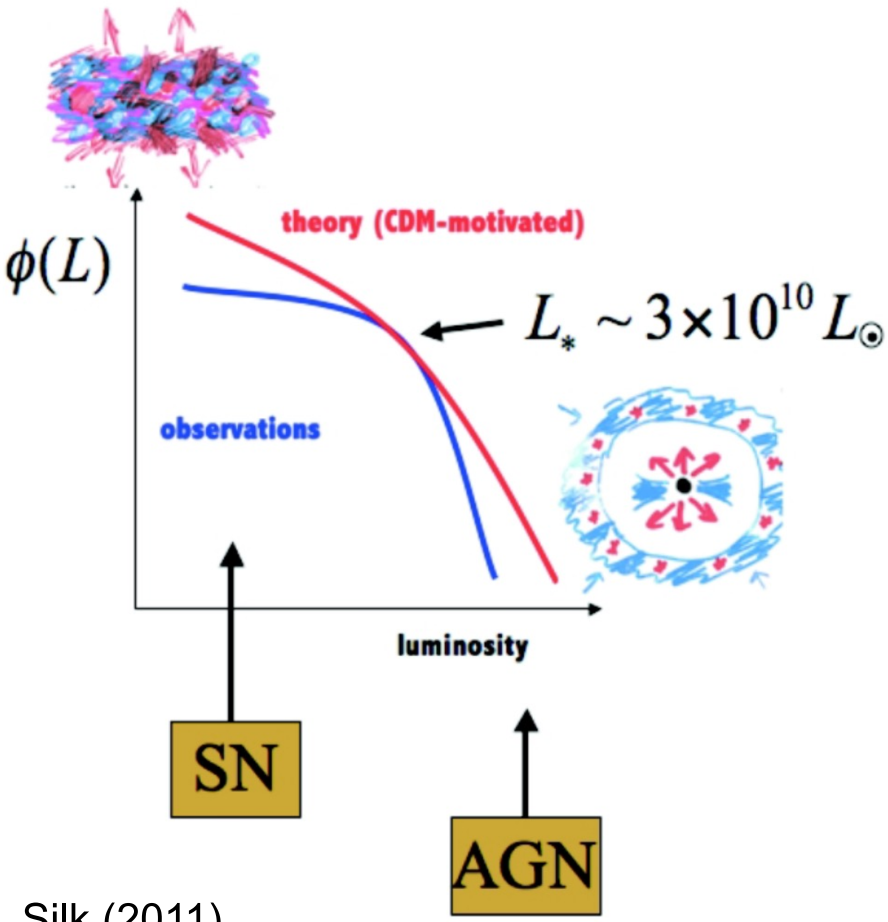
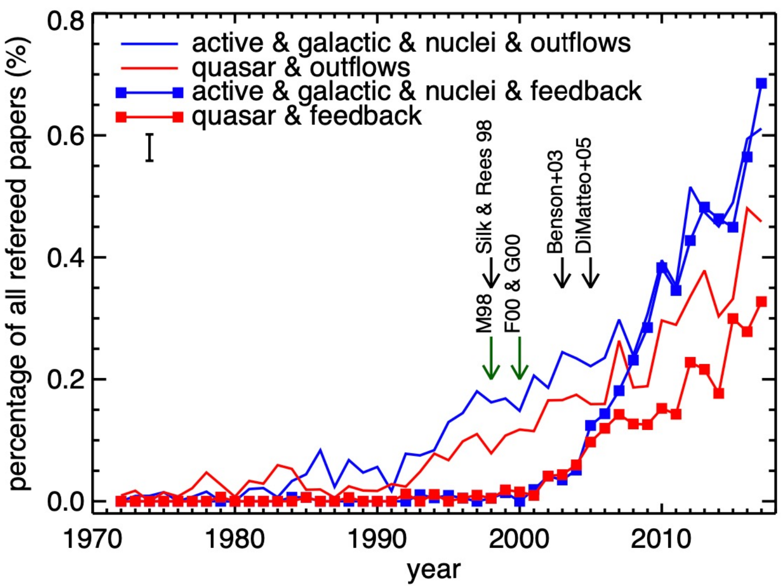
AGN feedback

Observed since a long time … but is it really needed to explain BH vs. host galaxy properties? What is its exact role?



