AGN negative and positive feedback

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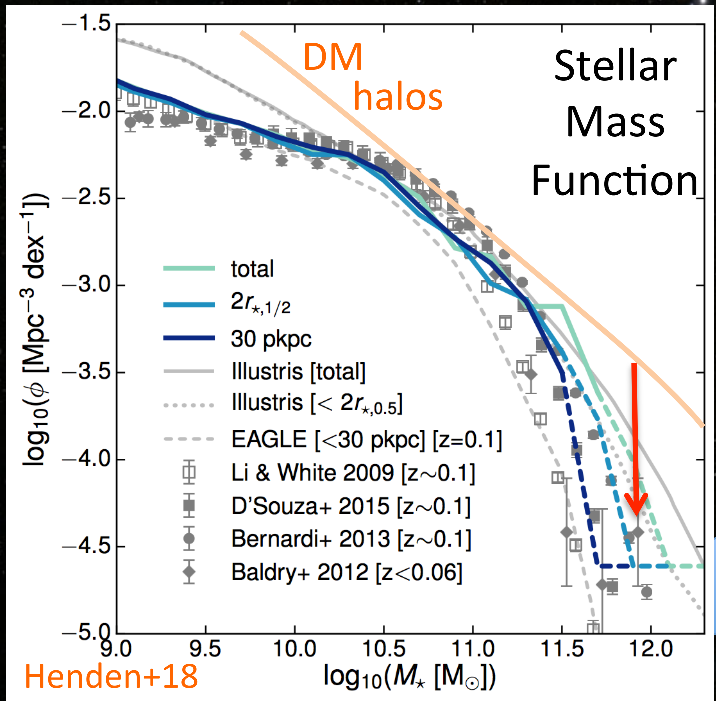
Negative feedback extreme case: quenching of star formation

AGN negative feedback invoked to:

- Transform star forming into passive at high masses
- Reproduce the mass function at high masses
- Account for the BH-galaxy scaling relations

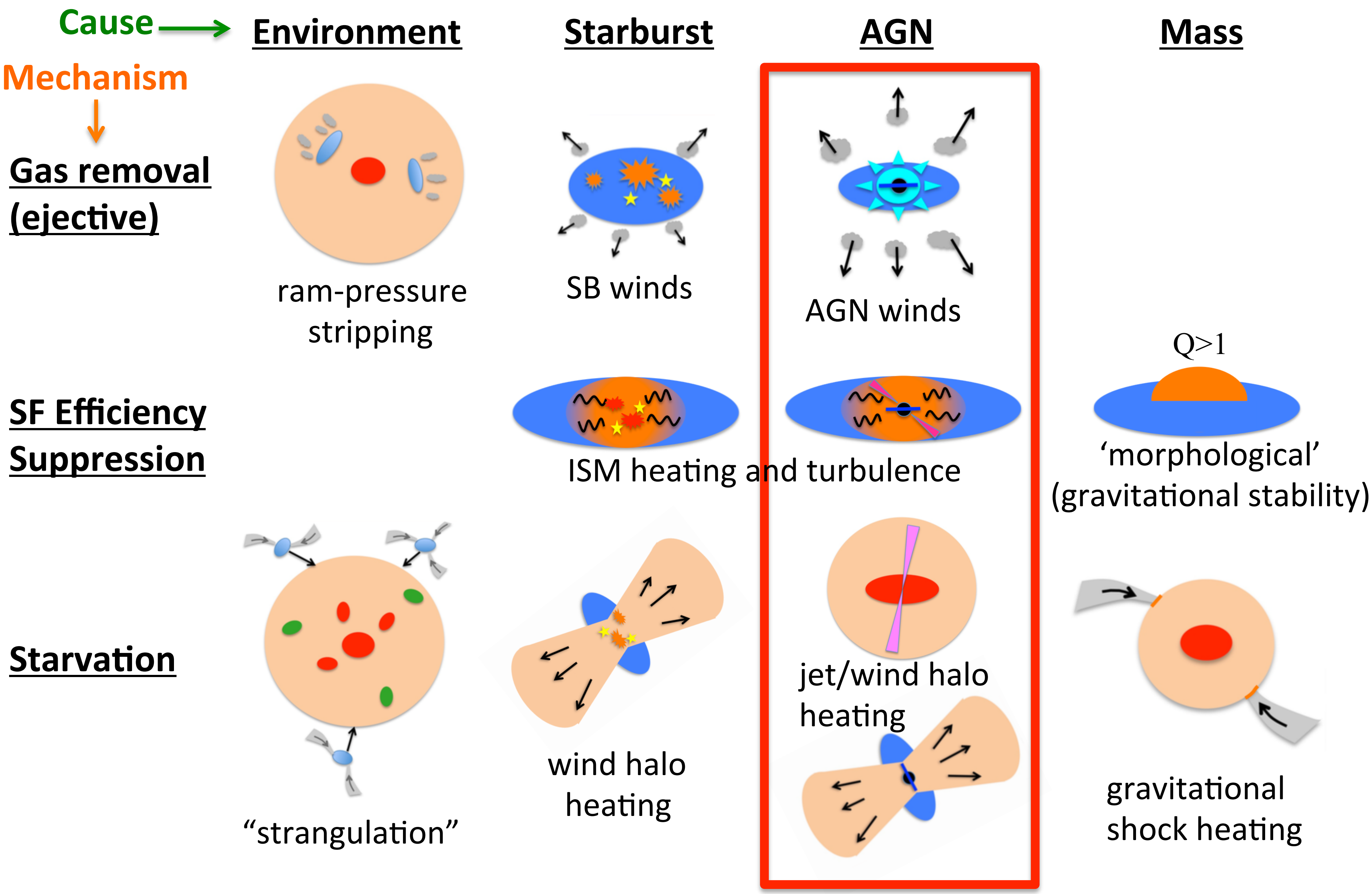


AGN-driven quenching?

Passive, quiescent, little/no gas older (red) stellar population

Star forming galaxies,
gas rich
young (blue) stellar population

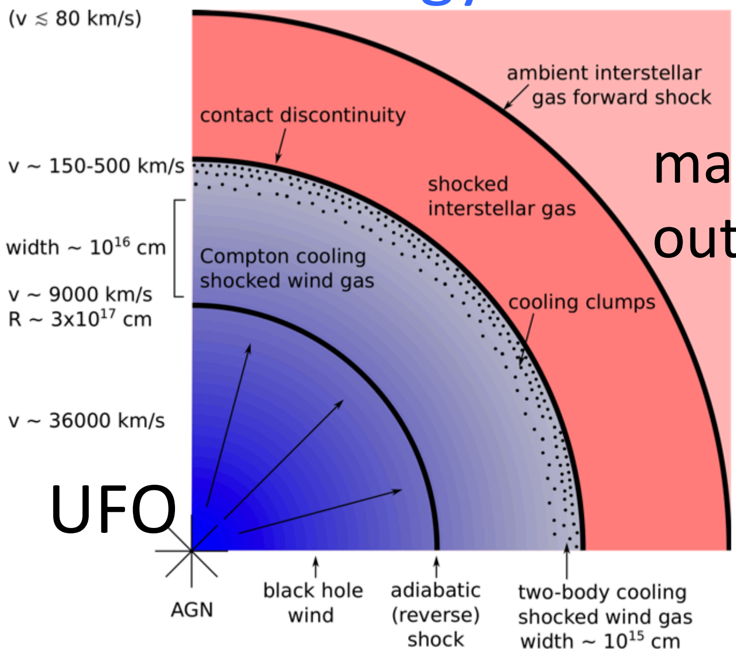
Star formation quenching: causes and mechanisms



Identifying the primary cause often difficult because of degeneracies

AGN 'ejective' mode

Blast wave: energy-driven wind



UFO

massive outflow

Wind Kinetic Power ~ a few % L_{AGN}

Momentum rate ~ 20 x L_{AGN}/c

(modulo wind-ISM coupling factor)

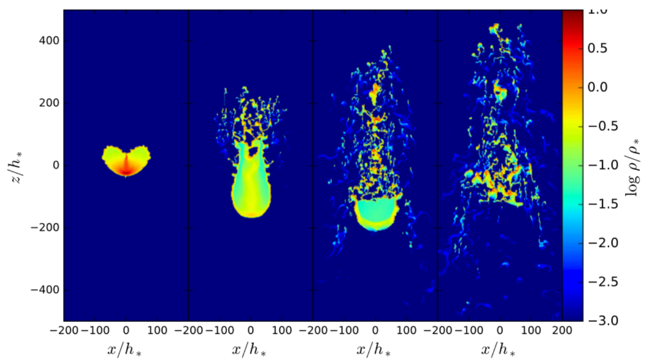
King+10
Zubovas+12
King & Pounds 2015
Harrison+18
...

Radiation pressure on dusty clouds

Wind Kinetic Power < 1 % L_{AGN}

Momentum rate ~ 1-5 x L_{AGN}/c

Fabian+12
Ishibashi+17
Costa+17
...

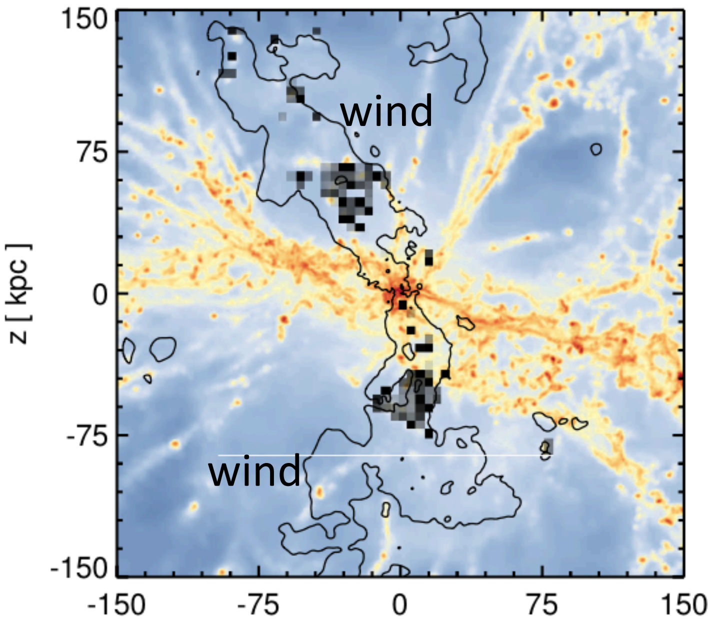


Instability problem

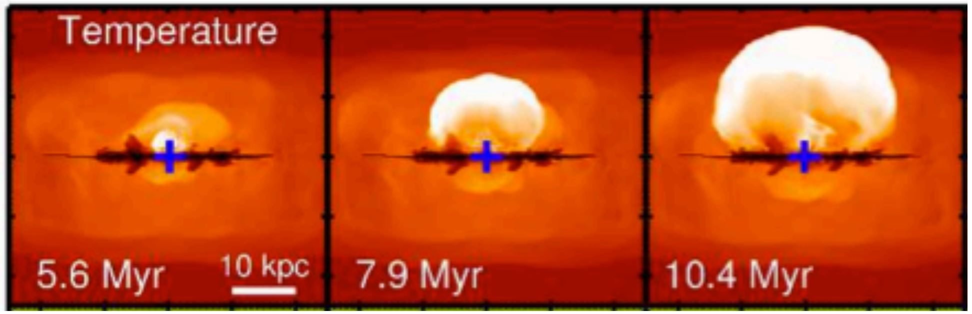
Scannapieco+12
Bruggen+16
Zhang+18

3D simulations:

AGN-driven outflows eject gas from central regions,
but primarily escape through low density, least resistance regions

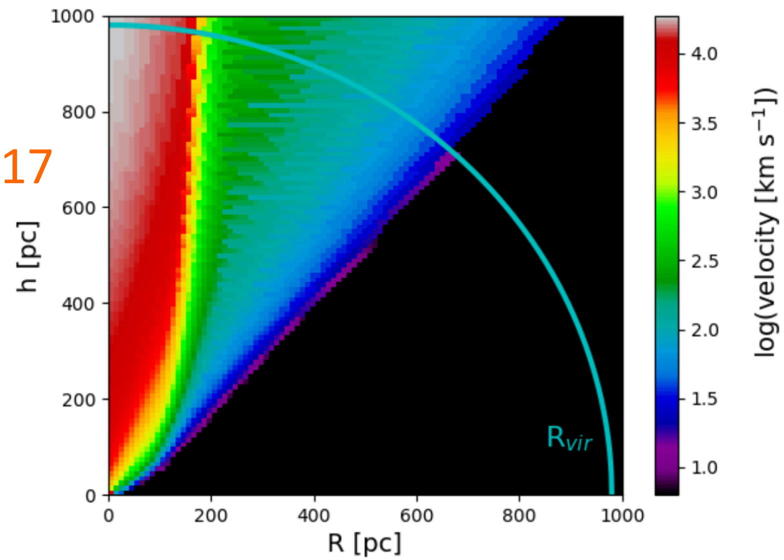


Costa+14,15,17



Gabor+14
Roos+15

Hartwig+17

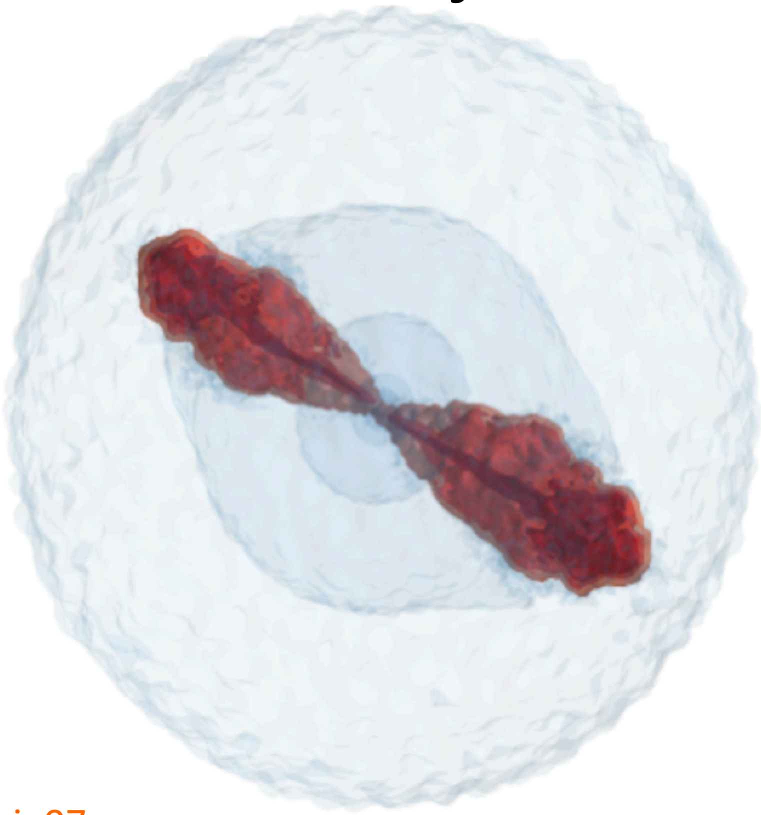


Certainly major negative feedback
but probably not quenching star formation across entire galaxy

