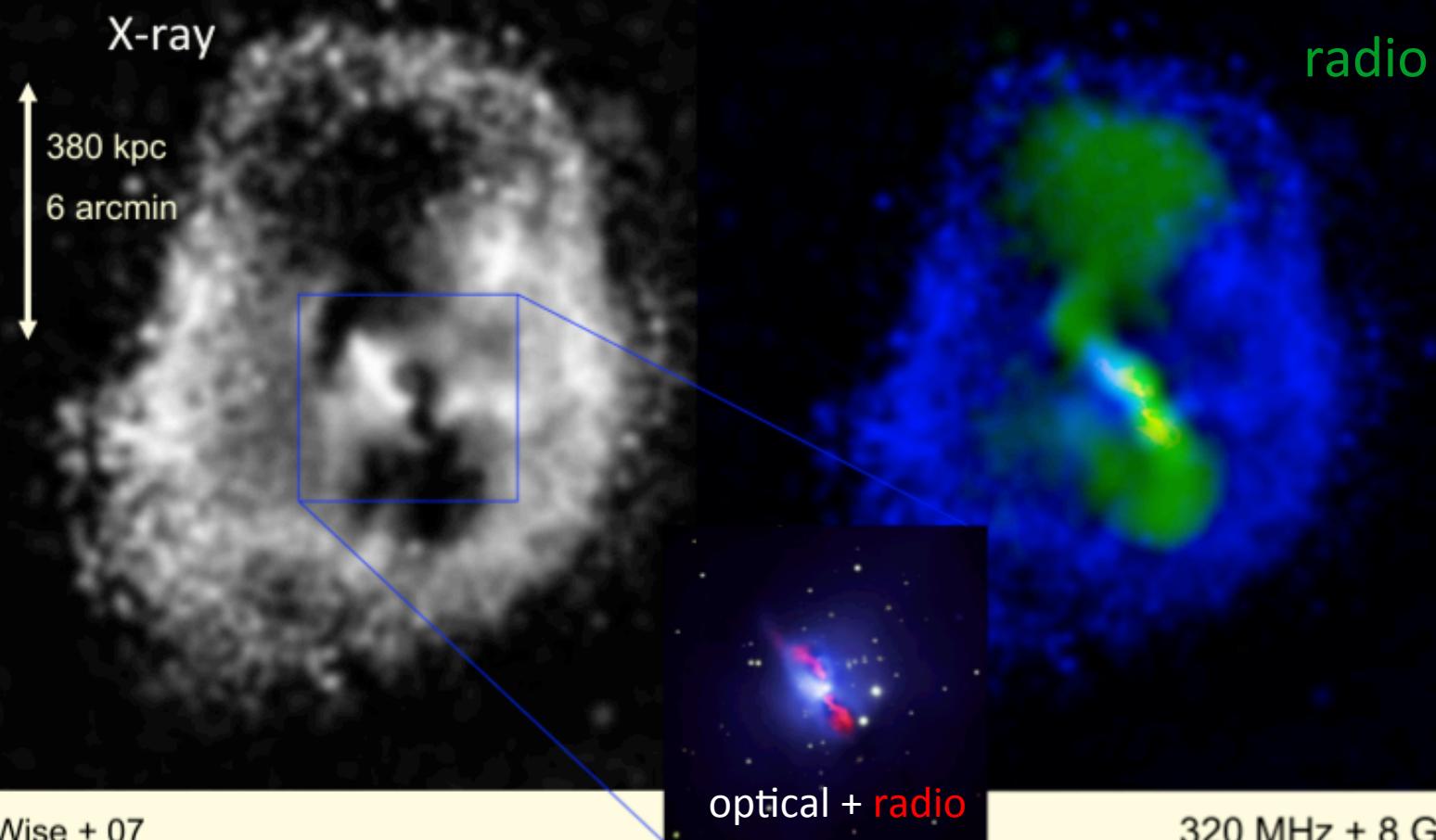


**Episodic “quasar mode”
associated with accretion
from gas returned by stars**

Evidence for radio-mode AGN feedback in LOCAL galaxies (maintenance mode)

Hydra A Cluster $z=0.05$

$E_{\text{jet}} > 10^{61}$ erg AGN outburst: swiss cheese morphology to hot atmosphere