Silk (2011)



Harrison et al. (2018)

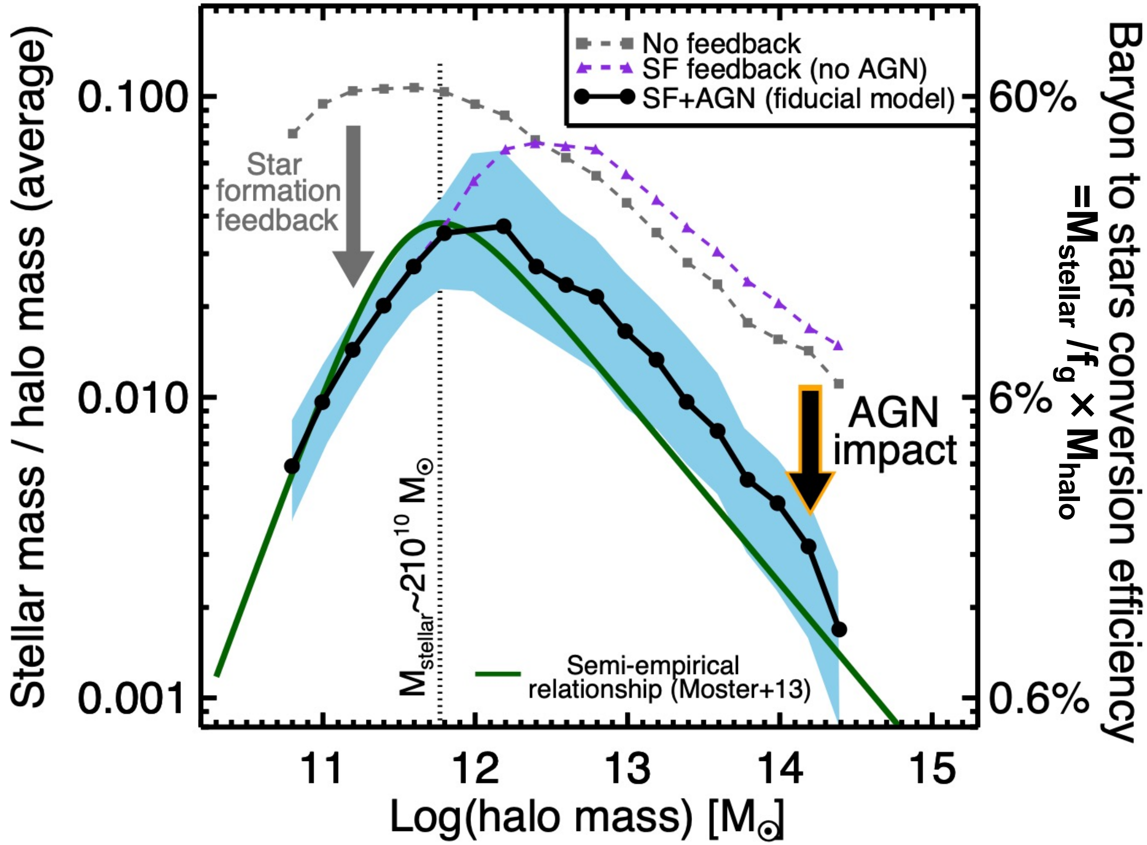
AGN feedback

Observed since a long time … but is it really needed to explain BH vs. host galaxy properties? What is its exact role?