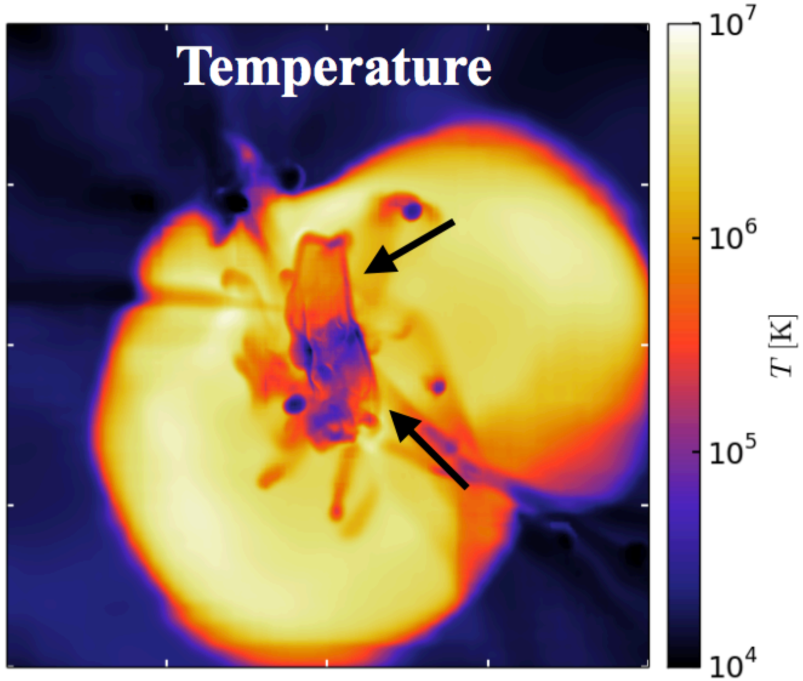
Theory/simulations: halo heating

- 'preventive' feedback
- delayed quenching
- maintenance mode

Radio-jets



AGN-driven Winds



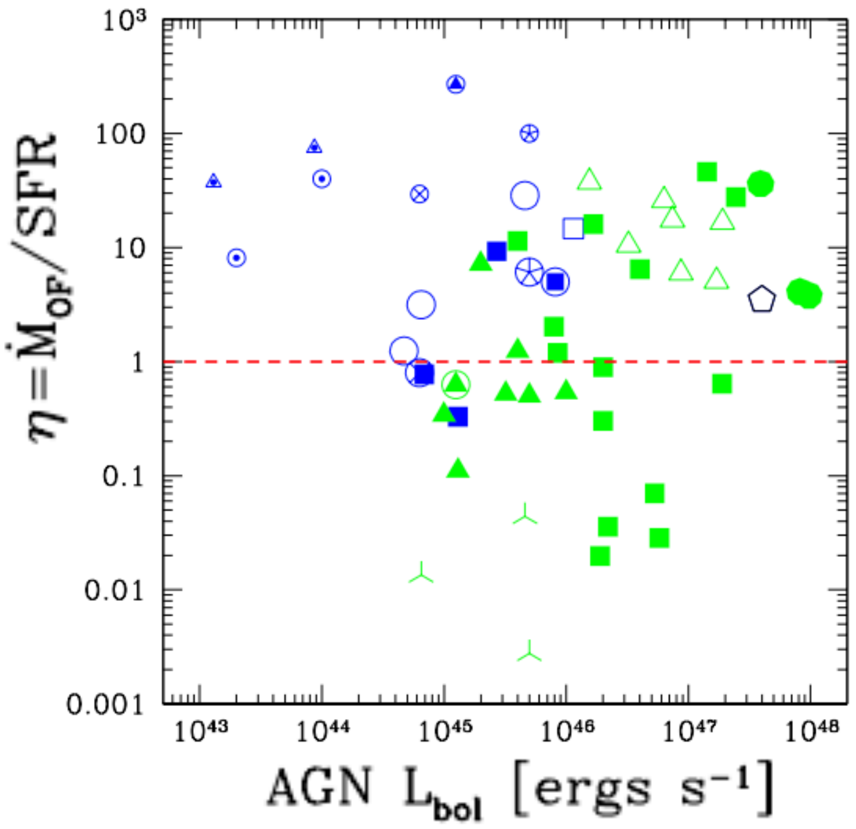
Sijaki+07
Weinberger+17
Bourne+17
Gaspari+17
-- (many other)

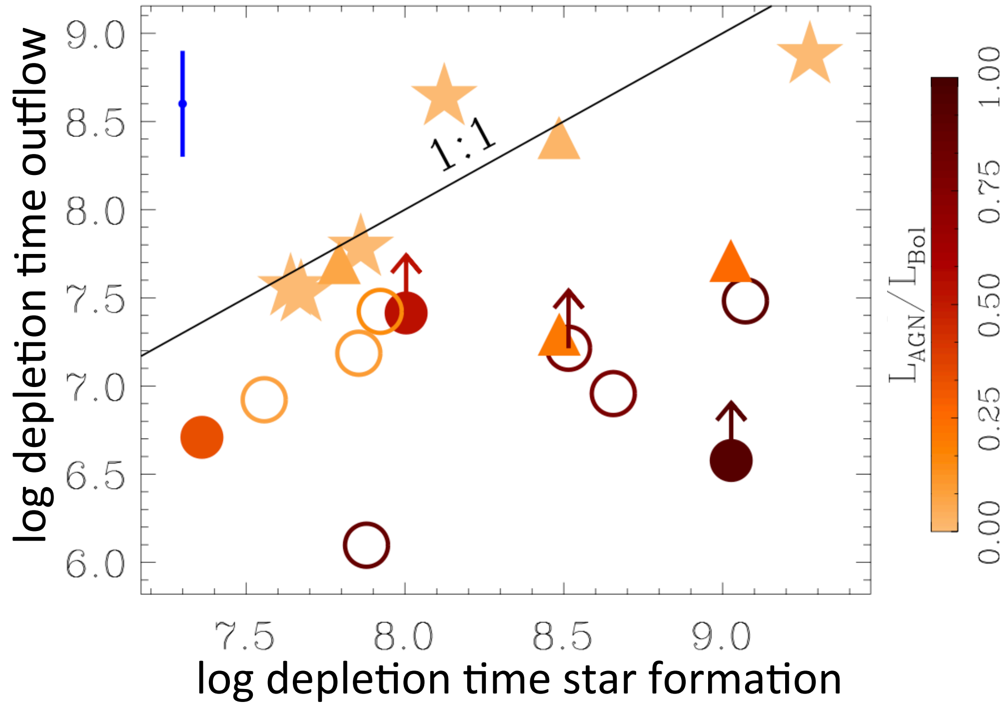
- Halo heating
- Buoyant hot bubbles

Pillepich+17
Weinberger+17
Bowens+17
Costa+18

Observations: is AGN 'ejective' mode effective?

Outflow rate > SFR

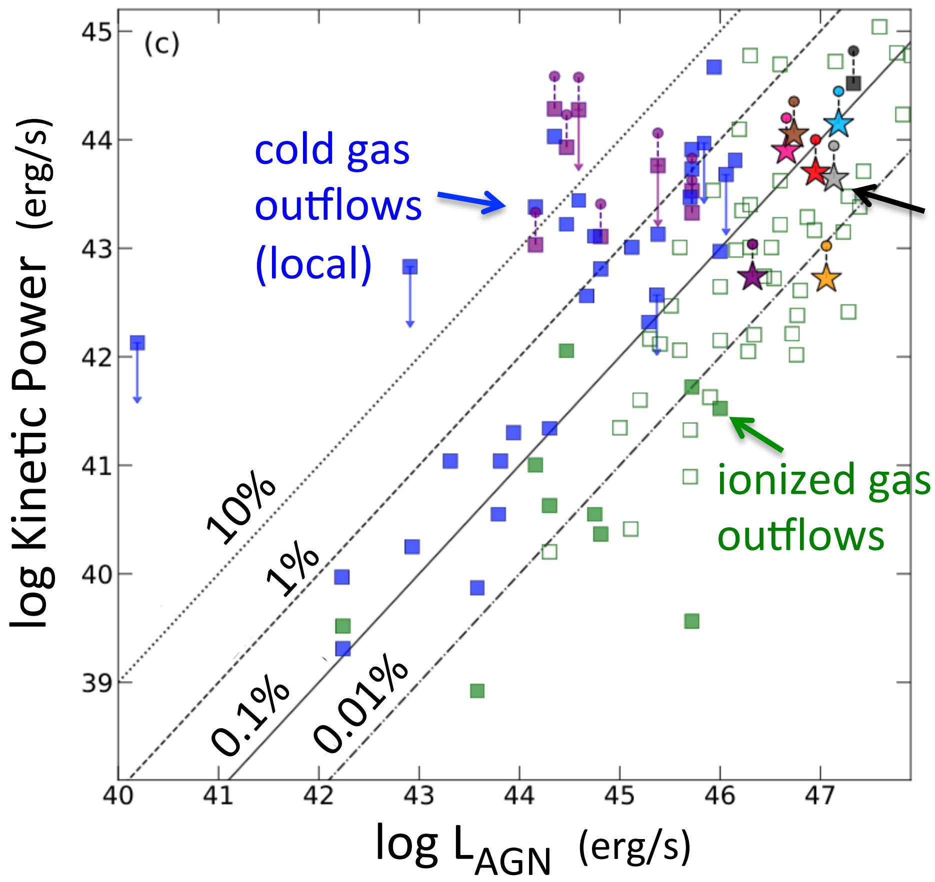




Feruglio+10, Cicone+14, Fiore+17, Fluetsch+18, ...

⇒ AGN-driven outflow can have a major negative feedback

Yet, AGN-driven outflows may be not capable of quenching?

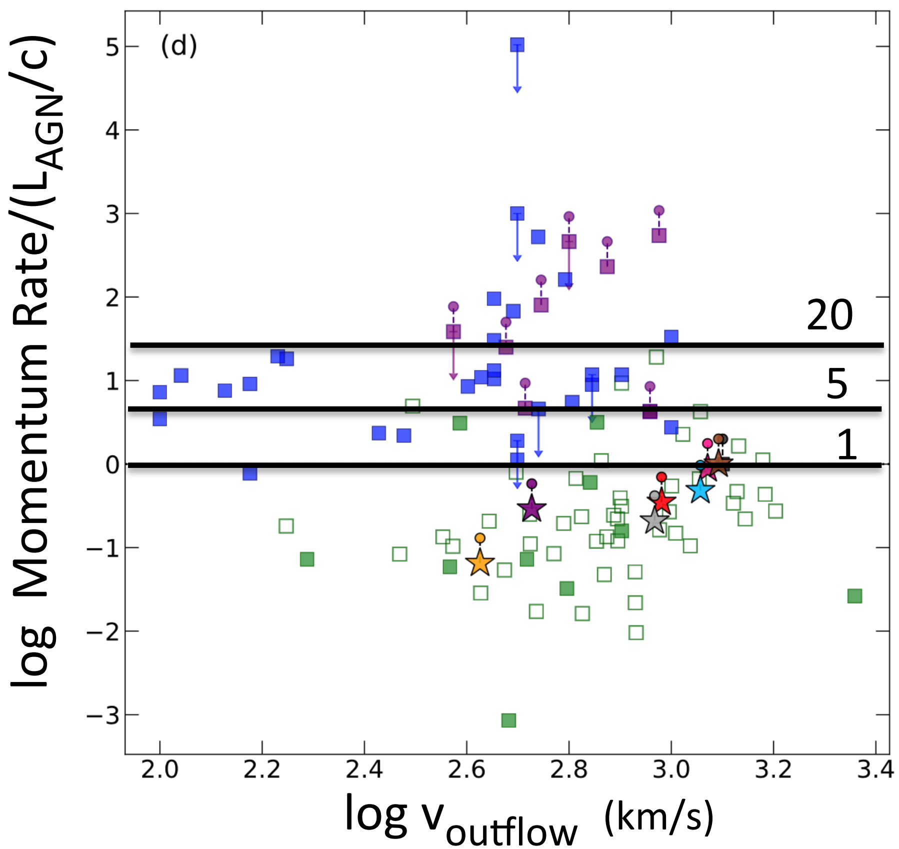


Kinetic power

cold gas outflows (high-z)

Cicone+14, Fiore+17, Fluetsch+18, Bischetti+18, Tombesi+15, Feruglio+17, Veilleux+17...

Momentum rate



Broad dispersion:

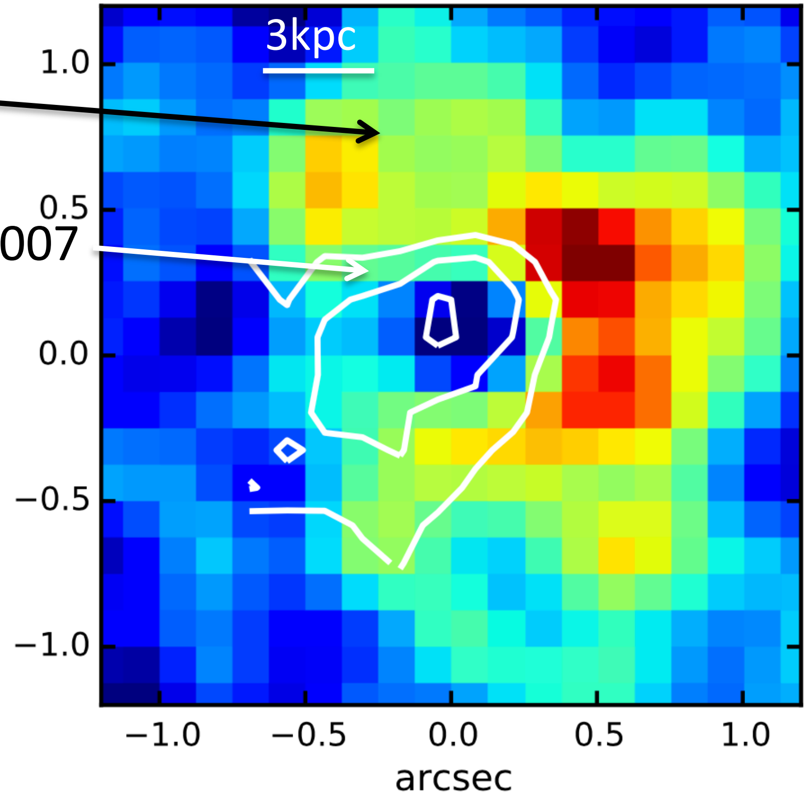
- either Energy-driven with broad range of coupling
- or radiation pressure driven

Directly mapping negative feedback effect outflows at high-z

Outflows in the most powerful quasars at z~1-2

Color: narrow Hα = SFR

Contours: high velocity gas (outflow) from [OIII]5007



Carniani et al. 2016

Cano Diaz et al. 2012

Cresci et al. 2015

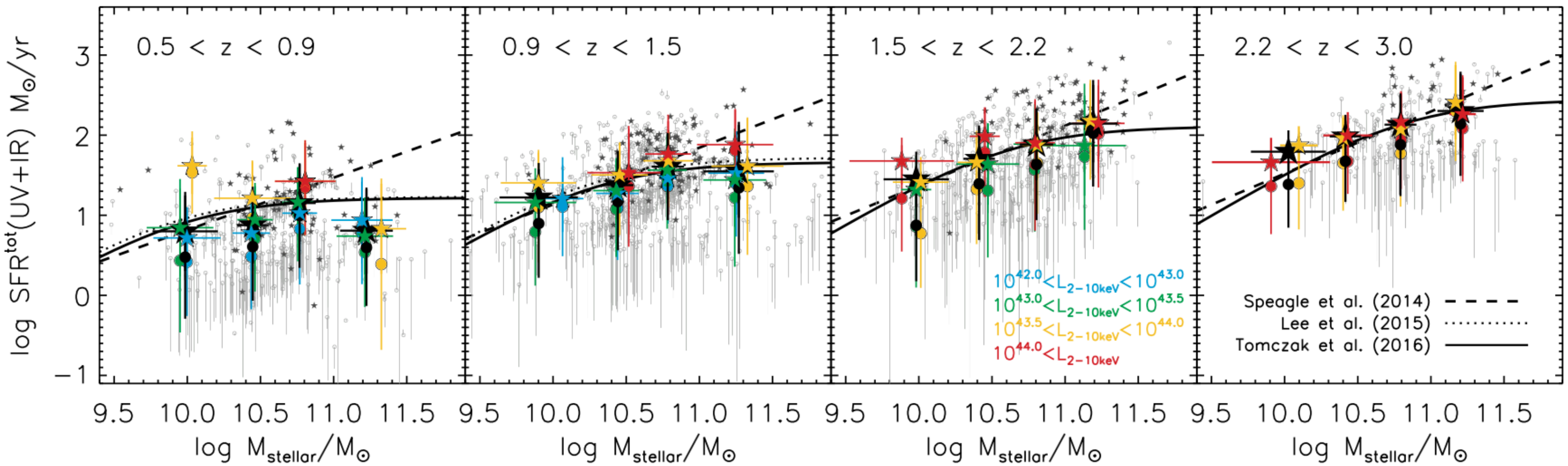
Half full glass: Clear evidence that star formation is suppressed in regions affected by the quasar-driven outflow

Half empty glass: The quasar driven outflow escapes without quenching star formation over the entire galaxy

Statistical evidence for suppressed Star Formation in AGN hosts? Conflicting claims:

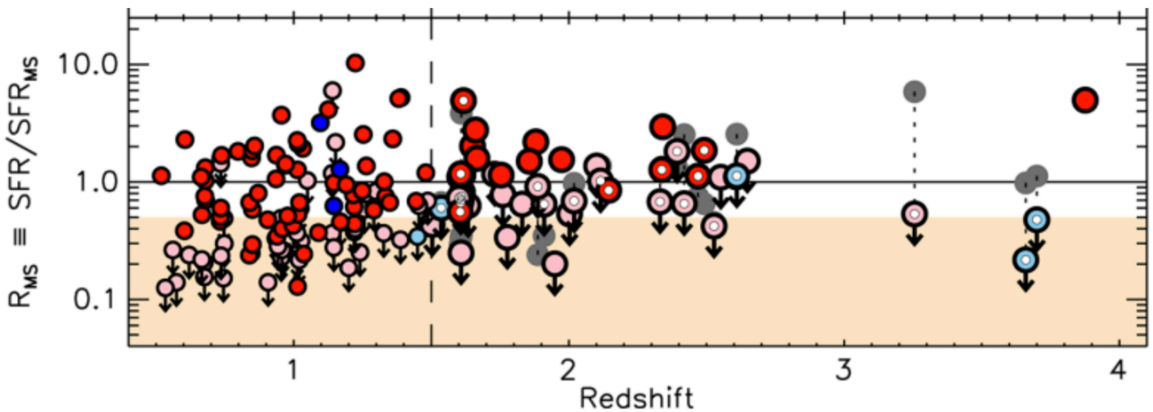
Suh+17, Mullaney+13, Santini+13, Rosario+15, Del Moro+15, Ellison+16, Brusa+09:

AGN hosts on and above the Main Sequence

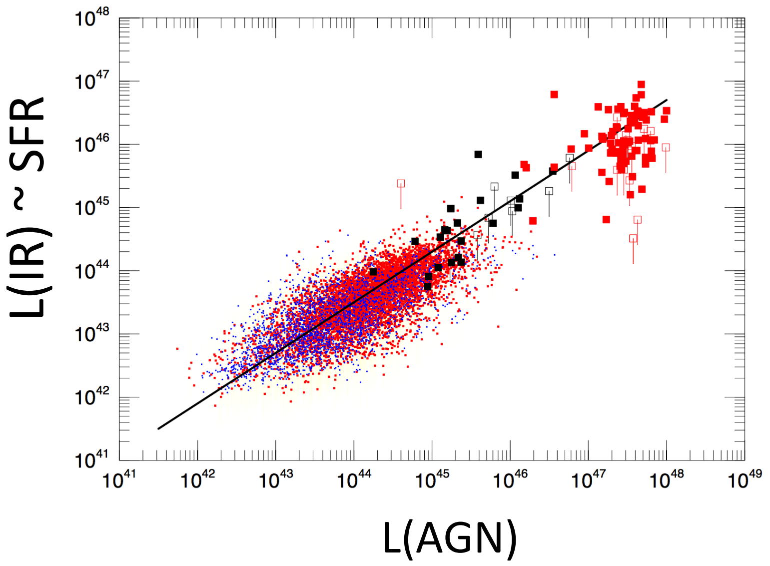


Mullaney+12, Matsuoka+15, Bongiorno+12, Brusa+09, Georgakakis+14, Ellison+16:

AGN hosts on and below the Main Sequence

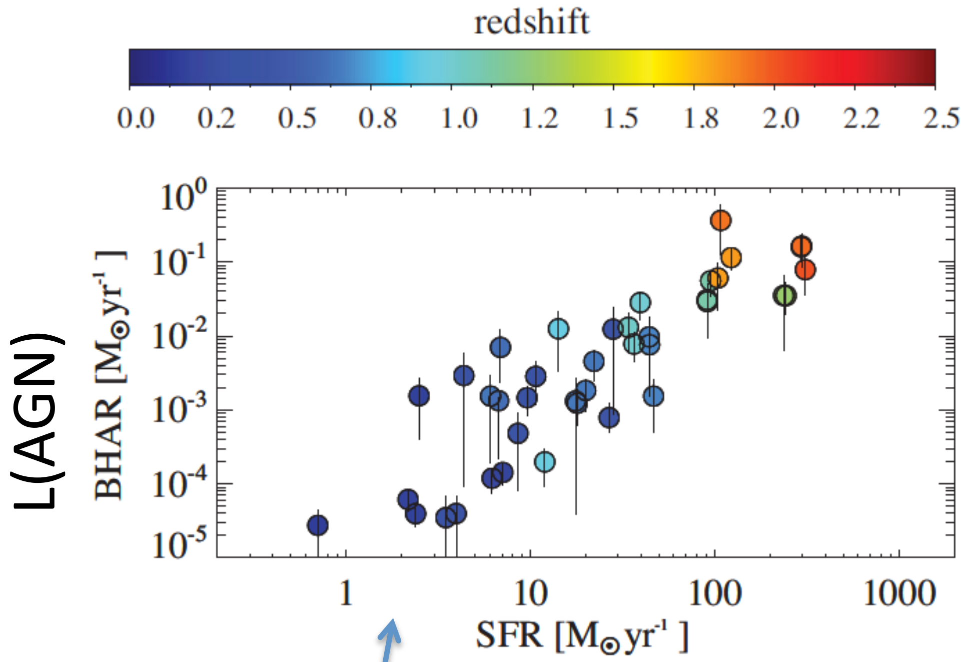


Correlations between AGN luminosity activity and SFR...
not really what expected from negative feedback... different timescales?

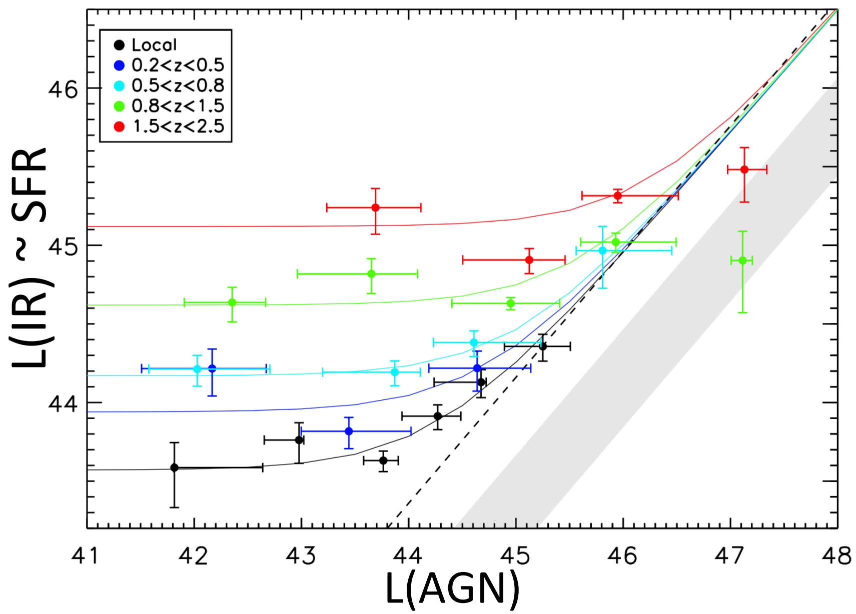


Netzer+07,09
Harrison+16
Bernhard+16

Del Vecchio+15



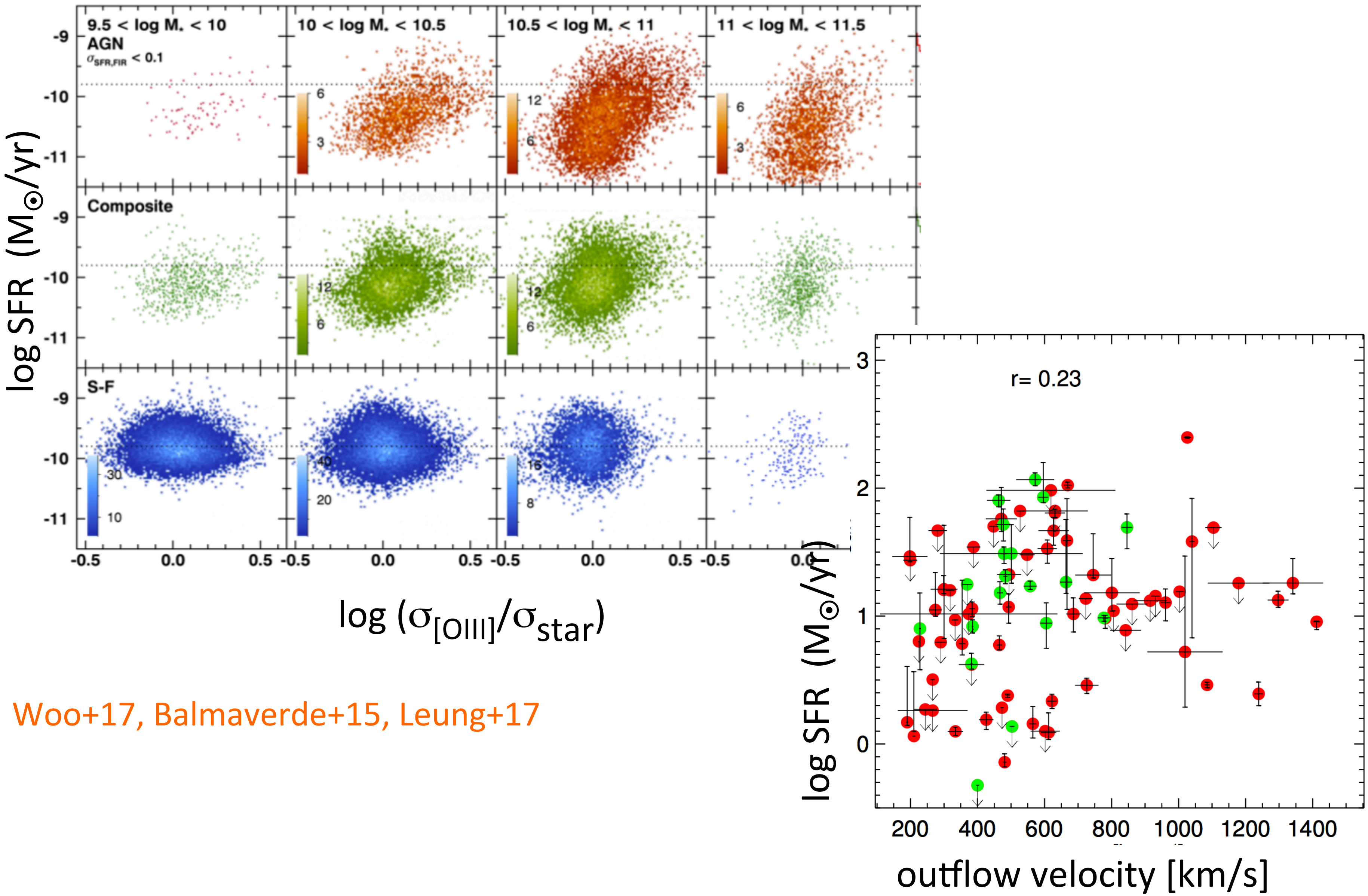
Correlation only at high luminosities



Lutz+10
Shu+10
Rosario+13)

Stack in X-ray
-> better technique
to deal with AGN flickering

No correlation between outflow and SFR (opposite trend). Either no feedback from outflows or delayed effect

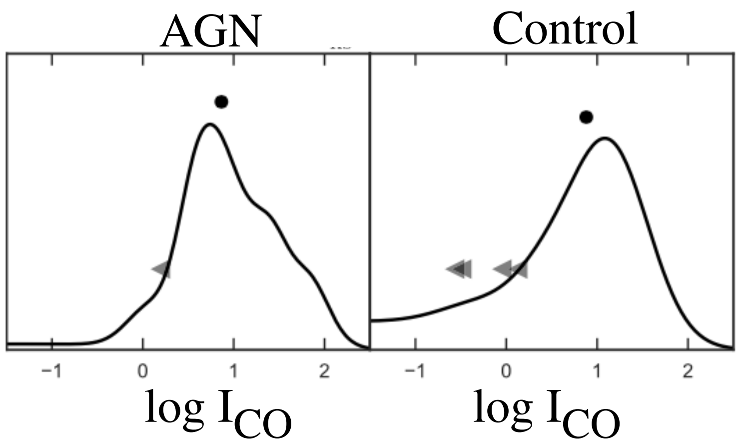


Woo+17, Balmaverde+15, Leung+17

Directly looking at the effect of gas removal:
Gas content in AGN host galaxies
-> conflicting results

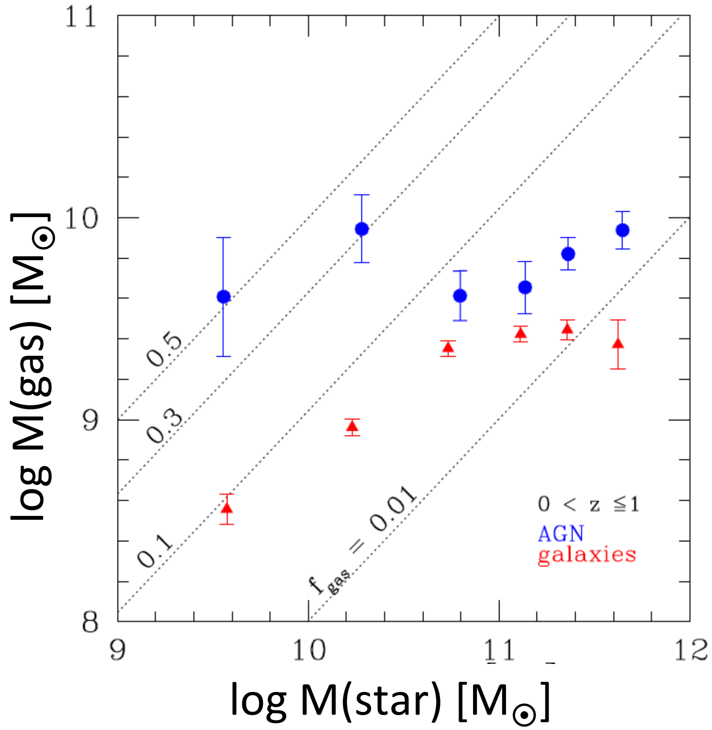
Rosario+18
Maiolino+97:

No difference

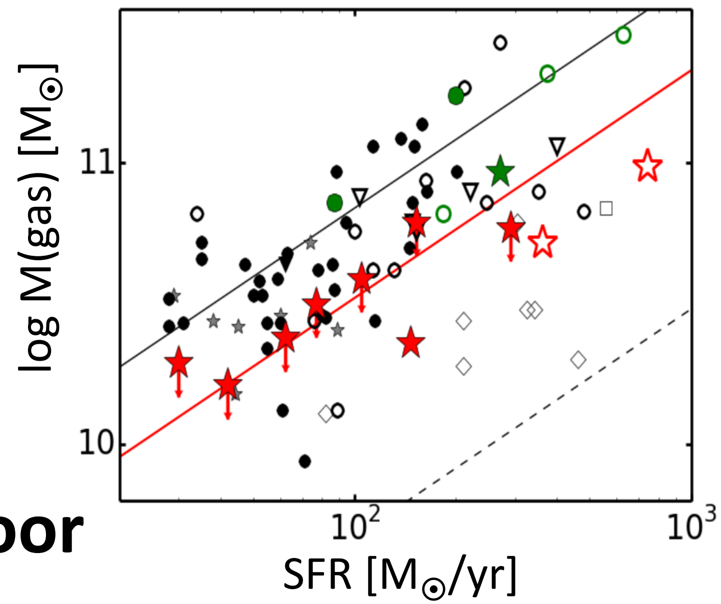


Vito+14:

Gas rich



Luminosity effect?