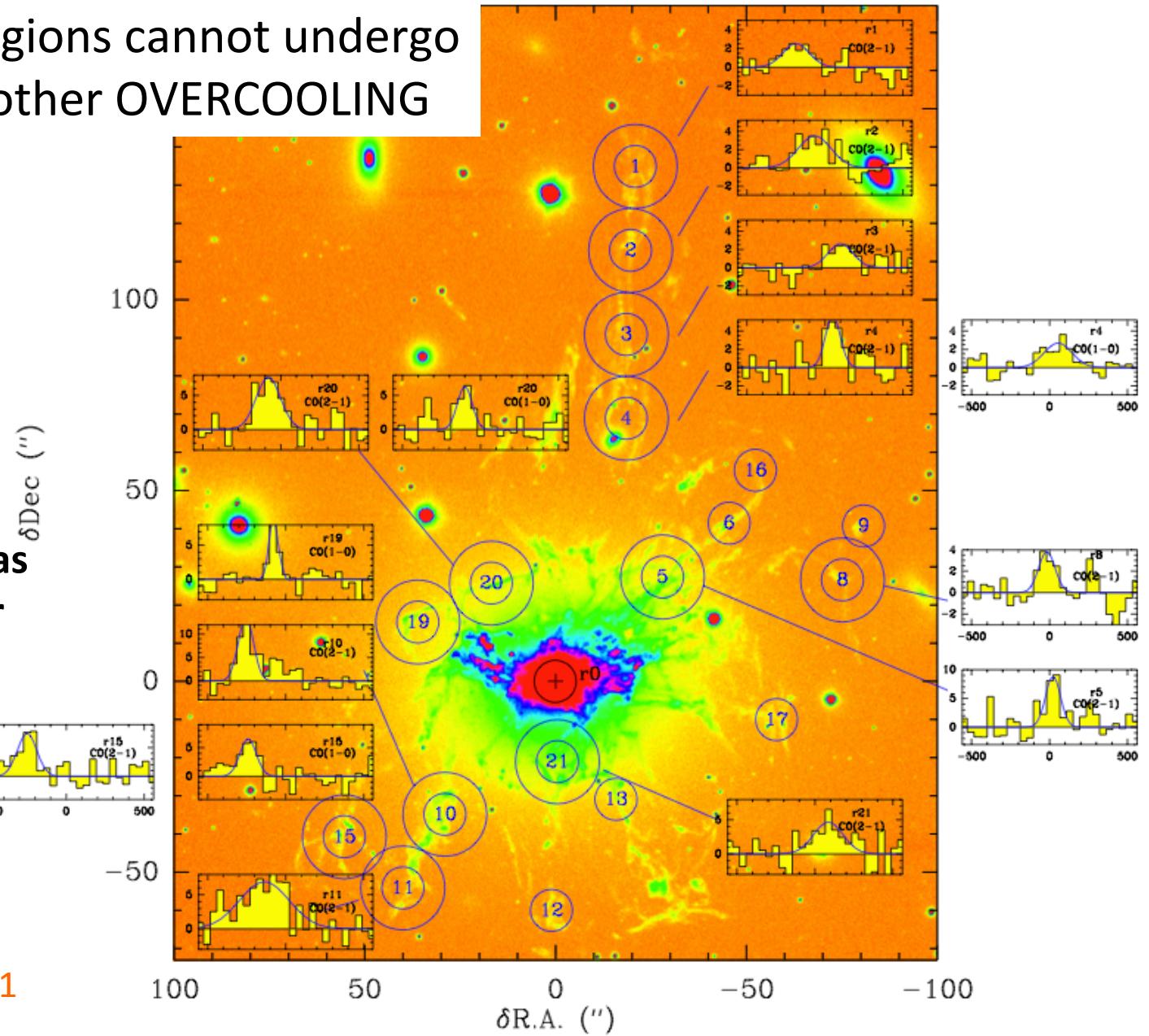


Heating \sim Cooling \Rightarrow it works! ... Really a proof?

Having, ON AVERAGE, balance between heating and cooling does not mean that some regions cannot undergo overheating and other OVERCOOLING

**Streams of
cooling molecular gas
towards the center
of Perseus**

Salome'+11



Episodic quasar activity: accretion from stellar winds

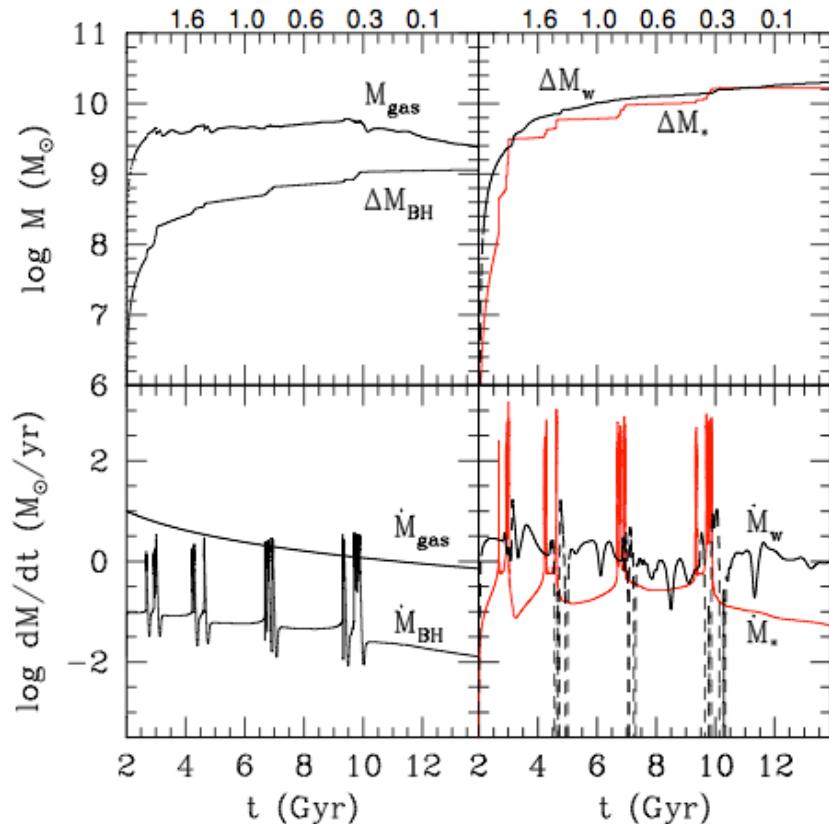
“Dead” early type galaxy with $M_{\text{star}} = 3 \times 10^{11} M_{\odot}$

-> since $z \sim 2$ stars return $3 \times 10^{10} M_{\odot}$ of gas in the ISM

-> $\sim 10\%$ of it should naturally accrete onto the BH and make it 10(!) times more massive than $M_{\text{BH}} - \sigma$ relation

(no need for gas accretion from the halo, merging or cold flows)