Low-mass haloes: SF is efficient in reducing the conversion of baryons into stars

At high masses, AGN is required to reduce the conversion efficiency

Cosmological models cannot avoid the inclusion of AGN feedback



Harrison (2017, review)

Possible impact of AGN feedback onto the host galaxy: Some numbers. I

$$E_{BH} = \eta M_{BH} c^2 \sim 0.1 M_{BH} c^2 \sim 2 \times 10^{61} M_8 \ erg$$

Energy release via accretion

M_8 = BH mass in units of $10^8 \ M_\odot$

$$M_{BH} \sim 2 \times 10^{-3} M_{bulge}$$

from local relations

$$E_{bulge} \sim M_{bulge} \sigma^2 \sim \frac{M_{BH}}{2 \times 10^{-3}} \ \sigma^2 = 4 \times 10^{58} \ M_8 \ \sigma_{200}^2 \ erg$$

Binding energy of the bulge

σ_{200} = velocity dispersion in units of 200 km/s

$$E_{gas} = f_g \ E_{bulge}$$

Binding energy of the gas in the bulge

f_g = cosmological baryon fraction = $\Omega_B/\Omega_M = M_{gas}/M_{tot} \sim 0.16$

$$\frac{E_{BH}}{E_{gas}} \sim \frac{2 \times 10^{61} M_8}{6.4 \times 10^{57} M_8 \sigma_{200}^2} \sim 3000 \ \sigma_{200}^{-2}$$

Possible impact of AGN feedback onto the host galaxy: Some numbers. II

Often reported in this way (w/o considering the gas fraction in the host)

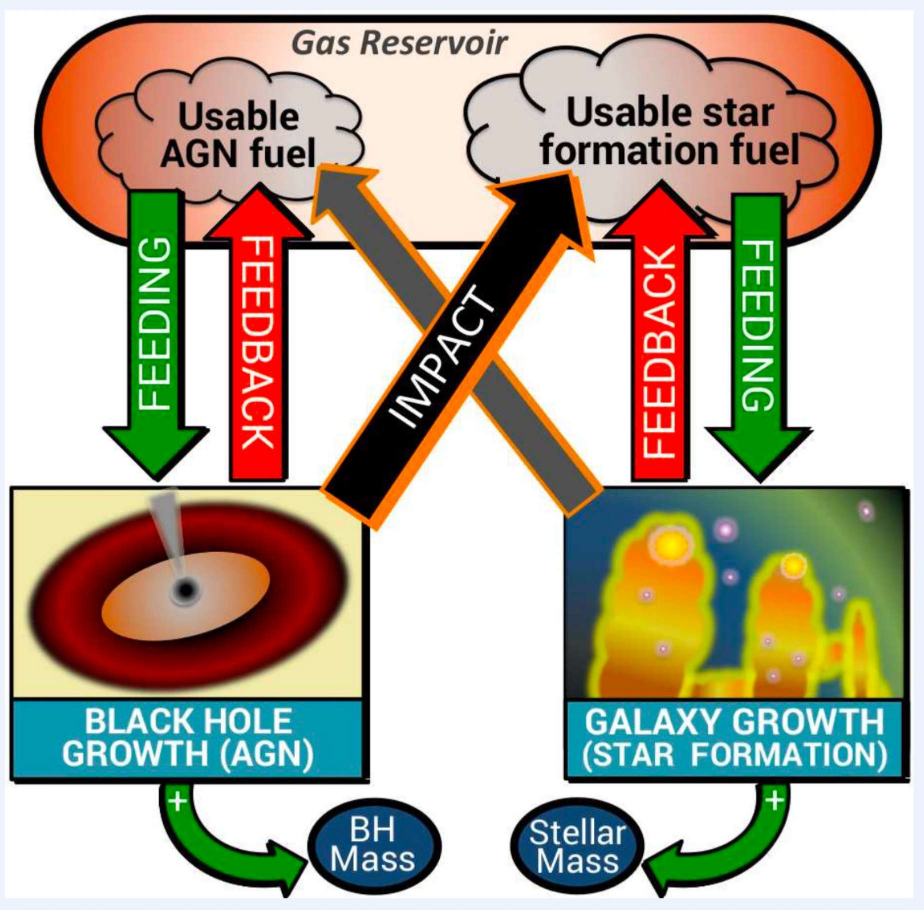
$$\frac{E_{BH}}{E_{gal}} \sim \frac{0.1 M_{BH} c^2}{M_{gal} \sigma^2} = 2 \times 10^{-4} \left(\frac{c}{\sigma}\right)^2$$

The total energy output due to accretion onto the SMBH is ≫ host-galaxy binding energy