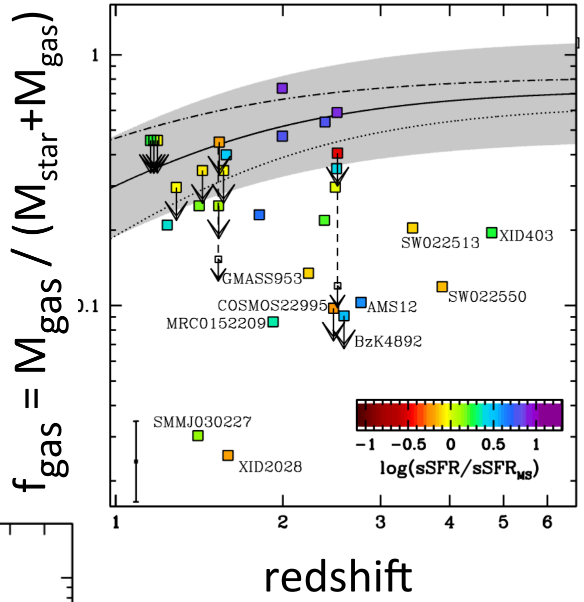


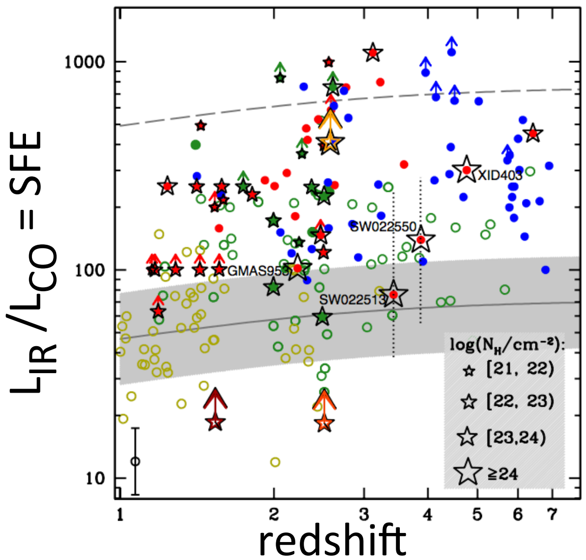
Fiore+17, Kaddad+17, Brusa+16, Perna+18: **Gas Poor**

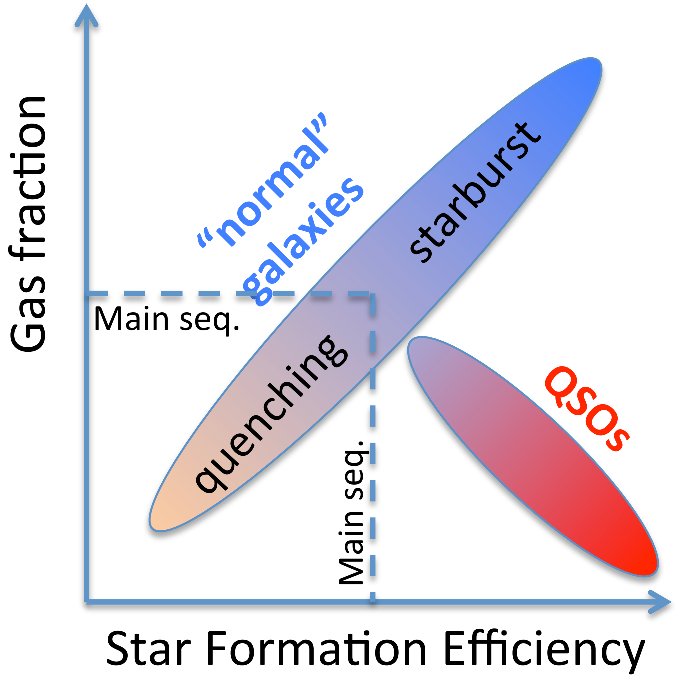
Obscured Quasars (Kaddad+17, Brusa+16,+17, Perna+18)

- Low gas fraction (-> negative feedback?)

- High star formation efficiency

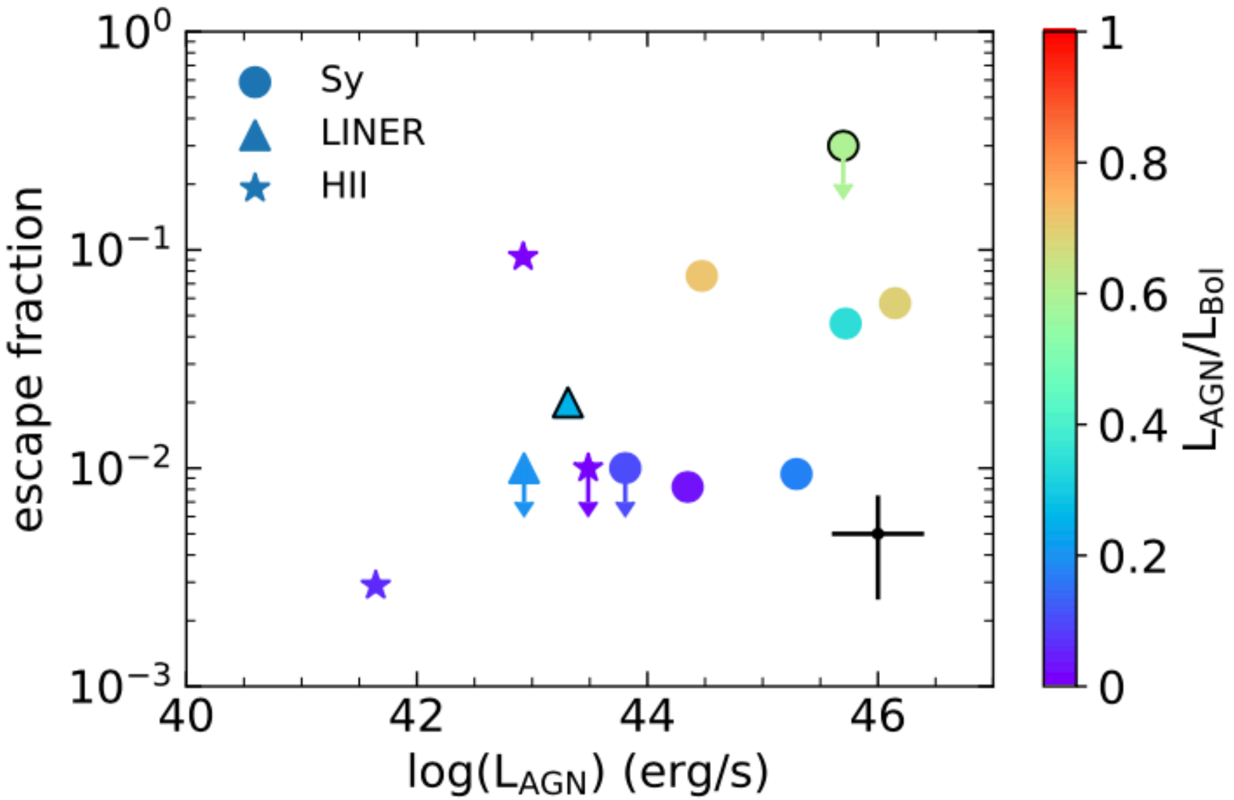






Quasars live in a different population of galaxies?

Fraction of outflowing gas that escapes the galaxy

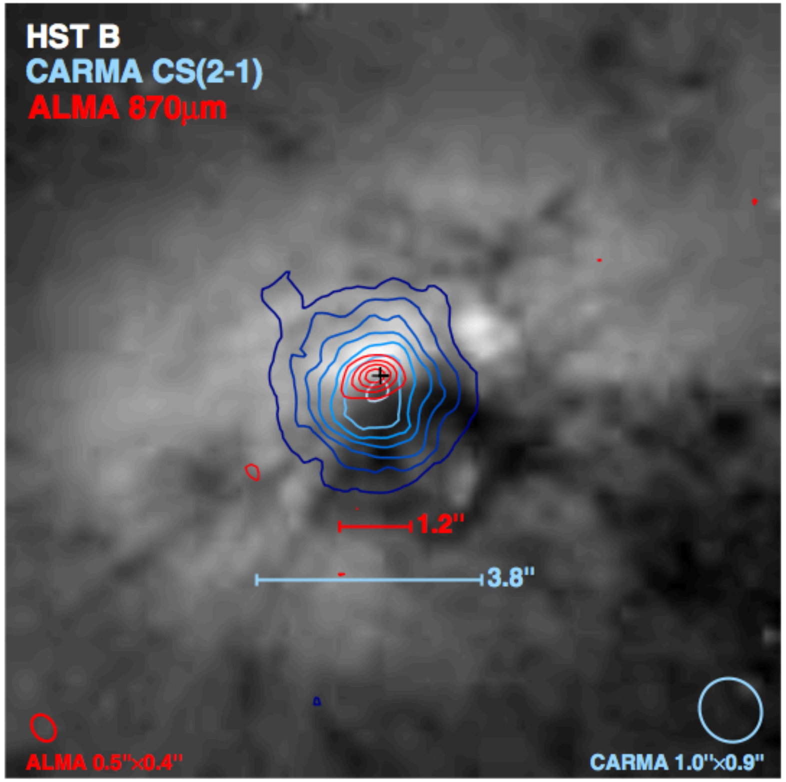


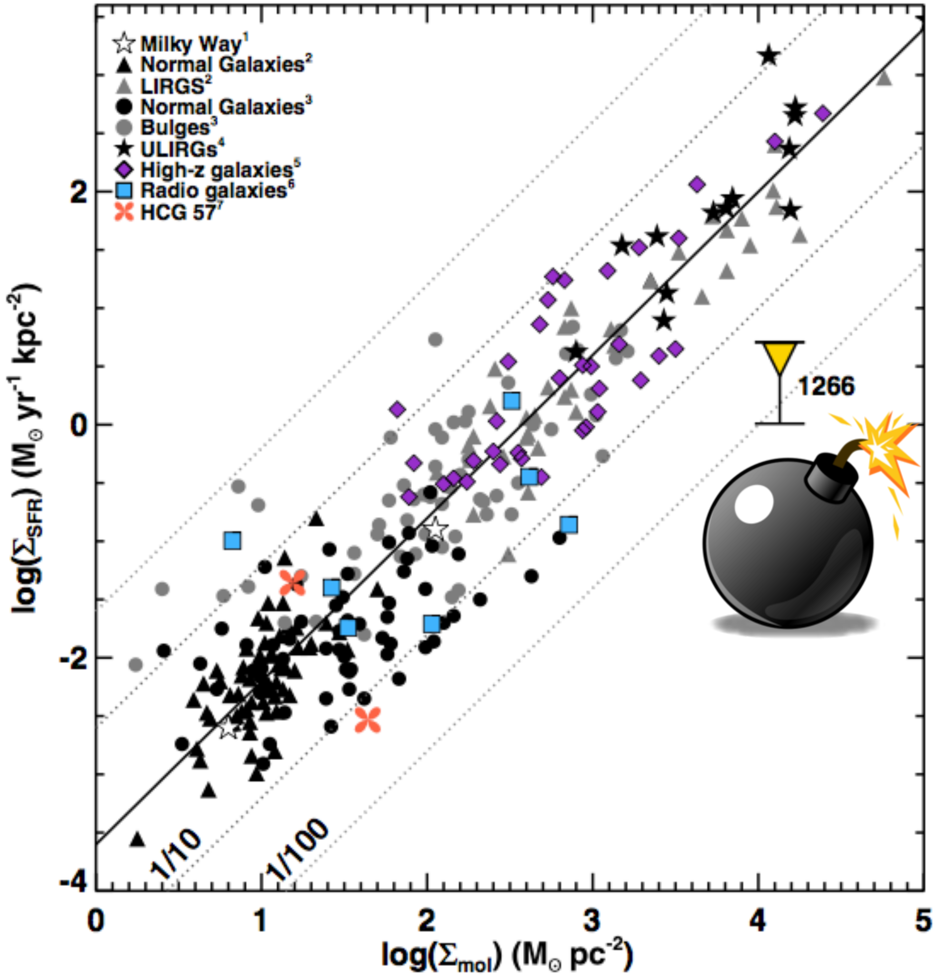
Fluetsch+18
Arribas+14
Bouchet+14

Vast majority of outflowing gas rains back onto the galaxy
-> ejective feedback effective only in the central region?

AGN-induced ISM turbulence/heating
-> suppression of star formation efficiency

OK… but can only be temporary… it's a "time bomb"!