Ciotti & Ostriker 2010, Scoville & Norman 1998, Davies+07

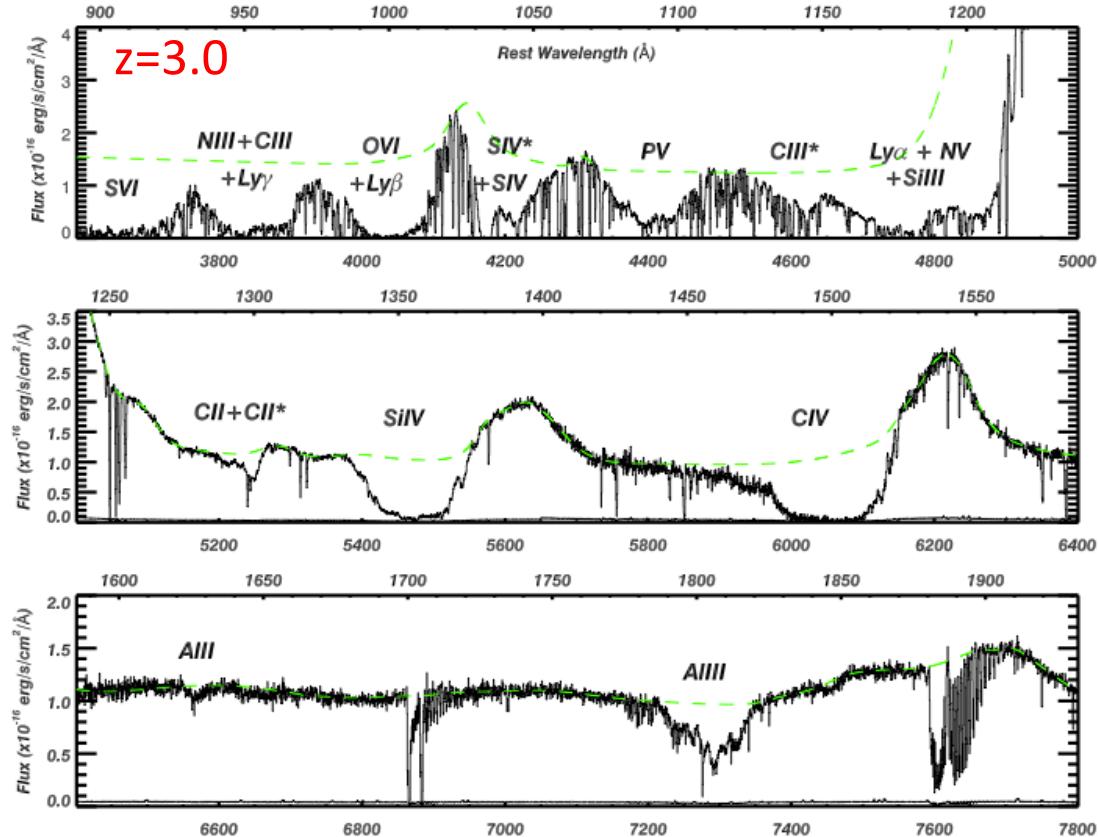


Short episodes of strong
AGN feedback
avoid BH overgrowth
(and help keeping
the galaxy clean)

AGN feedback at high redshift

To explain the local red-and-dead massive galaxies
(age 10 Gyr) the strongest feedback effect
should occur at high redshift ($z \sim 1-2$)...

BAL QSO's are probably the best example...
disregarded until recently



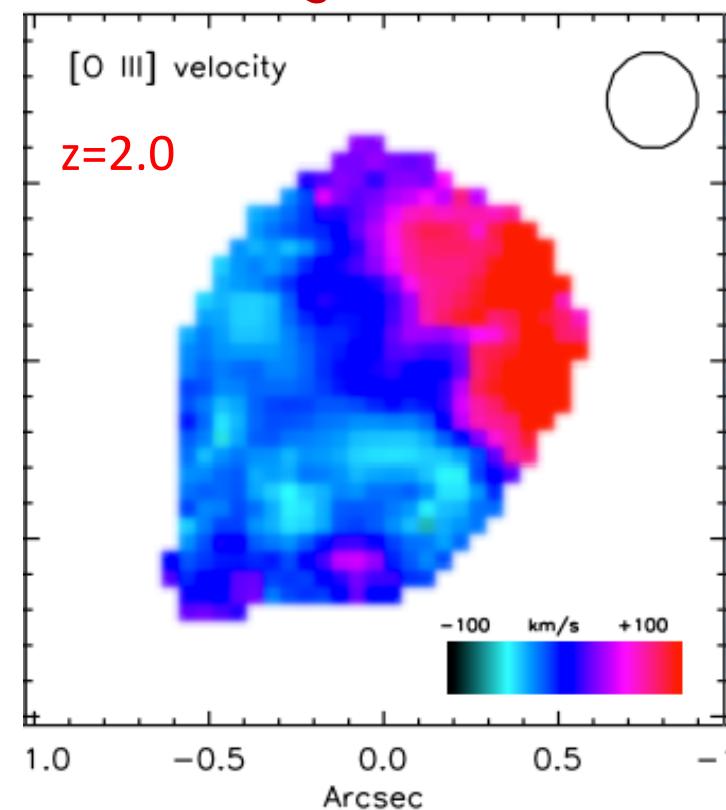
Bourget et al. 2012, 2013

R \sim 300-2,000 pc

V = 8000 km/s

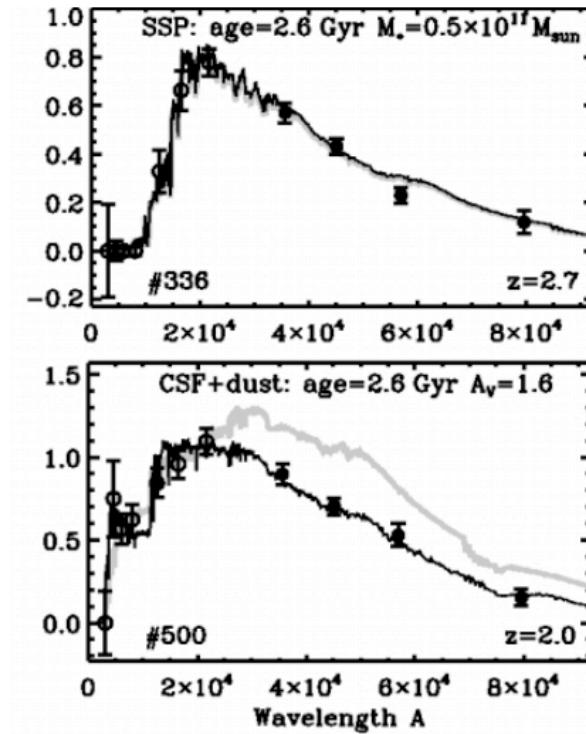
P_K > 10^{46} erg/s \sim 5% L_{AGN}

[OIII]5007 velocity maps
of high-z AGNs

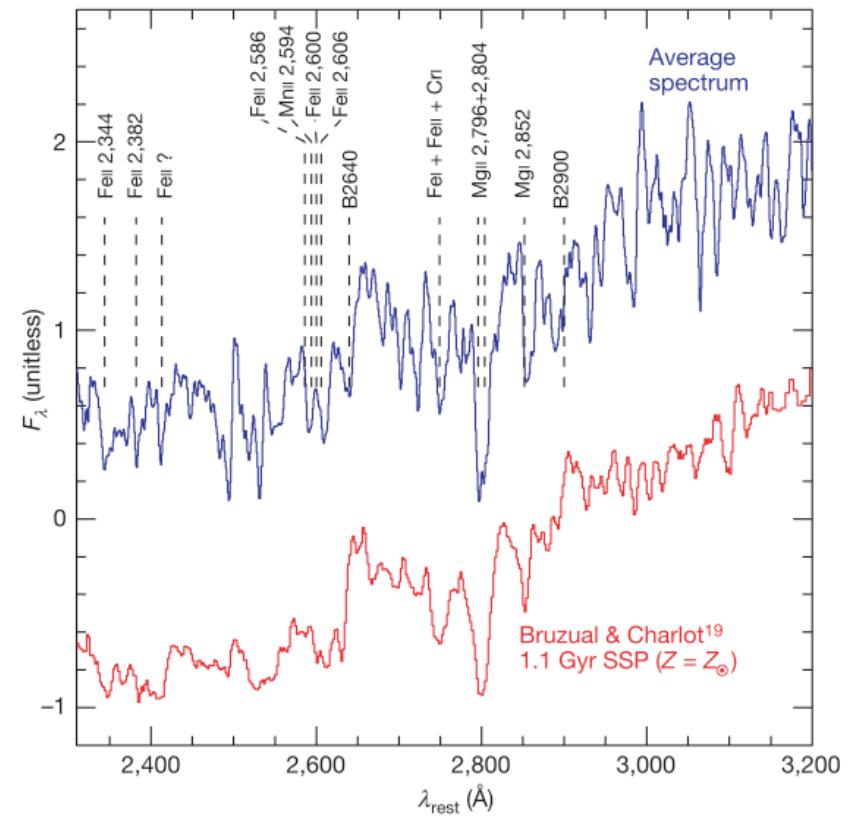


Alexander+10

Massive passive and old (age \sim 2-3 Gyr) galaxies have been discovered at $z \sim 2.5$ (age of the Universe \sim 3 Gyr !)