→ The AGN can have a profound impact on the host

The fact that we observe galaxies means that how the BH communicate some of its accretion energy to the host should be highly inefficient, thus 'avoiding' galaxy disruption

Fuel supply, galaxy growth and BH growth



The gas reservoir inside the galaxy halo can be fed by gas-rich mergers, recycled material from internal galactic processes and accretion of gas from the intergalactic material

The gas supplies BH accretion (once angular momentum is lost), BH growth and SF

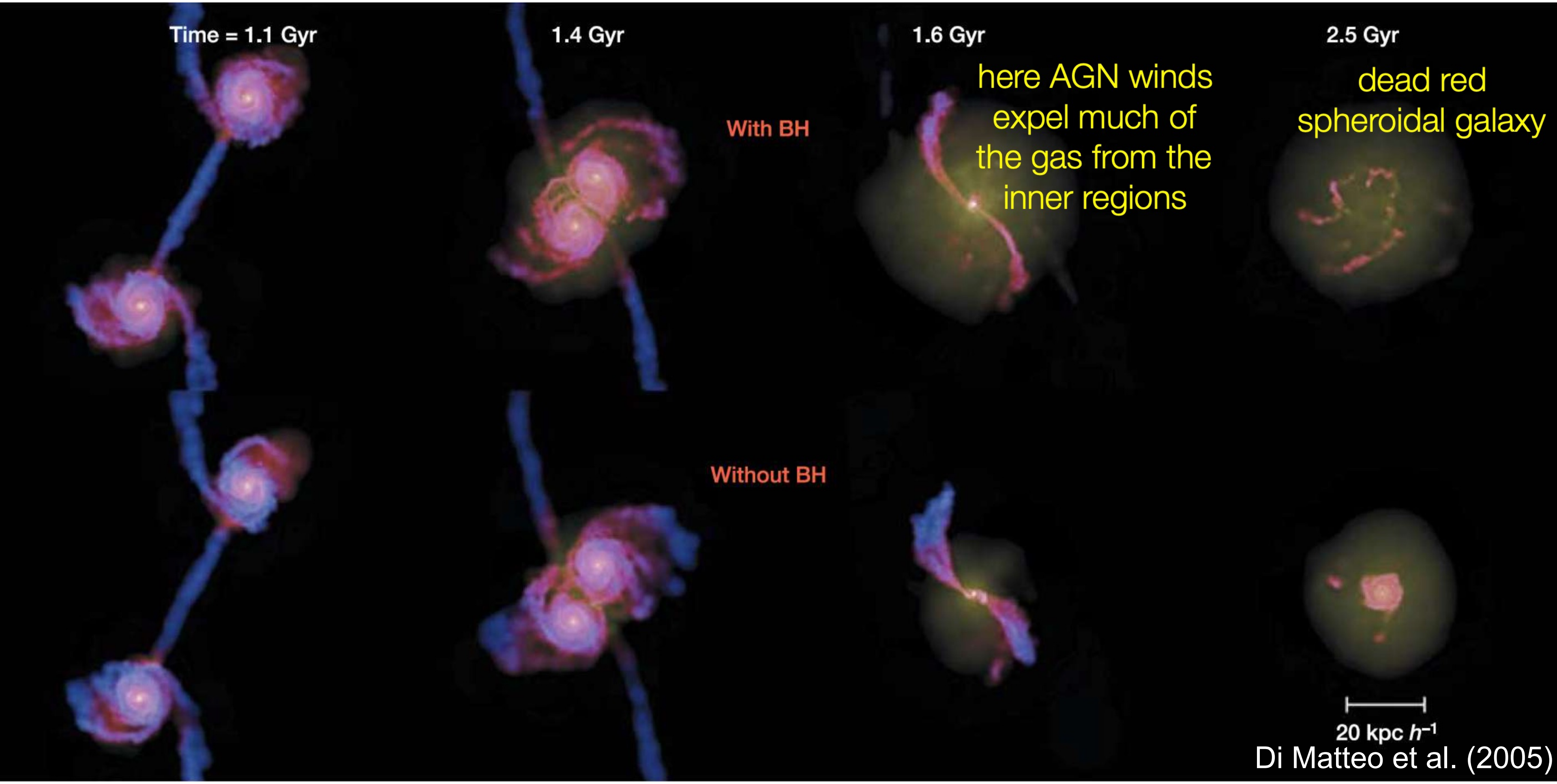
Both BH accretion and SF inject energy and momentum (via radiation, winds and jets) that can reduce the availability of usable fuel through ionising, heating, shocking or expelling material