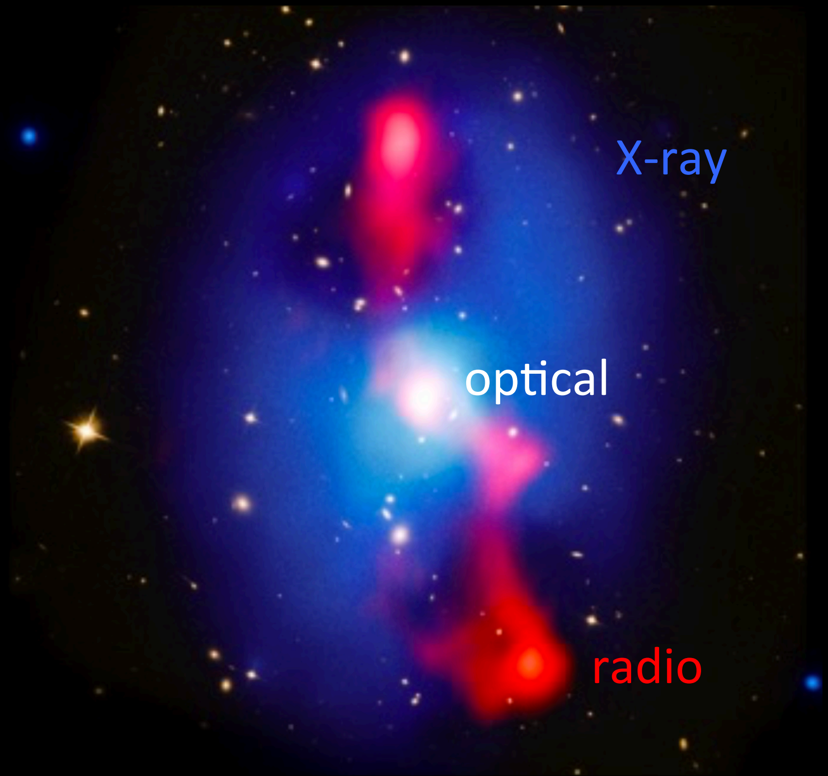


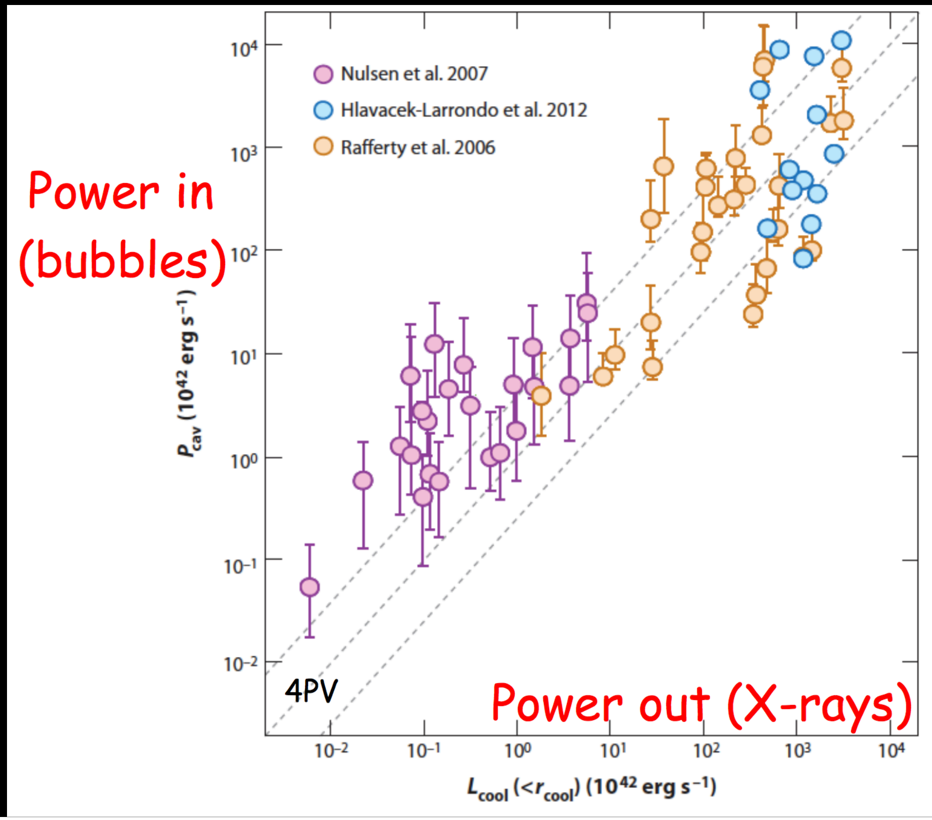


Alatalo+15, Costa+18

Halo heating
-> prevents cooling onto the galaxy

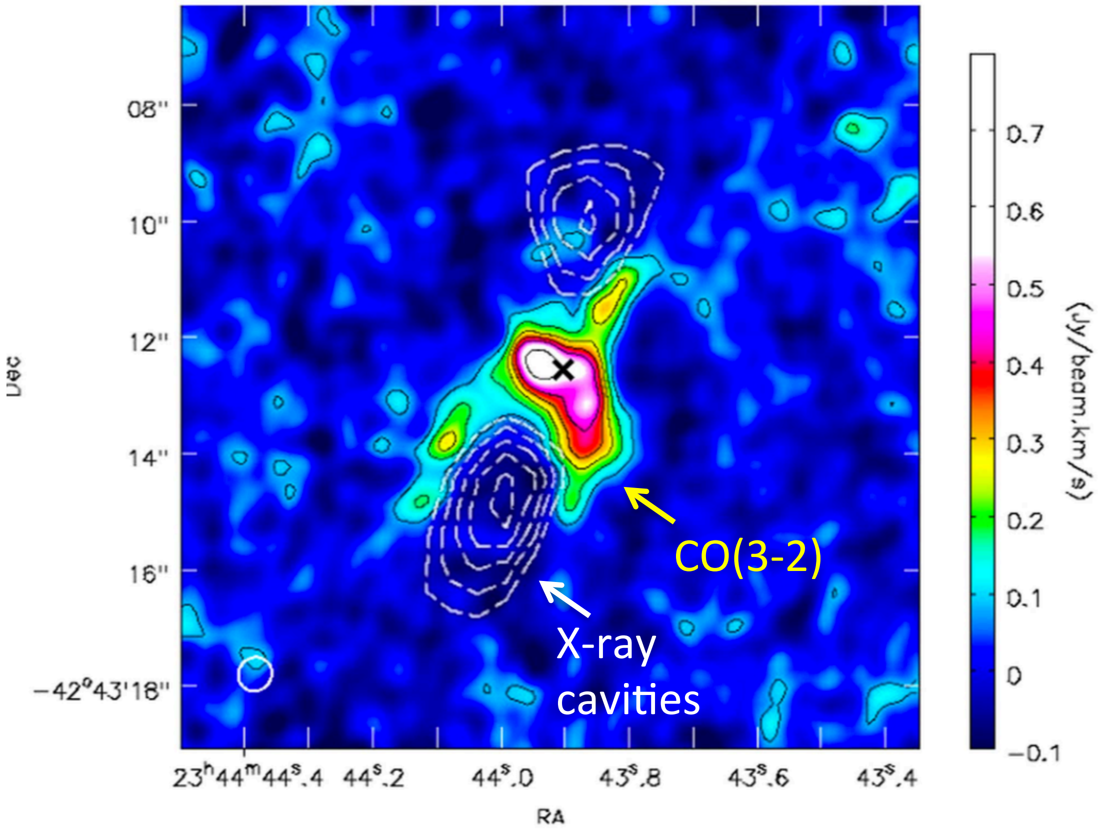
- 'preventive' feedback
- delayed quenching
- maintenance mode

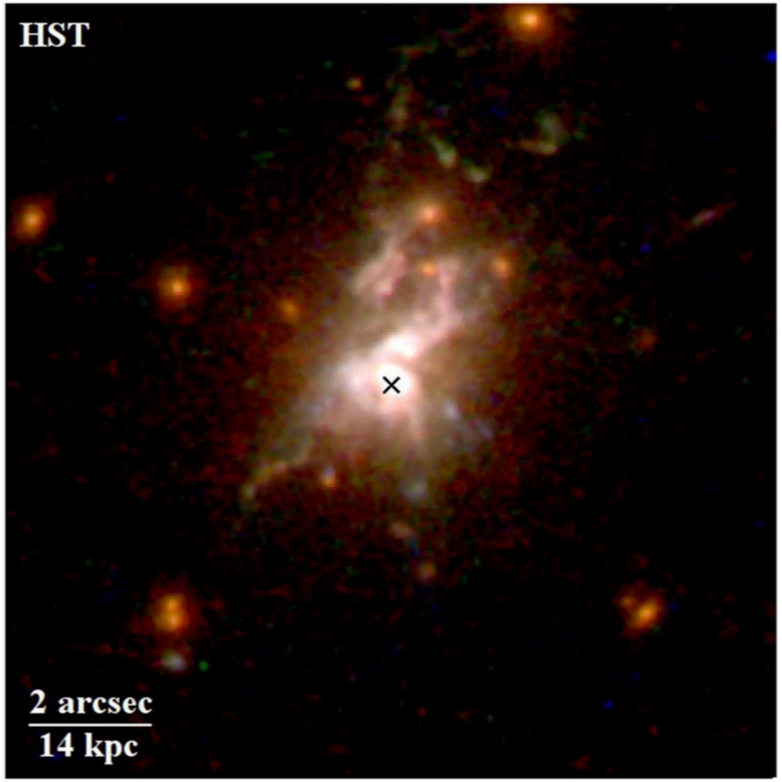




Heating ~ Cooling

Hot bubbles also capable of lifting large amount of cold gas from the host galaxy (=> quenching role)

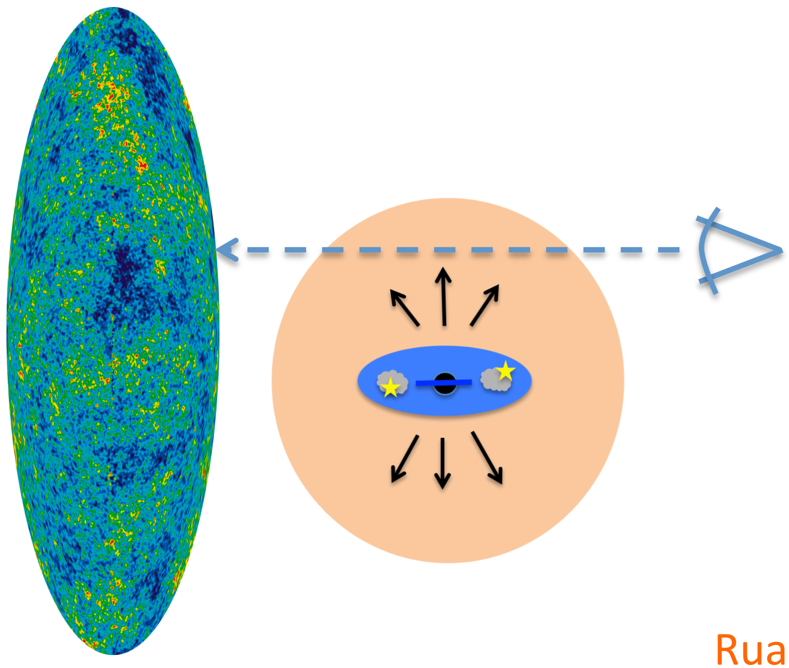


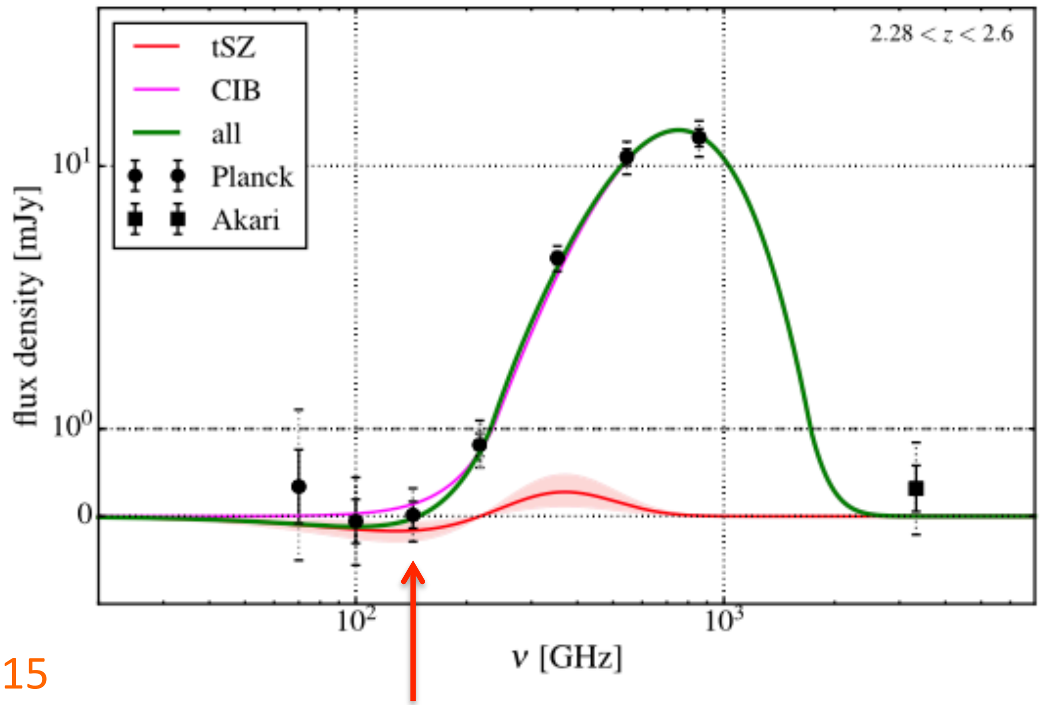


Russell+17, 18
McManar+14

Halo heating through quasar-driven winds: difficult to test presence of hot gas

Attempts to detect associated S-Z by
using CMB data and stacking at quasar positions (Planck, ACT)





Ruan+15
Verdier+16
Crichton+16
Soergel+17

tentative (marginal) detection
~ in agreement
with models

ALMA needed
to make progress

Negative feedback summary

- Ejective mode:
  important regulatory mechanism (central regions)
  probably no quenching

- Suppression of star formation efficiency
  (ISM turbulence/heating): may be, but temporarily?

- Jet/wind halo heating:
  effective (delayed/preventive)
  but yet to be fully tested

AGN positive feedback

Two modes:

- SF triggered in host galaxy or CGM
  by AGN-driven jet/outflow

- SF taking place *inside* the outflowing gas

AGN positive feedback

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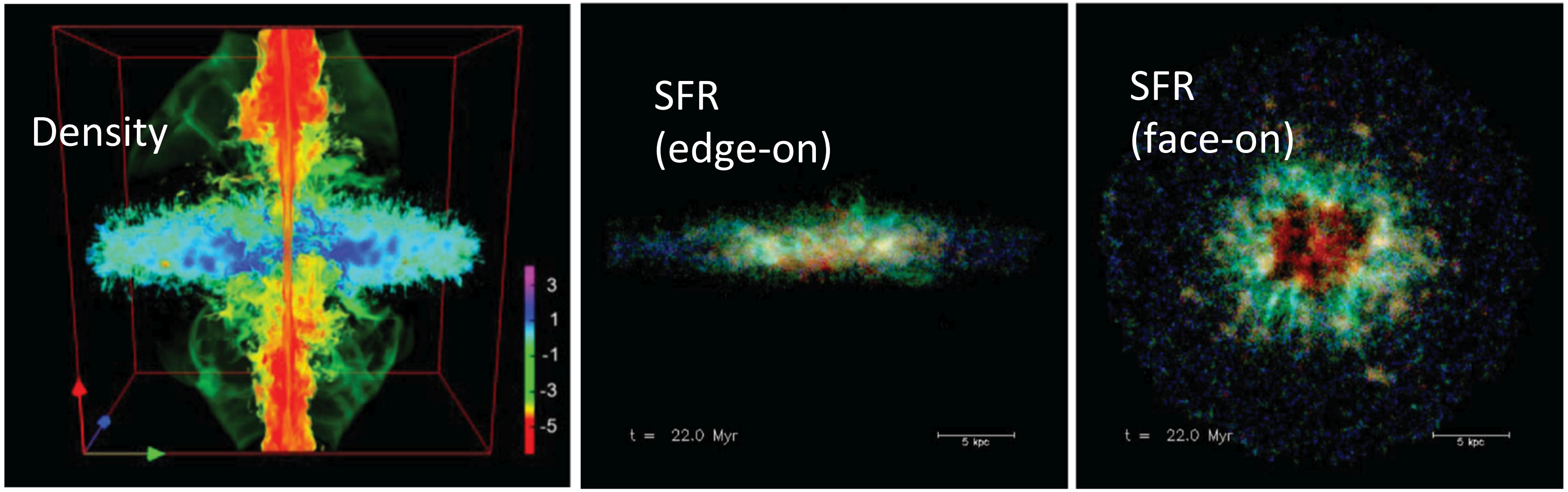
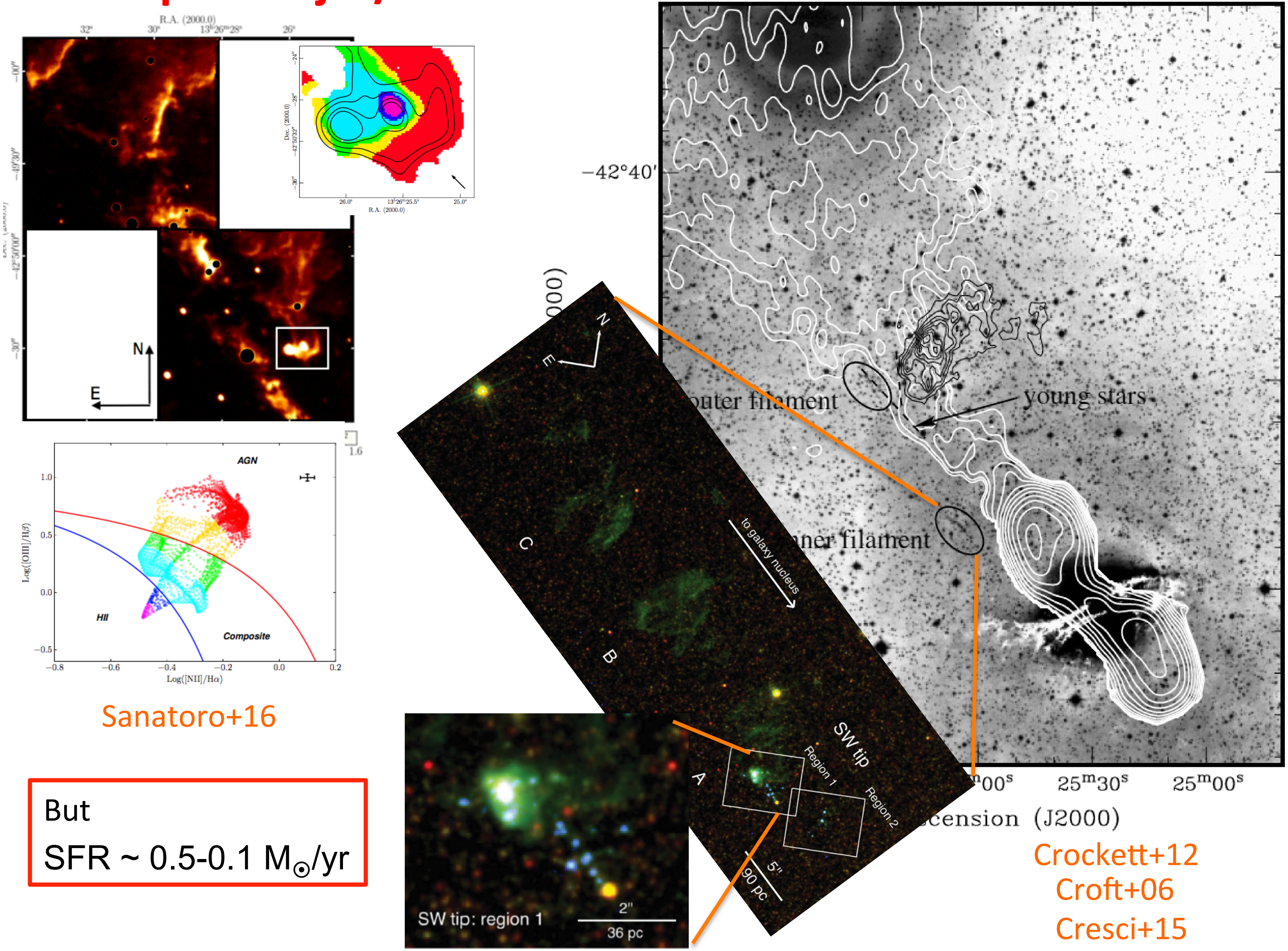