Kriek+06, Labbe+05, Saracco+05, Cimatti+04



→ Quasar feedback quenching star formation must already be **in place at $z \sim 6$** (close to the re-ionization epoch, age of the Universe less than 1 Gyr) in a fraction of very massive galaxies

Massive quasar outflow detected at $z=6.4$

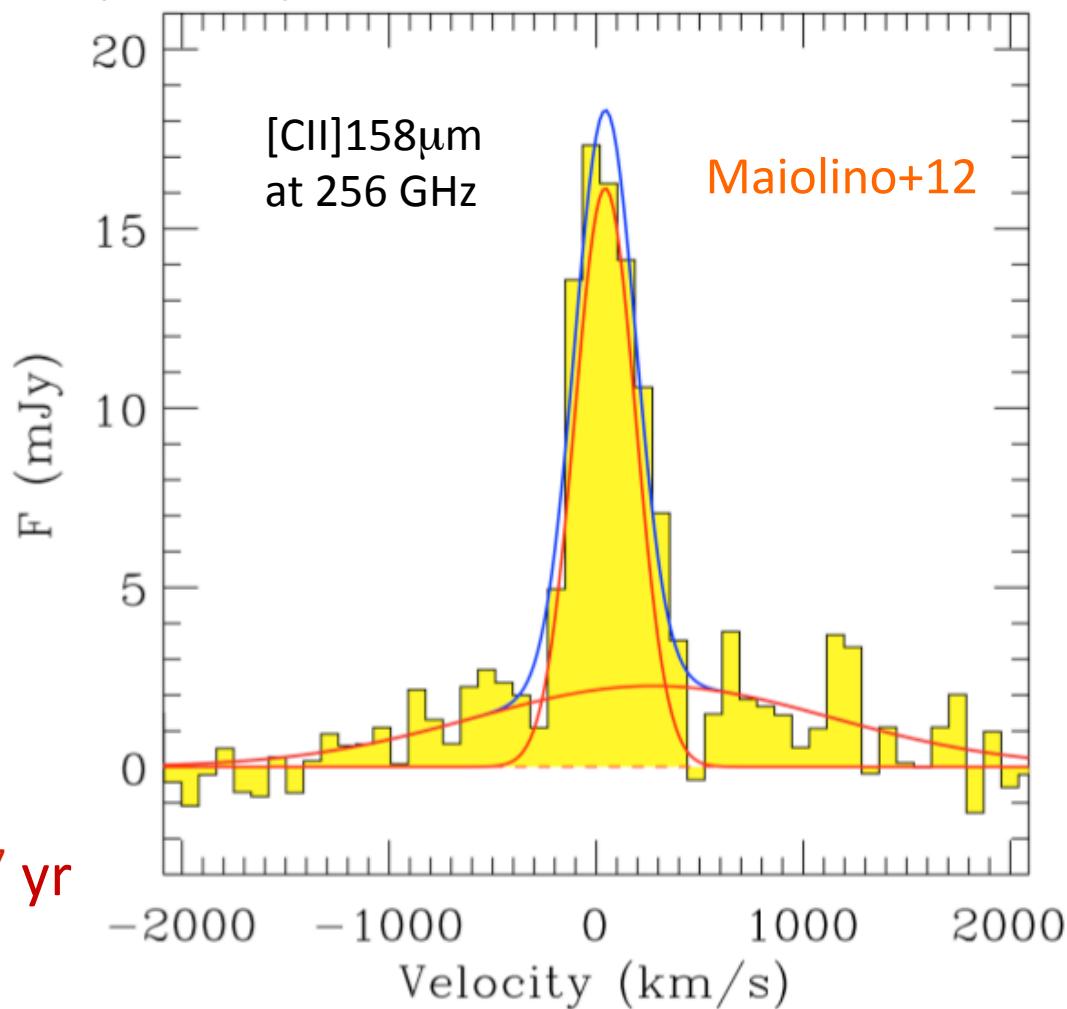
Broad wings
tracing outflow
with $v \sim 1300$ km/s

Size: ~ 16 kpc !