→ *self-regulatory feedback mechanisms*

Harrison (2017, review)

Feedback and cosmological evolution of galaxies

Simulation of BH accretion and star formation after the mering of two Milky Way-like galaxies



Di Matteo et al. (2005)

Two modes of AGN feedback

AGN feedback (i.e., 'how this energy influences the host galaxy' via 'communication' with the surrounding medium), can manifest in two modes.
The energy injected by the AGN can either prevent the cooling of gas or expel it from the host galaxy, quench the star formation (thus limiting the number of massive galaxies), and lower the growth of the BH

RADIATIVE MODE
(quasar/wind mode)

associated with high Eddington ratios (>0.01) and high-luminosity AGN
It is mostly concerned with pushing cold gas (i.e., the release of energy drives fast outflows expelling gas)

Radiative coupling

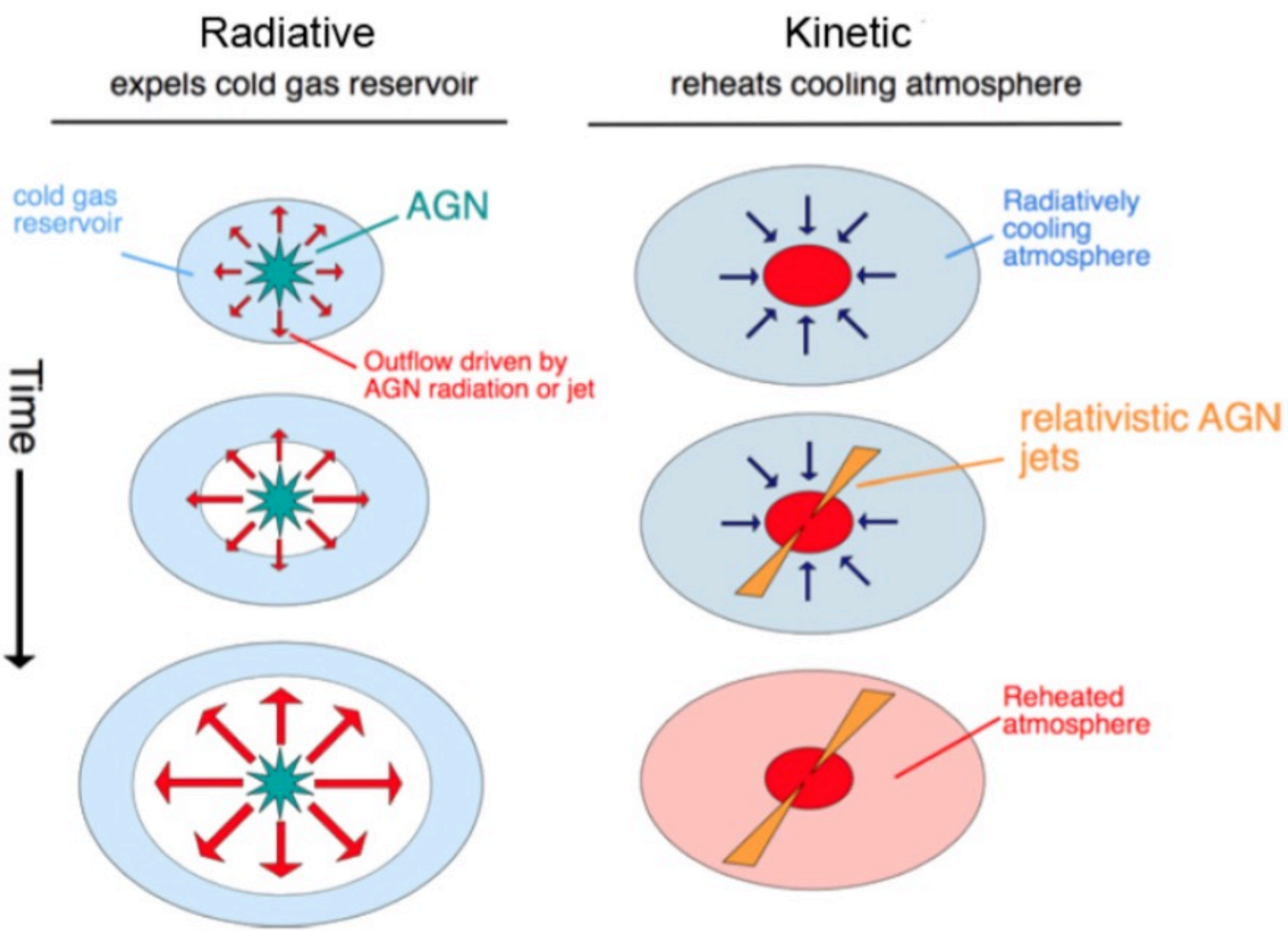
Wide-angle winds are launched from the accretion disc and driven by the coupling of the radiation to the ambient medium through radiation pressure on dust. It is also possible to have a hot thermal wind (e.g., Compton-heated) colliding and accelerating the ISM