Geibler+12
Silk+13
Mukherjee+18
Many others…

Examples of jet/outflow induced star formation

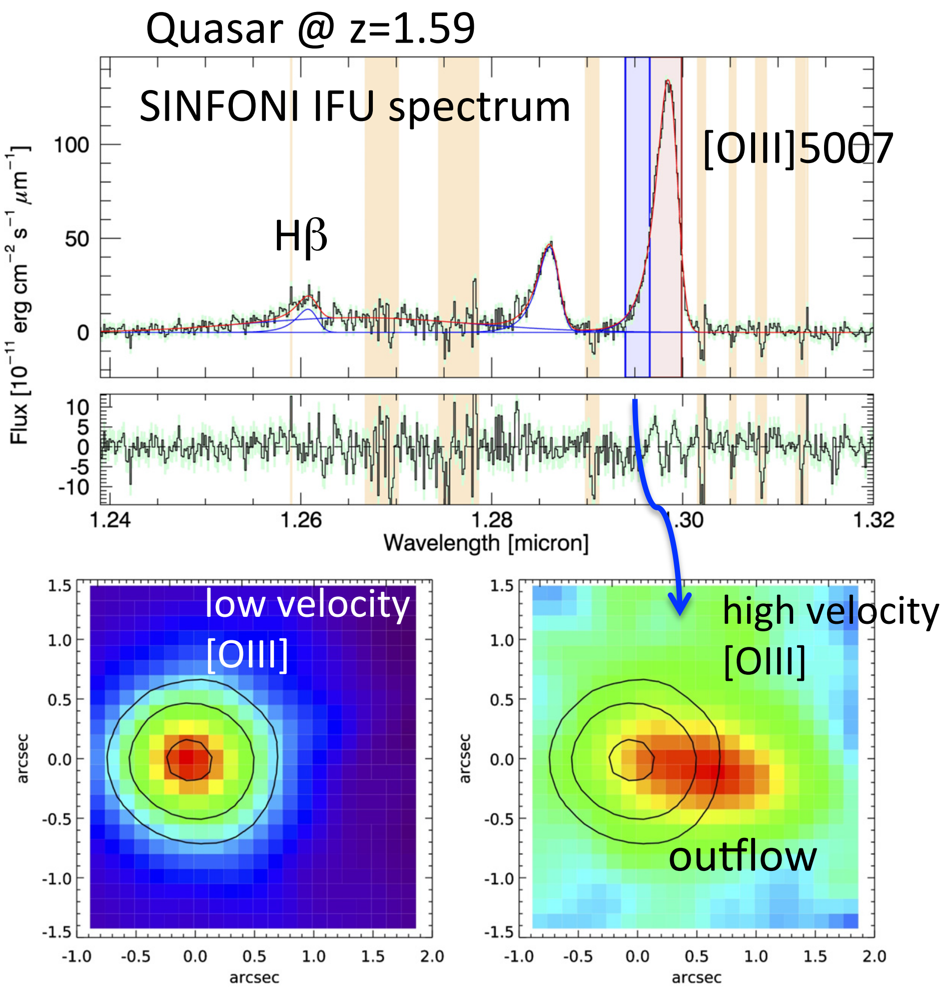


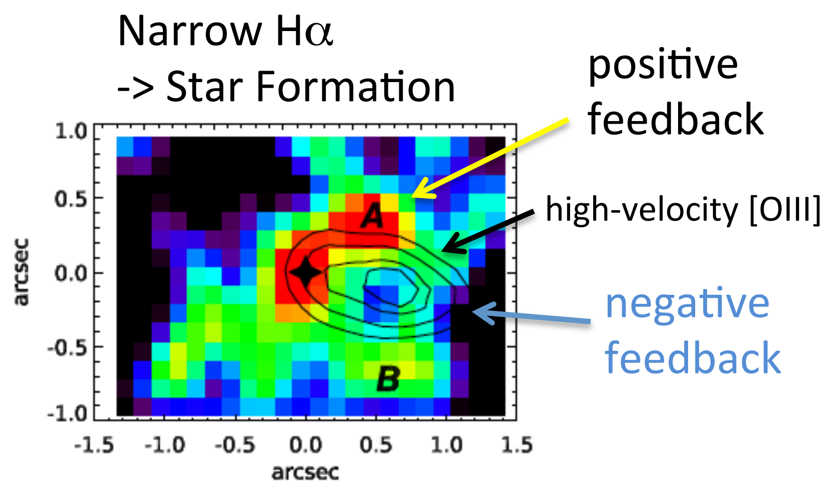
Sanatoro+16

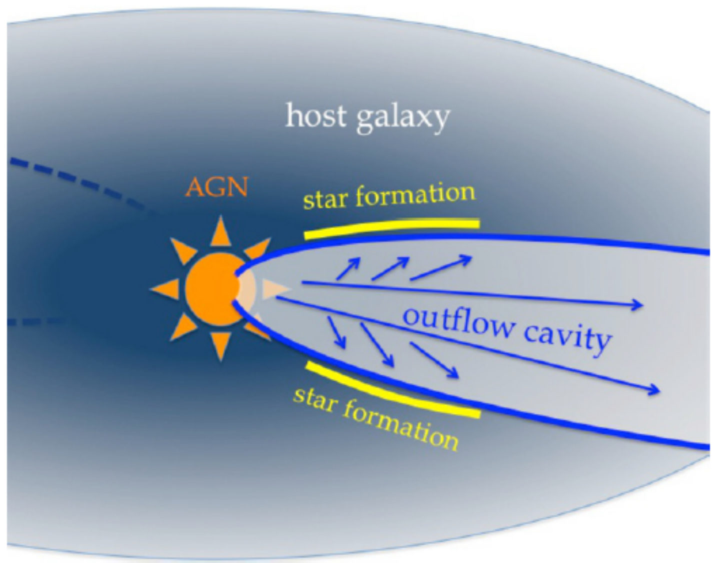
Crockett+12
Croft+06
Cresci+15

But
SFR ~ 0.5-0.1 $M_\odot$/yr

Star formation triggered by quasar-driven winds at high-z







Cresci+15

SFR ~ 230 $M_{\odot}$/yr!

AGN positive feedback

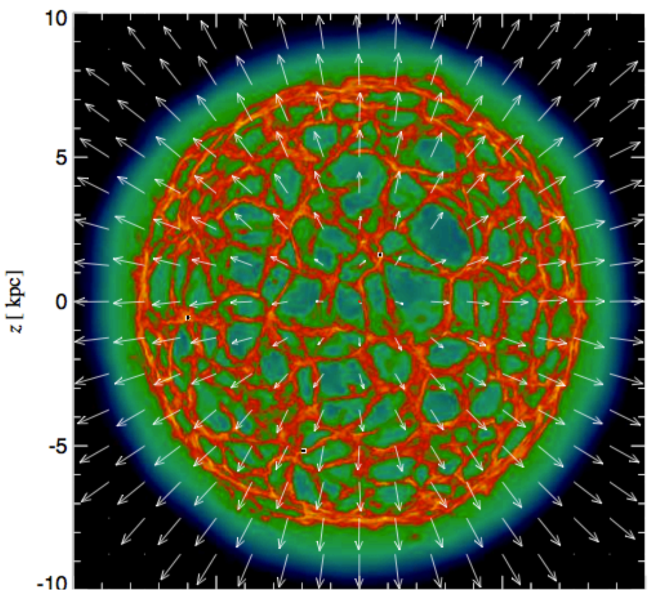
Two modes:

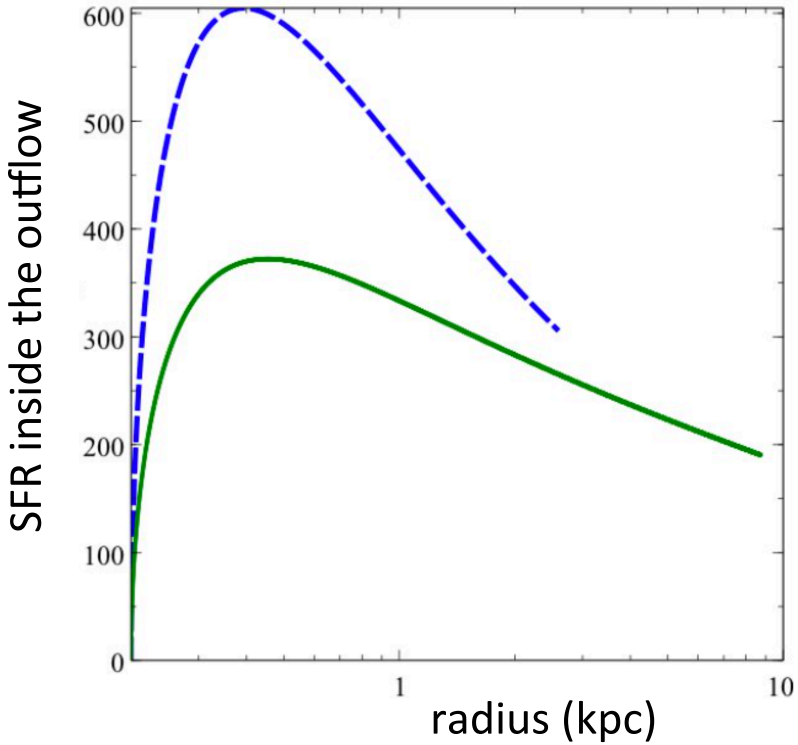
- SF triggered in host galaxy or CGM
  by AGN-driven jet/outflow

- SF taking place *inside* the outflowing gas

Several models do expect star formation *inside* outflows
-> Stars should form at high velocities on ~radial orbits
➔ major potential implications!

e.g. Contribution to the galaxy spheroidal component...

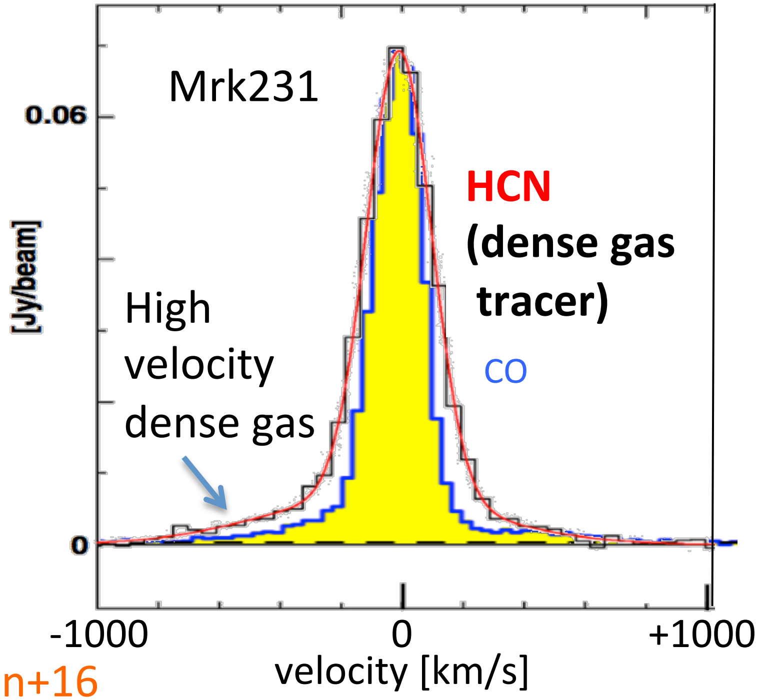


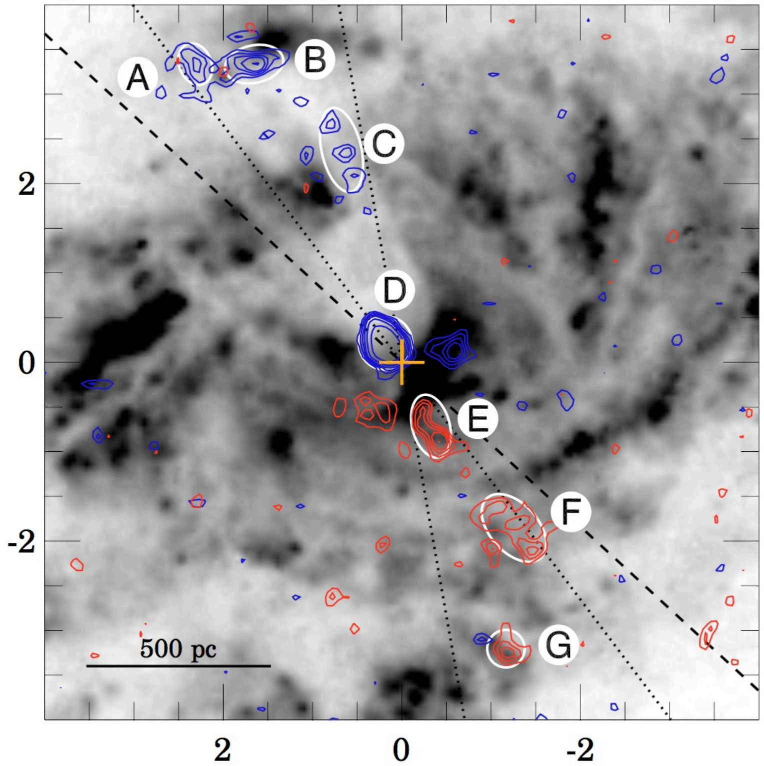


Expected also by properties of outflowing gas: molecular dense, cold and clumpy gas...

Zubovas+13,17, Zubovas & King '13
Silk+15, +17
Ishibashi & Fabian +14, +15,+17 Nayakshin+12,
Zachary+14, Gaibler+12, Wang & Loeb '18
Dugan+2014, El-Badry+2016,
Mukherjee et al. 2018

A large fraction of the outflowing molecular gas is
- very dense ~10^5-10^6 cm^{-3}
- very clumpy (clump sizes 1-100 pc)



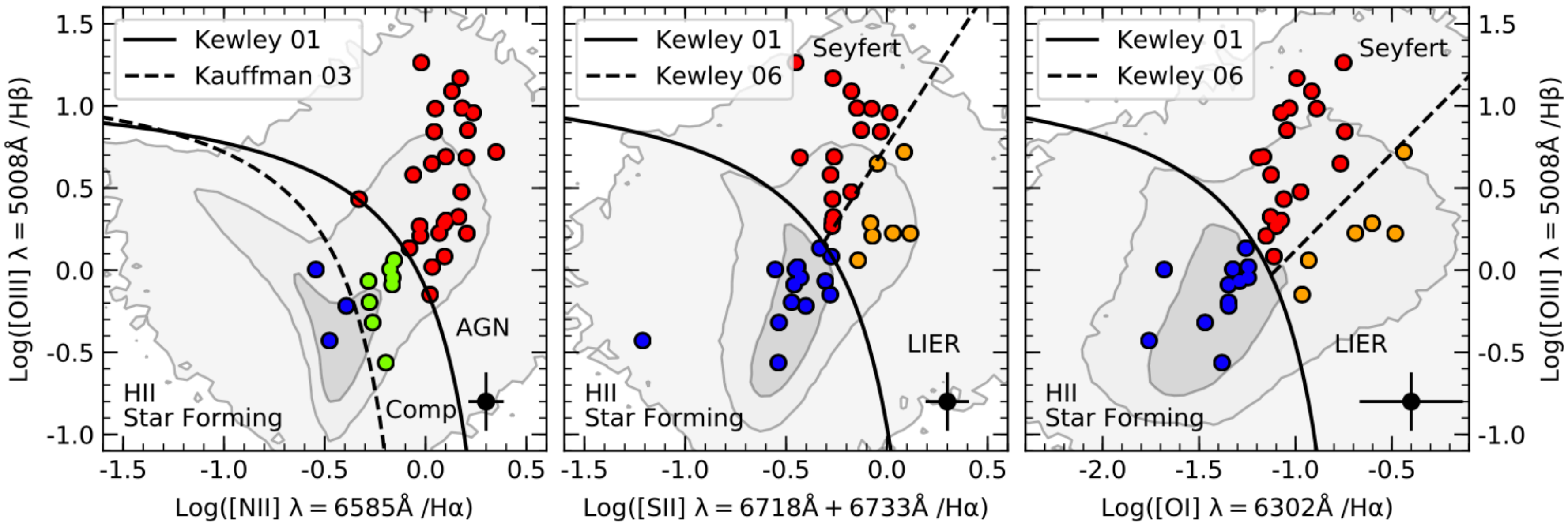


Lin+16
Aalto+15, 16
Walter+17
Alatalo+15
Gonzalez-Alfonso+17
Zschaechner+15
Tunnard+15
Sakamoto+08