$\dot{M}_{\text{outflow}} > 3500 M_{\odot}/\text{yr}$

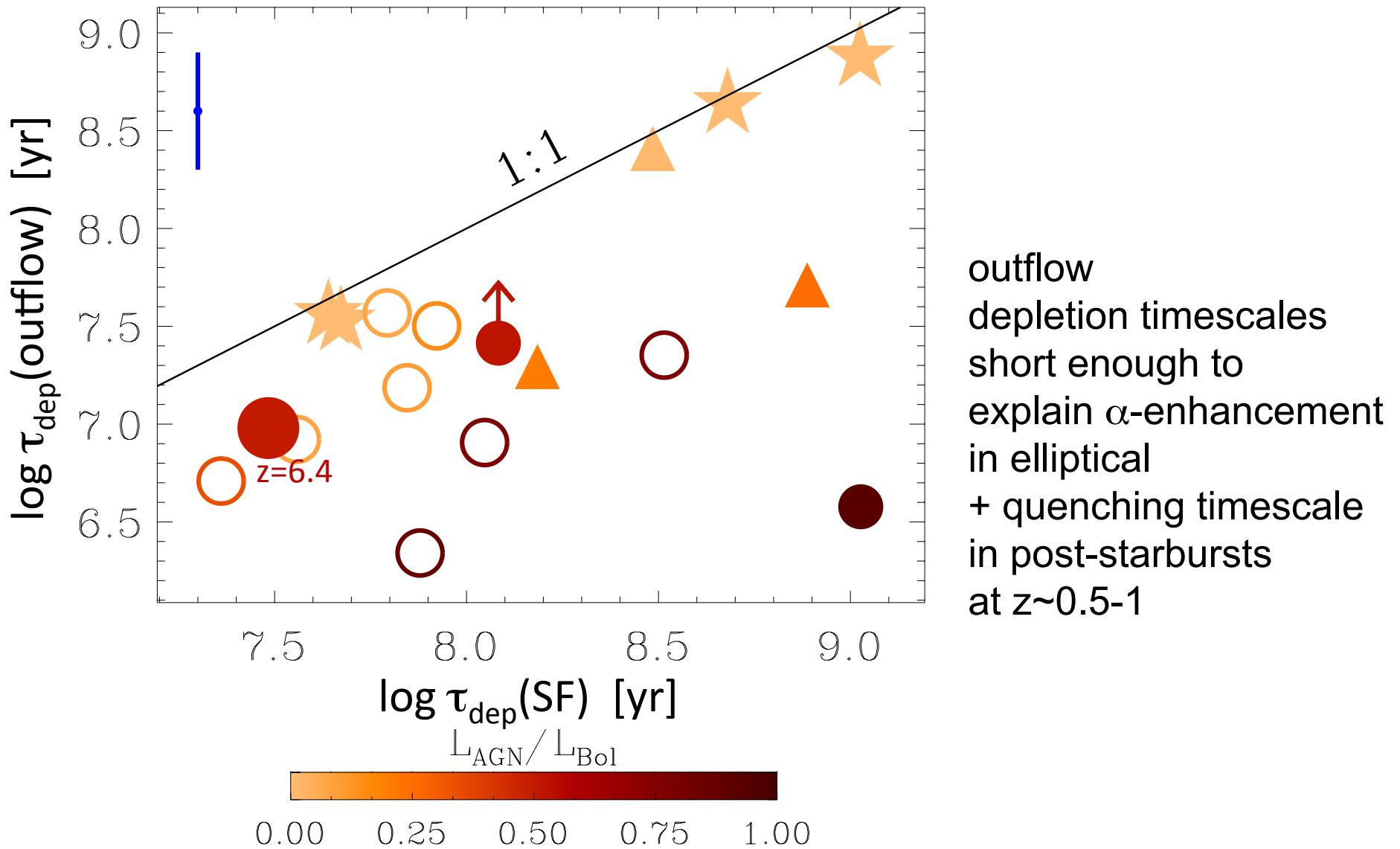
Depletion timescale $< 10^7$ yr

α -enhancement
in massive spheroids

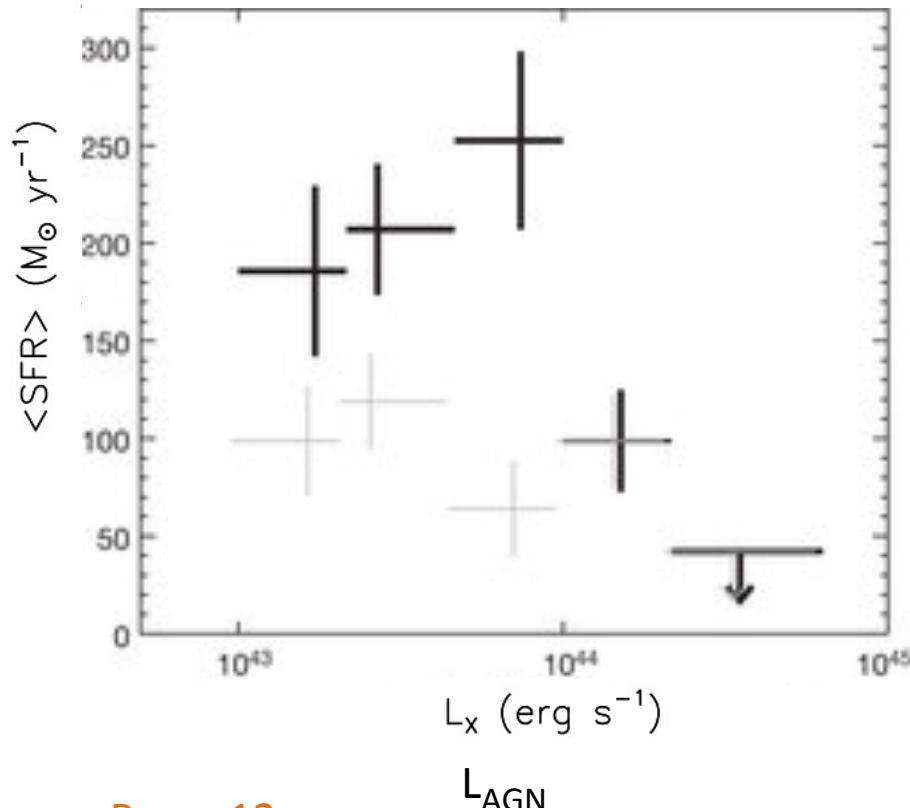


**Efficient quenching of
star formation in the early Universe**

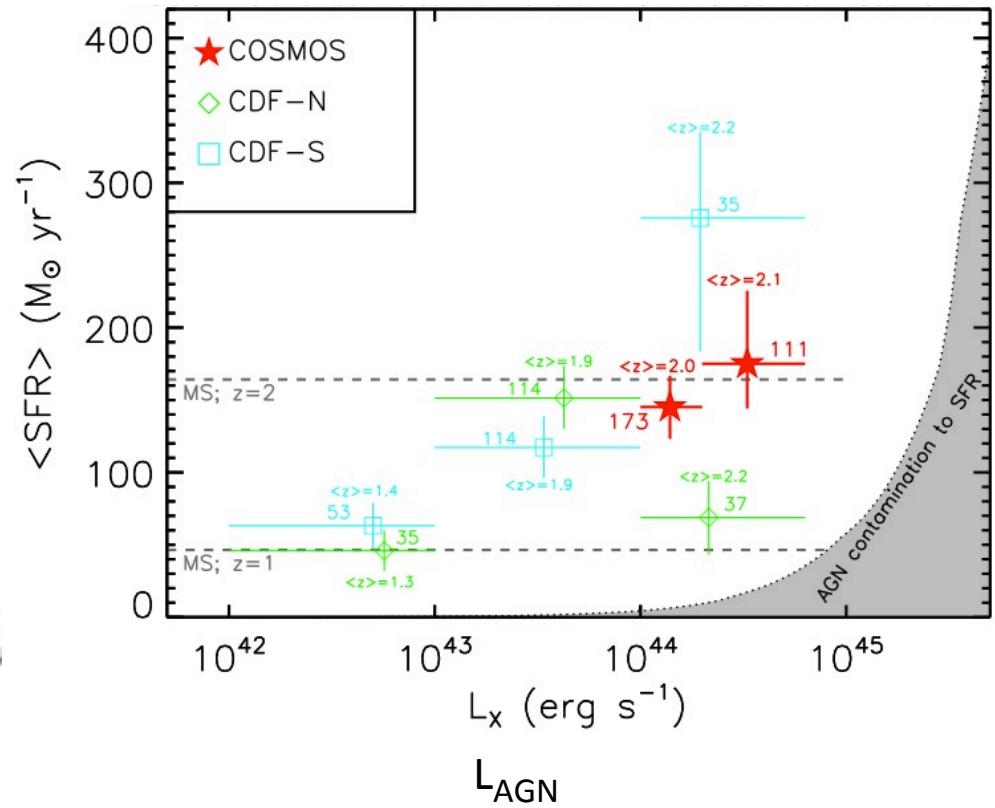
Depletion timescale due to AGN-driven outflow much shorter than depletion due to Star Formation



Direct evidence for star formation quenching?