KINETIC MODE
(radio jet/maintenance mode)

associated with low Eddington ratios
Typically operates when the galaxy has a hot halo. The radio plasma provides the main source of energy and prevent the gaseous atmosphere from cooling back into the galaxy

Mechanical coupling

Parsec-scale jets can produce over-pressured cavities from which the wide-angled outflows can be launched. Alternatively, outflows can be driven by the mechanical action of the radio plasma emanating from the AGN

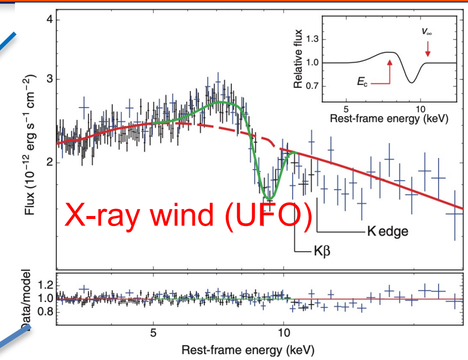


from Fabian review

Radiative feedback: the case of PDS456

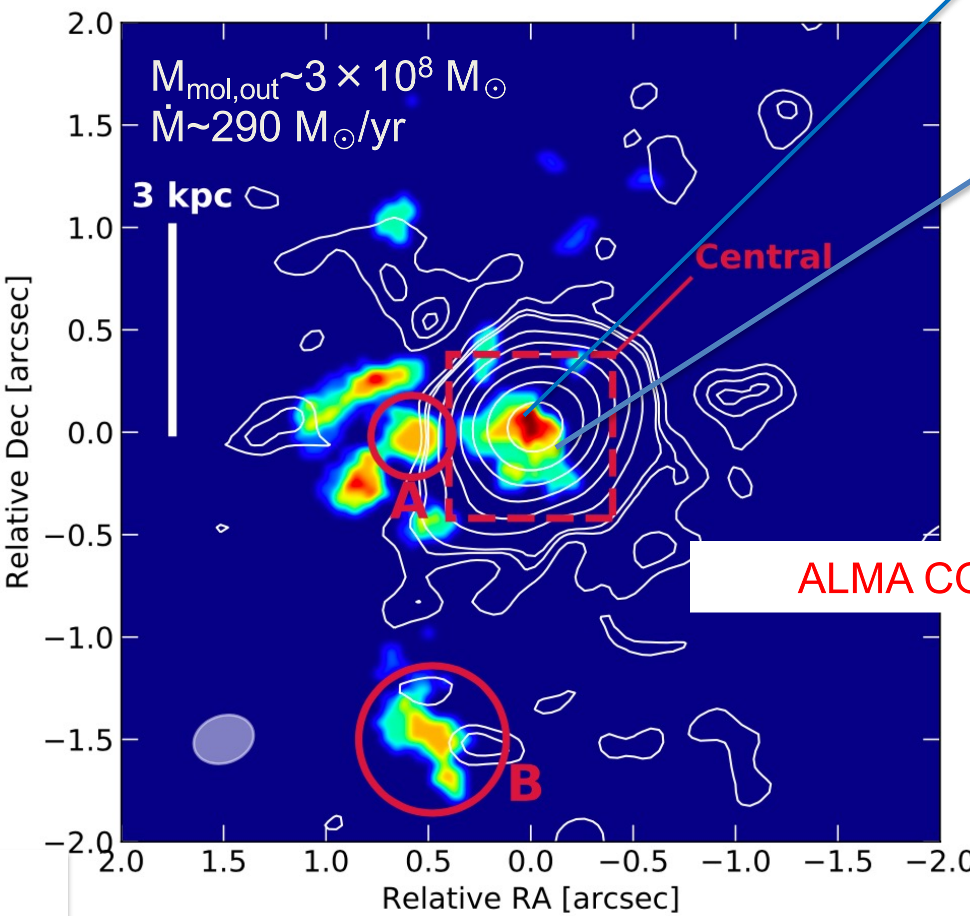
z=0.184 luminous QSO (L_{BOL}~10^{47} erg/s)