➔ **Gas properties similar to star forming regions**

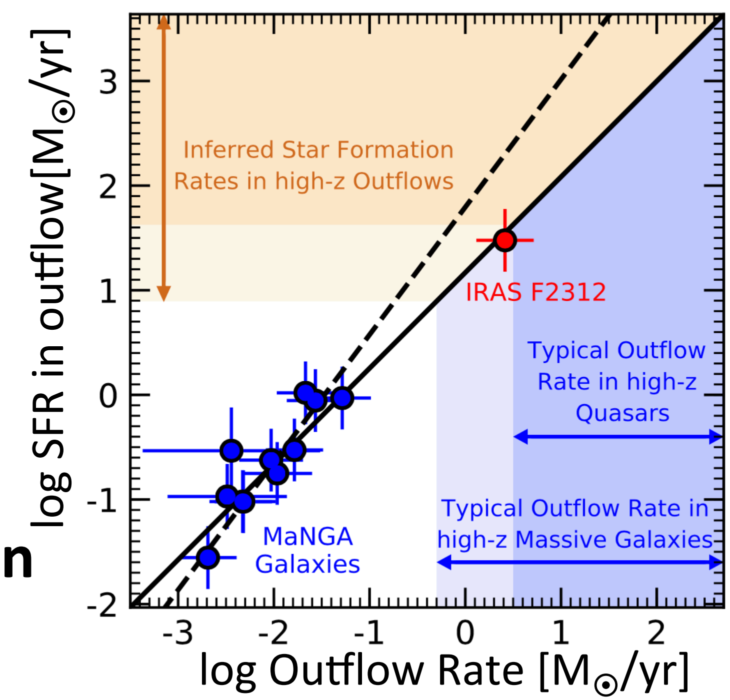
Pereira-Santaella+16
Aalto+15
Finn+15
Borguet+12
Feruglio+15

Manga Survey: Median BPT classification of galactic outflows



~30% of galactic outflows classified as "star forming"
-> star formation *inside* the outflow
(confirmed by near-IR diagnostics for some of them)

Extrapolation to high-z implies important contribution to galaxy formation

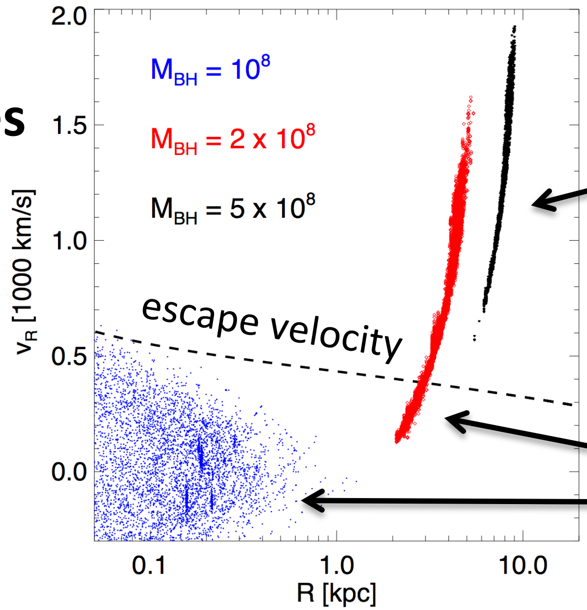


Gallagher+18
Maiolino+15

Implications of star formation inside outflows

Contribution to the formation of spheroidal component of galaxies (bulges, halos, ellipticals)

radial velocity of stars formed in outflow



escaping stars:
- intra-cluster light
- NIR background

Bulge-Halo stars
Elliptical gal. stars

Zubovas & King '13
Ishibashi & Fabian '17
Mukherjee+18
Wang & Loeb '18

BH-spheroid correlations

Supernovae outside galaxies
-> *In-situ* chemical enrichment
-> *In-situ* halo heating

- **Re-ionization of the Universe**

Implications of star formation inside outflows

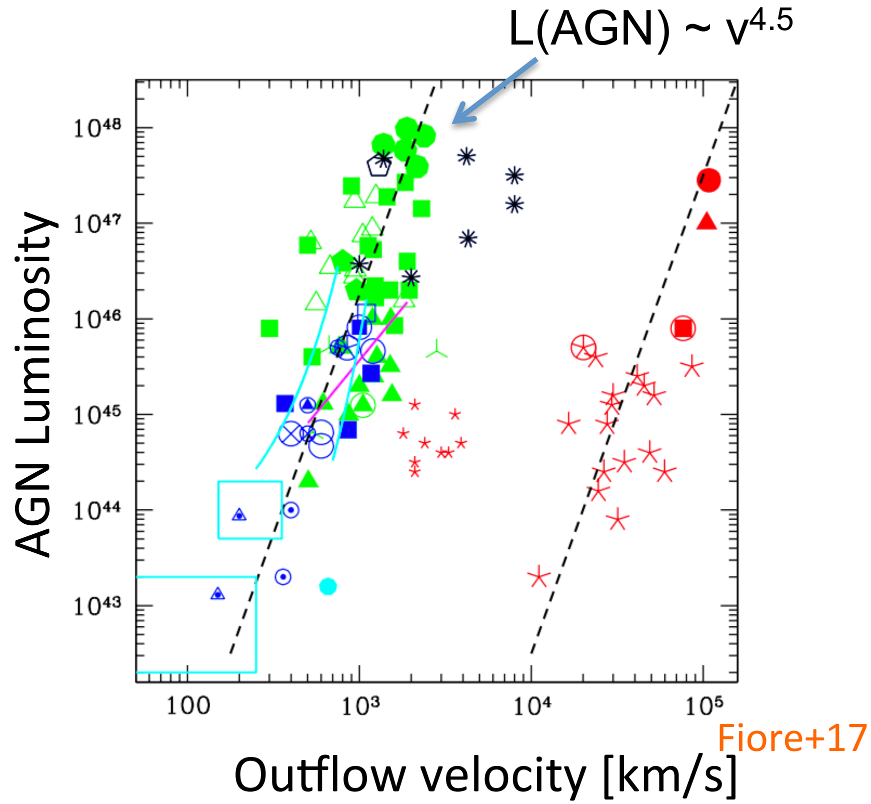
Contribution to the formation of spheroidal component of galaxies (bulges, halos, ellipticals)

BH-spheroid correlations

Obvious expectation for AGN – driven outflows

Supernovae outside galaxies
-> *In-situ* chemical enrichment
-> *In-situ* halo heating

- **Re-ionization of the Universe**



Automatically gives the observed M_{BH}-$\sigma_*^{4\text{-}5}$ relation

Positive feedback summary

- **Induced star formation in the galaxy:**
  several clear cases
  locally modest effect,
    possibly much stronger at high-z

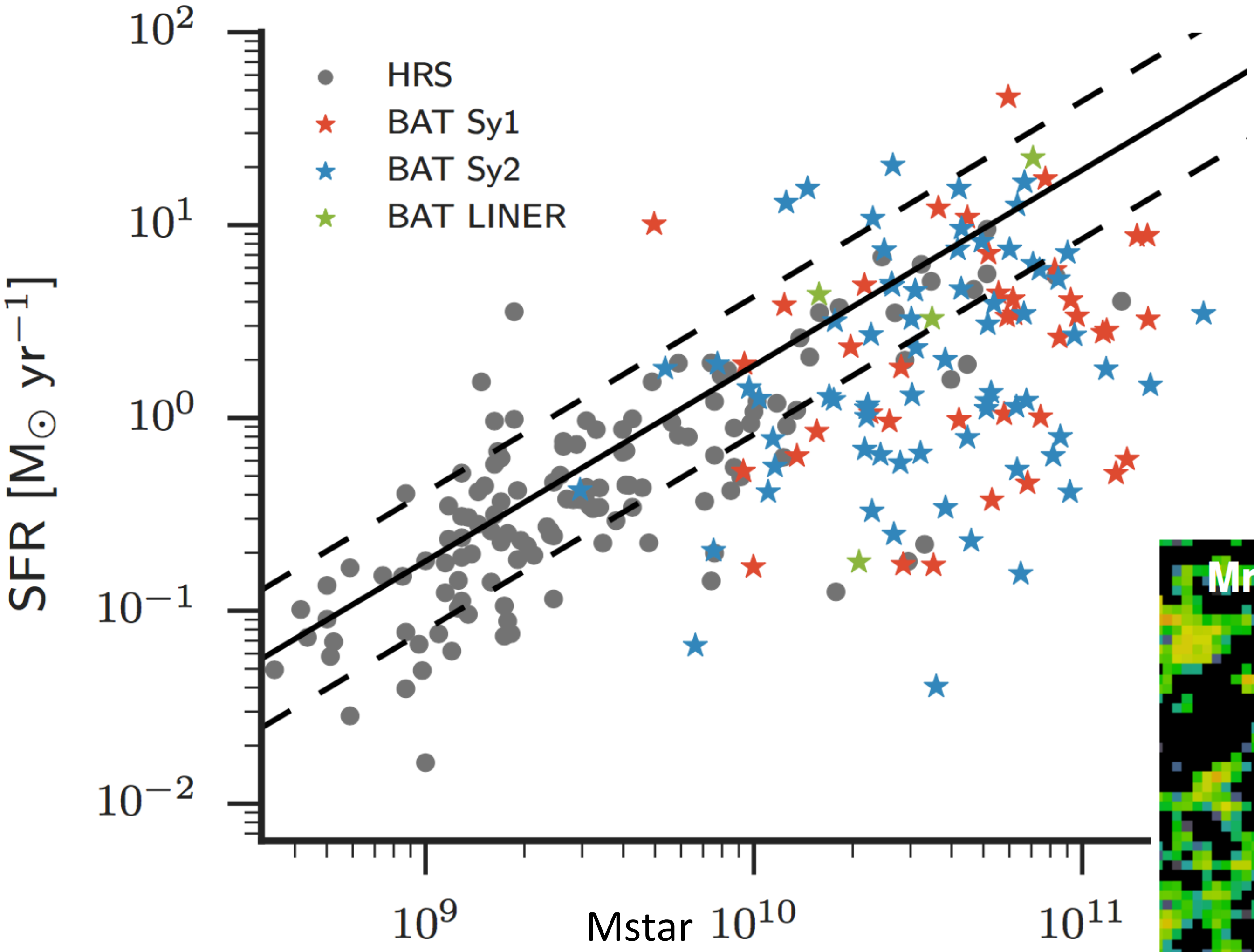
- **Star formation inside outflows:**
  now detected in multiple cases
  potential major implication:
    formation of spheroids
    BH-spheroid relations


Thank you!

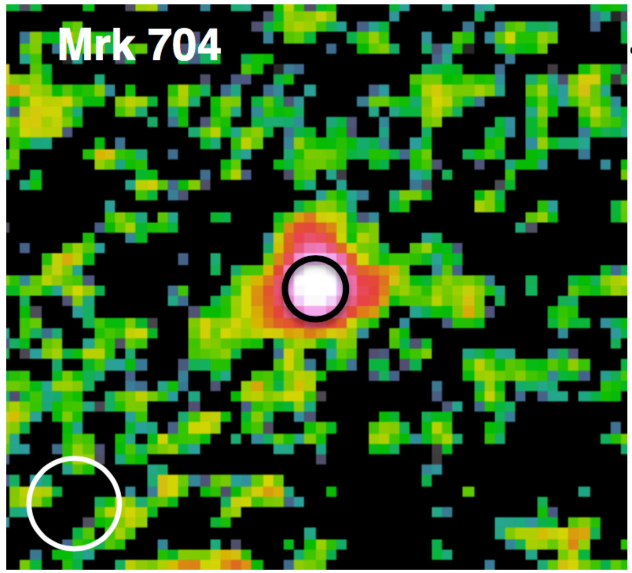
Spare slides

Just to make things even more puzzling...

Hard X-ray selected AGNs: in green valley... but centrally Star Forming

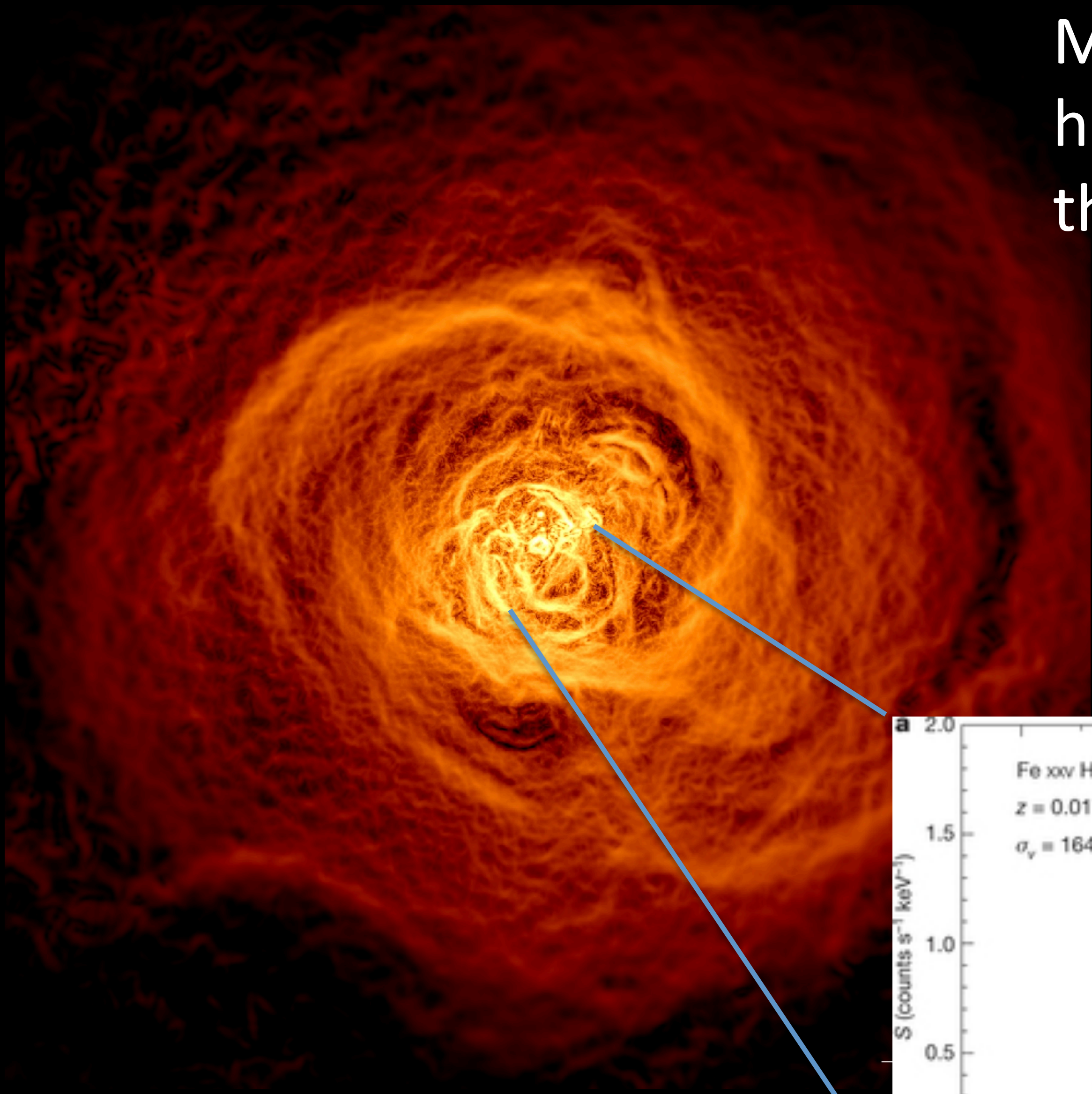


-> further evidence for a delayed (indirect) effect?