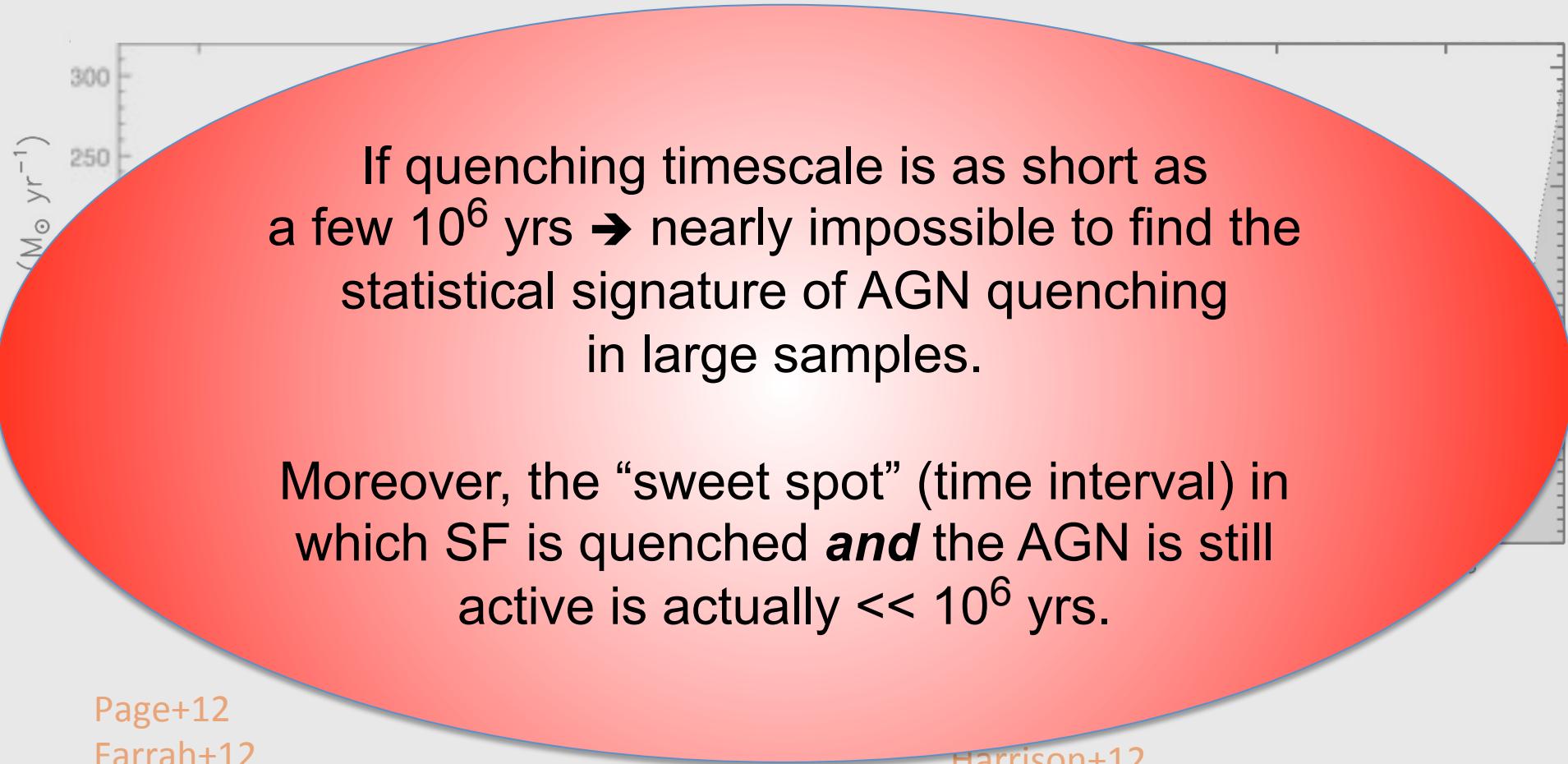


Page+12
Farrah+12



Harrison+12
Rosario+13
Santini+12

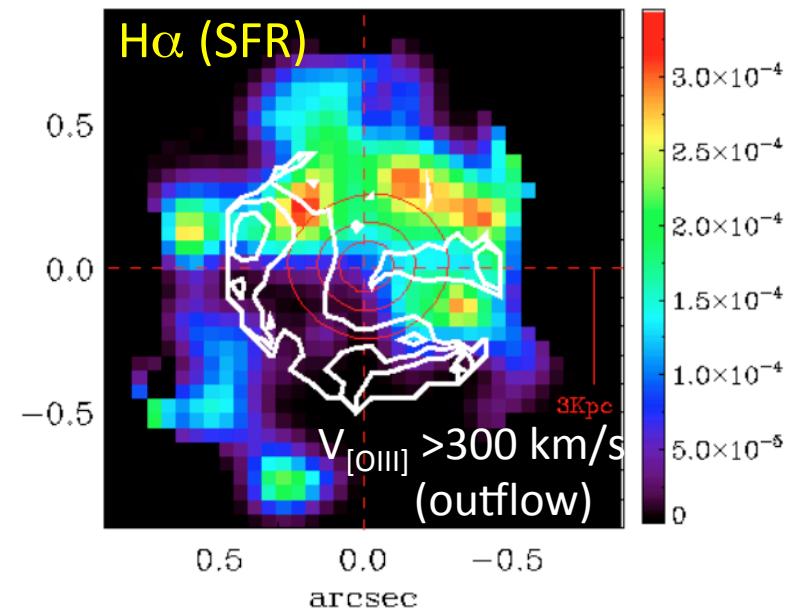
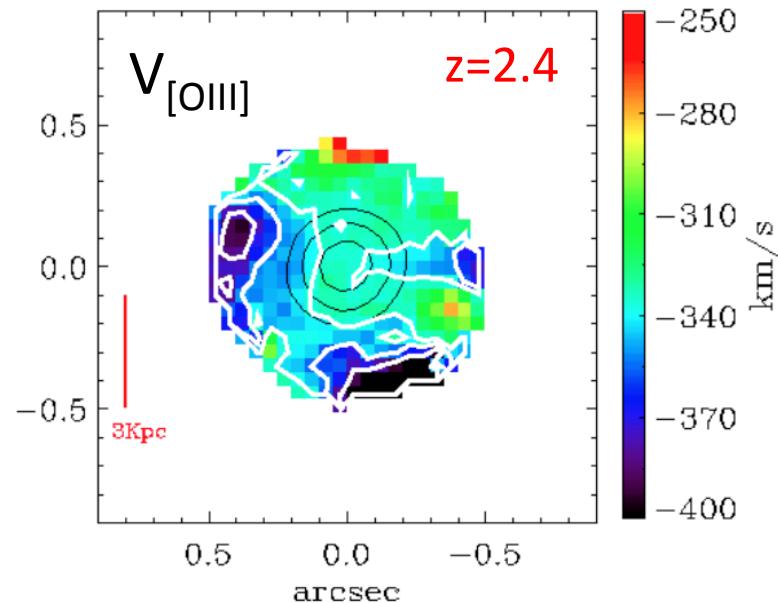
Direct evidence for star formation quenching?