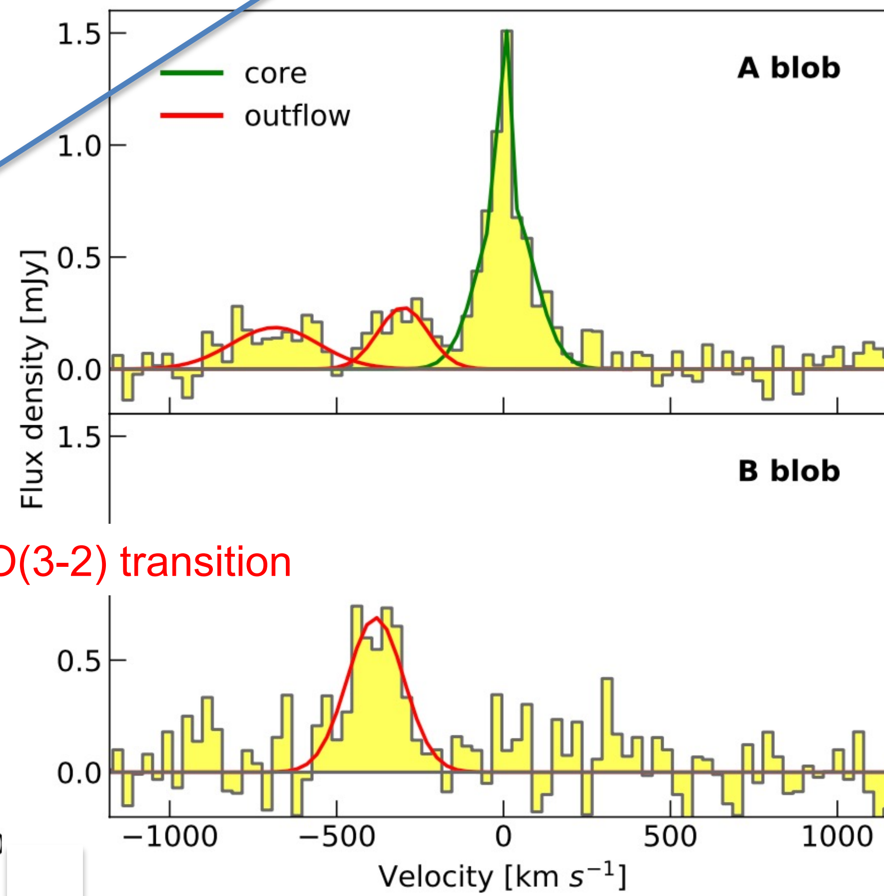
Current goal: to observe outflow signatures in the different gas phases (different scales)