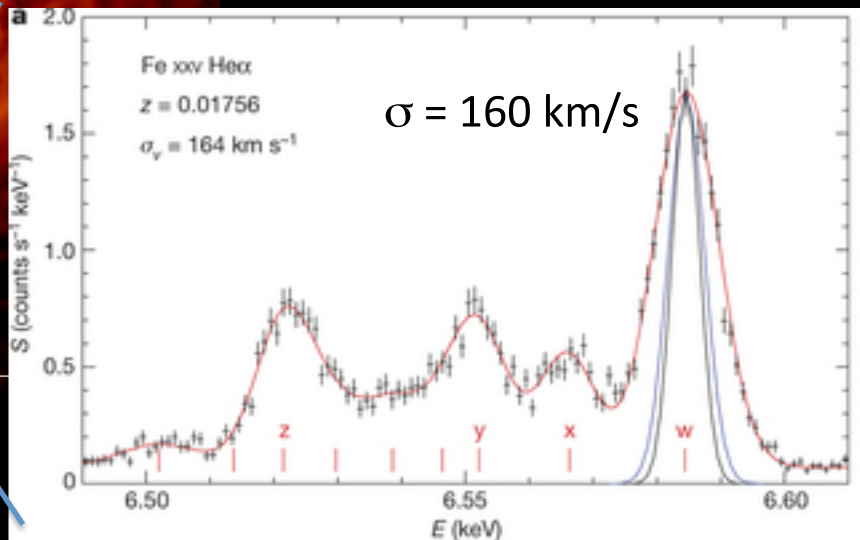


Shimizu+15, Mushotzky+14

Mechanical Halo heating, propagated 4π through sound waves



Hitomi spectrum: surprisingly low turbulence

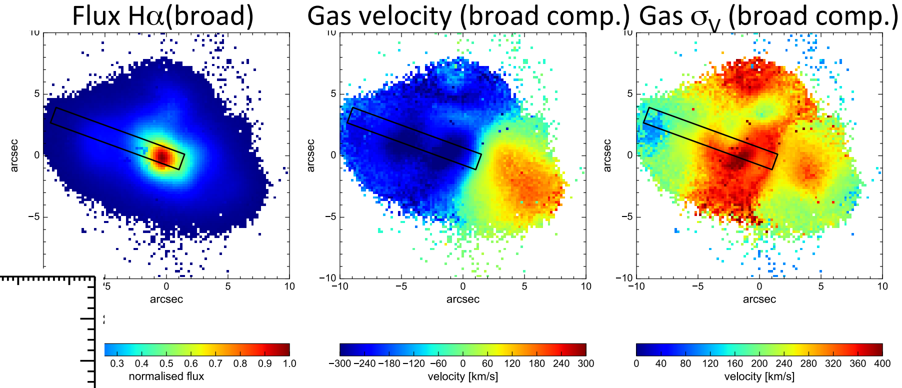


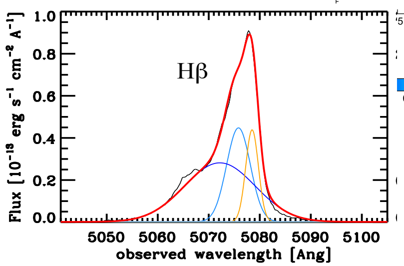
Sanders+15, McManera+17

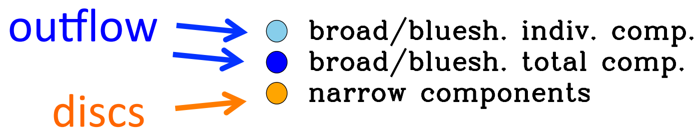
First observational evidence of star formation inside an AGN-driven outflow

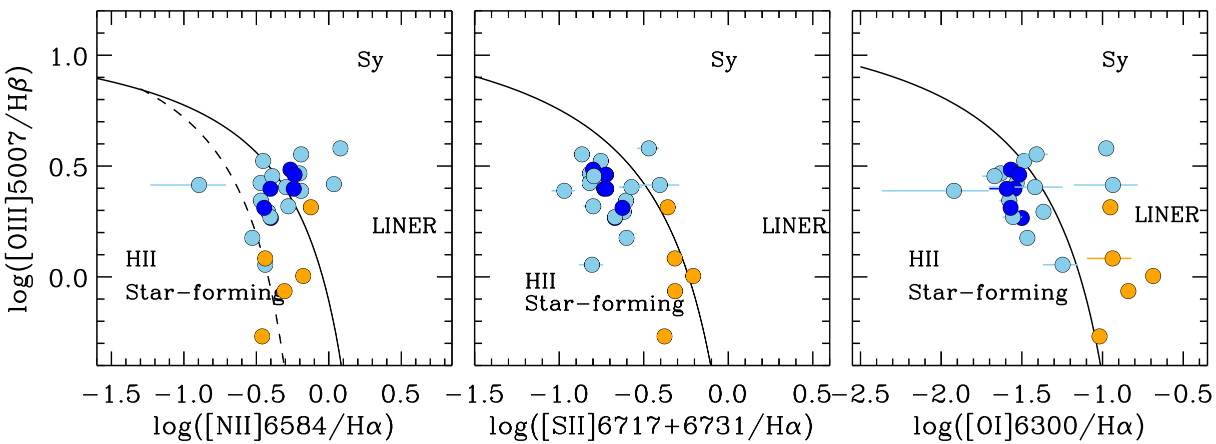
IRAS 2312-59

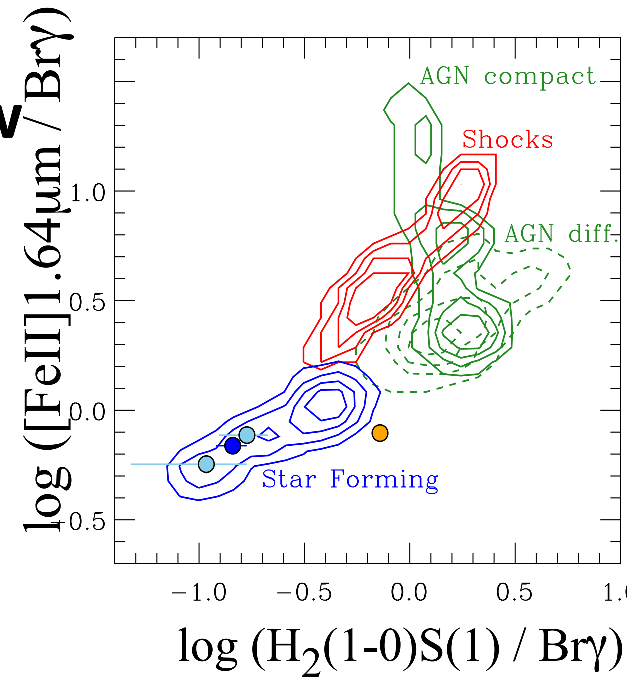
Maiolino+17

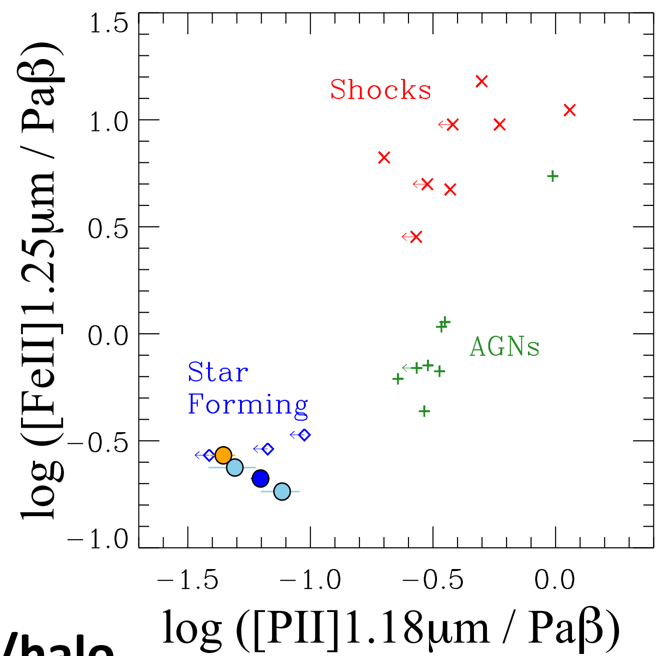








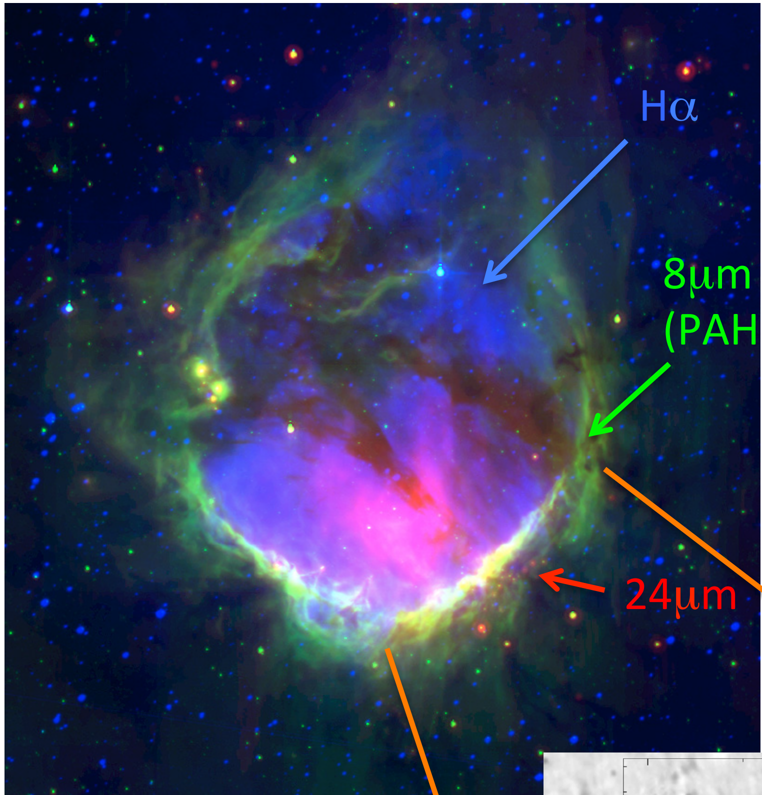


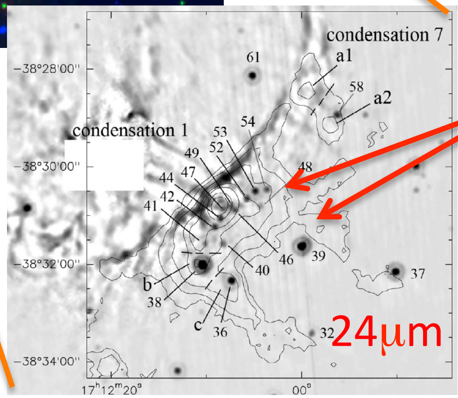


- **SFR in outflow ~15-30 $M_\odot$/yr**
- **Most stars formed in the outflow are bound -> bulge/halo**

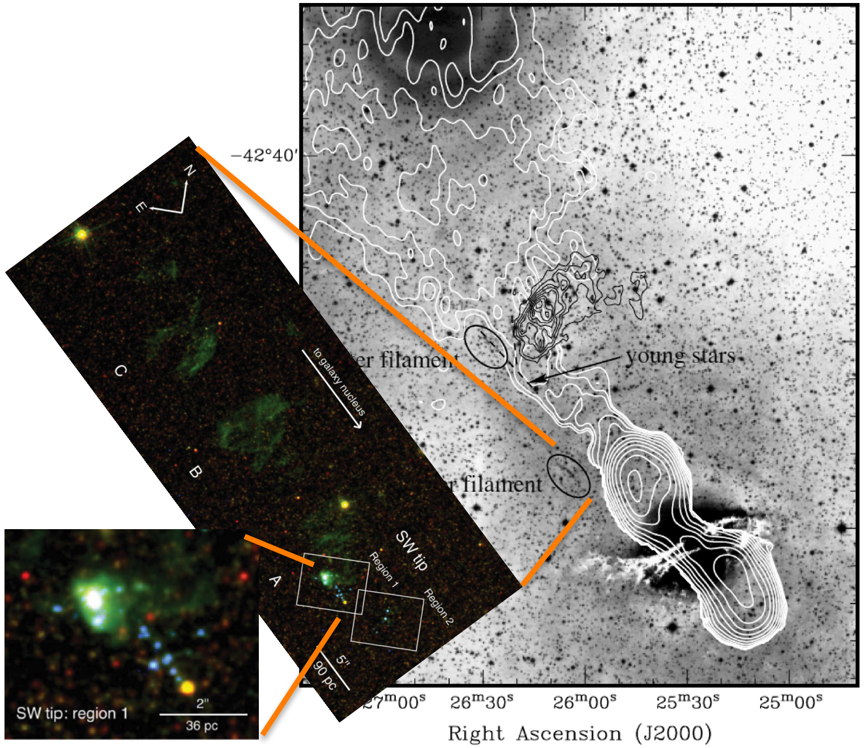
Star formation boosted in shocked gas

Multiple cases in our Galaxy and in other galaxies



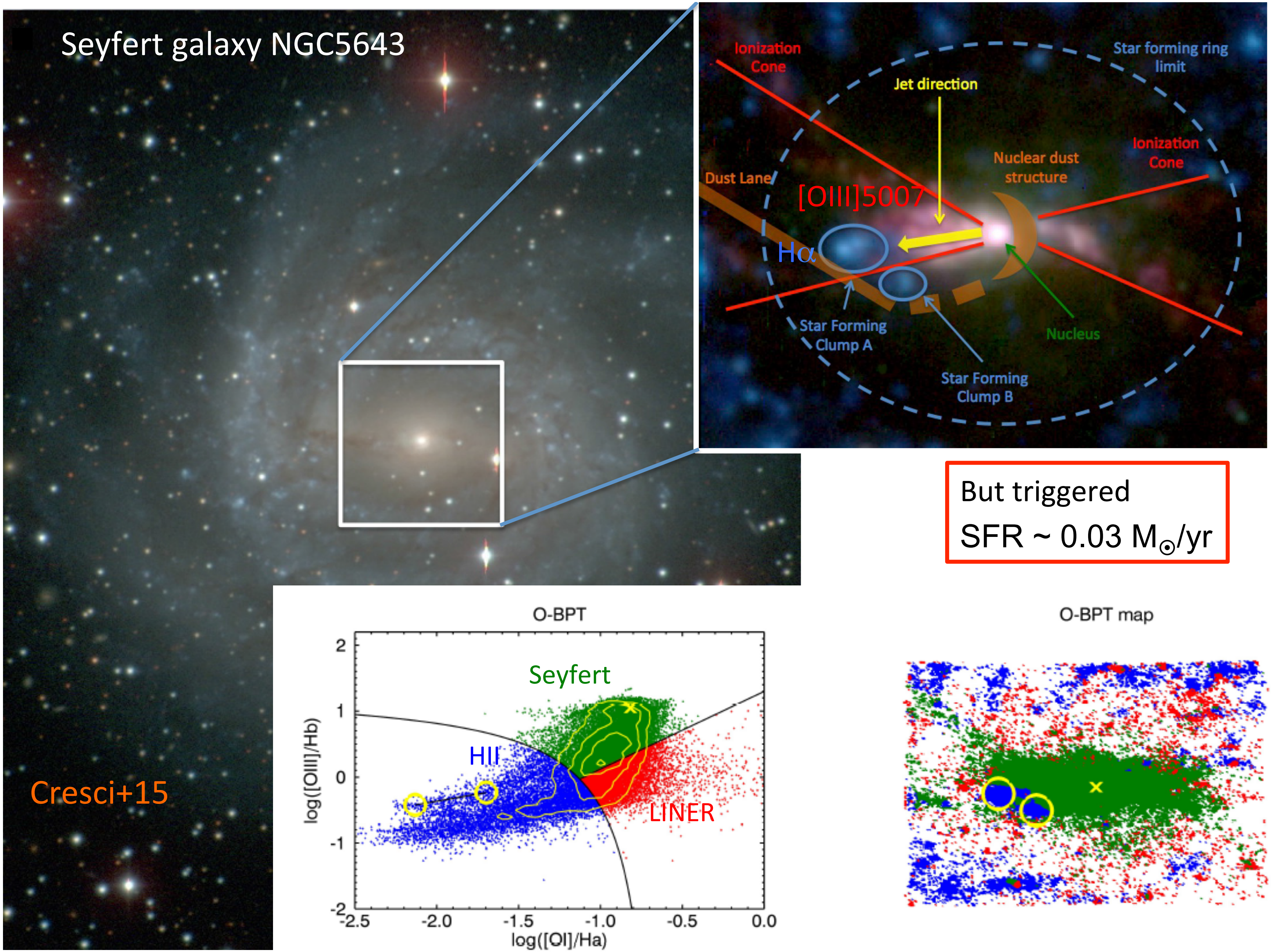


Stars formed in the shocked front



Crockett+12
Santoro+17
Croft+06

Zavagno et al. 2010
Lim et al. 2018
Baug et al. 2018
Dwarkadas et al. 2017
Duronea et al. 2017
Figueira et al. 2017
Deharveng et al. 2015
Ladeyschikov et al. 2015
Dewangan & Ojha 2013, Dewangan et al. 2012, Thompson et al. 2012, Brand et al. 2011


Seyfert galaxy NGC5643
Ionization Cone
Jet direction
Star forming ring limit
Ionization Cone
Nuclear dust structure
Dust Lane
[OIII]5007
Hα
Star Forming Clump A
Nucleus
Star Forming Clump B
But triggered
SFR ~ 0.03 $M_{\odot}$/yr
Cresci+15
O-BPT
Seyfert
HII
LINER
log([OIII]/Hb)
log([OI]/Ha)
2
1
0
-1
-2
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
O-BPT map