Page+12
Farrah+12

Harrison+12
Rosario+13
Santini+12

Better strategy:
investigate thoroughly individual, pre-selected targets



Cano Diaz et al. 2012

evidence of quasar-driven outflow
quenching star formation at $z=2.4$

Positive Quasar Feedback: the third mode of galaxy formation?

AGN feedback and triggering of star formation in galaxies

W. Ishibashi* and A. C. Fabian

Outflows of stars due to quasar feedback

Kastytis Zubovas¹, Sergei Nayakshin¹, Sergey Sazonov^{2,3} and Rashid Sunyaev^{3,2}

Jet-induced star formation in gas-rich galaxies

V. Gaibler^{1,2*}, S. Khochfar², M. Krause^{2,3} and J. Silk^{4,5}

**UNLEASHING POSITIVE FEEDBACK: LINKING THE RATES OF STAR FORMATION AND
SUPERMASSIVE BLACK HOLE ACCRETION IN DISTANT GALAXIES**

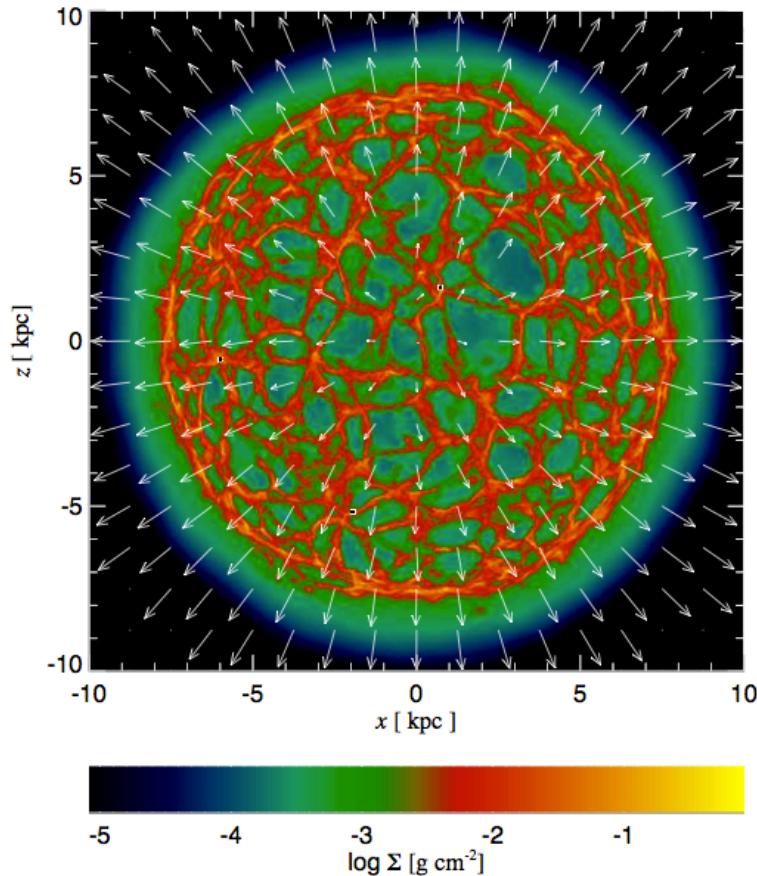
JOSEPH SILK

**Quasar feedback: accelerated star formation and chaotic
accretion**

Sergei Nayakshin and Kastytis Zubovas

AGN outflows trigger starbursts in gas-rich galaxies

Kastytis Zubovas^{1,2}, Sergei Nayakshin¹, Andrew King¹, Mark Wilkinson¹

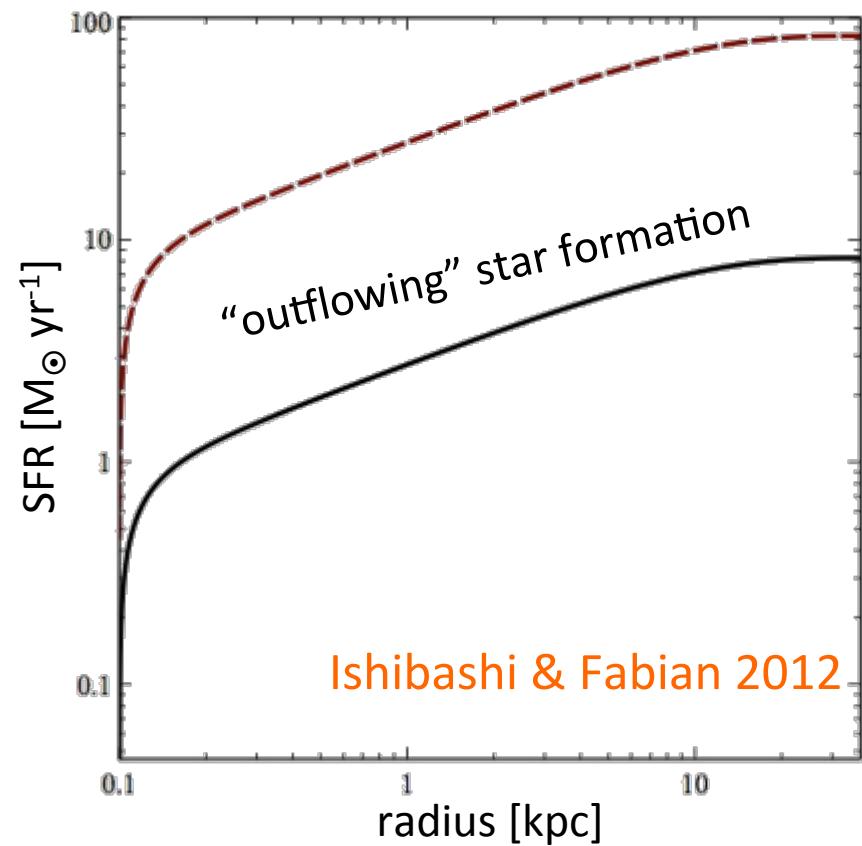


Dynamical and morphological implications for the “triggered” stellar population in massive galaxies

Silk & Norman 2010, Silk & Nusser 2011,
Gaibler et al. 2012

Outflowing gas is unstable and may undergo star formation

Zubovas et al. 2013

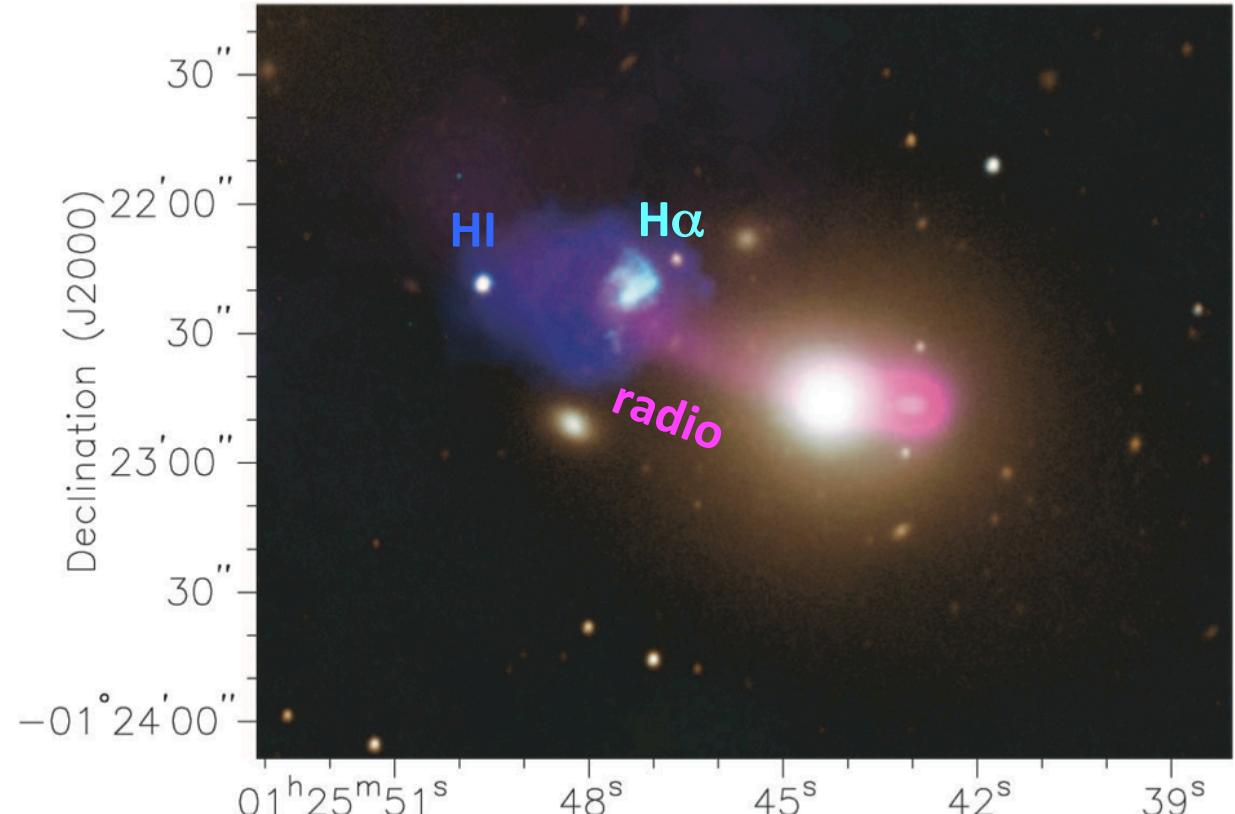


Ishibashi & Fabian 2012

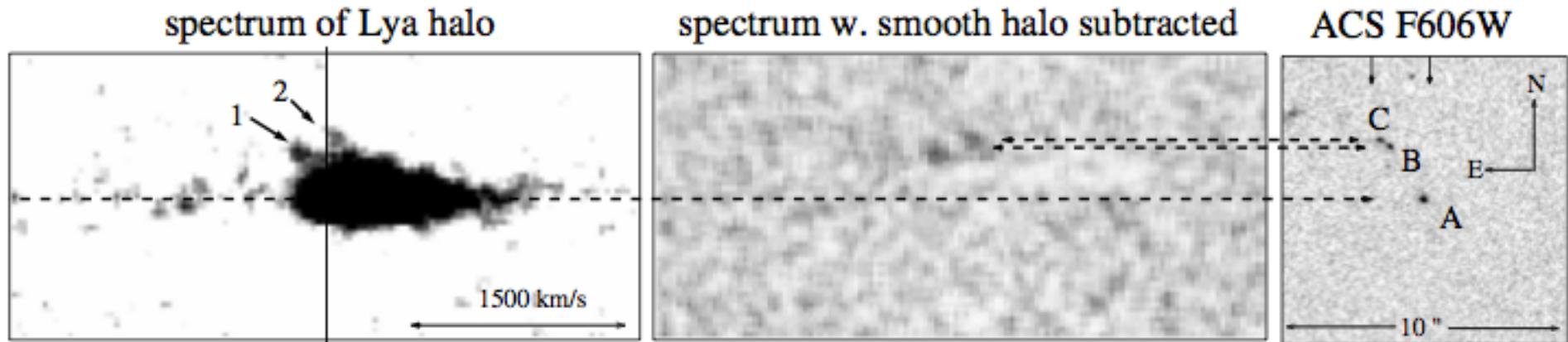
Observational evidence for AGN positive feedback?

Croft+06

Rauch+13



A $z=3.045$ Ly α emitting halo hosting a QSO and a possible candidate for AGN-triggered star-formation *



Summary and Outlook

- Negative AGN Feedback:
evidence revealed by multiple observational techniques.

Entering the phase of characterizing the detailed feedback physics and tracing feedback at different epochs

- Positive AGN Feedback:
new avenue, yet to be observationally explored.