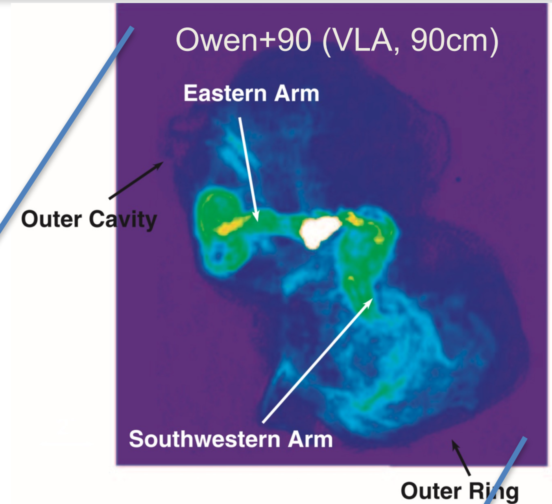
Nardini et al. (2015)

Bischetti et al. (2019)

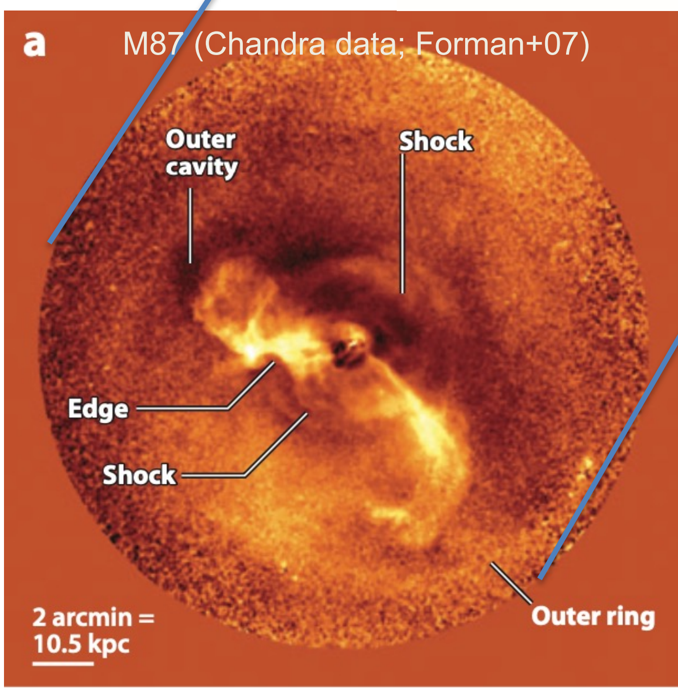


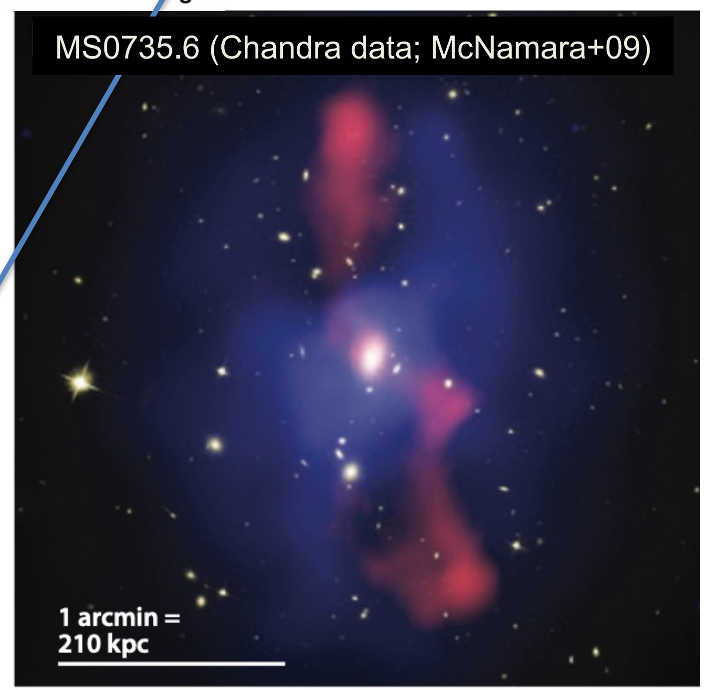


Kinetic feedback: the case of M87 and AGN in clusters



Cavities in X-ray emitting gas has associated with radio jets and lobes from central cluster galaxy



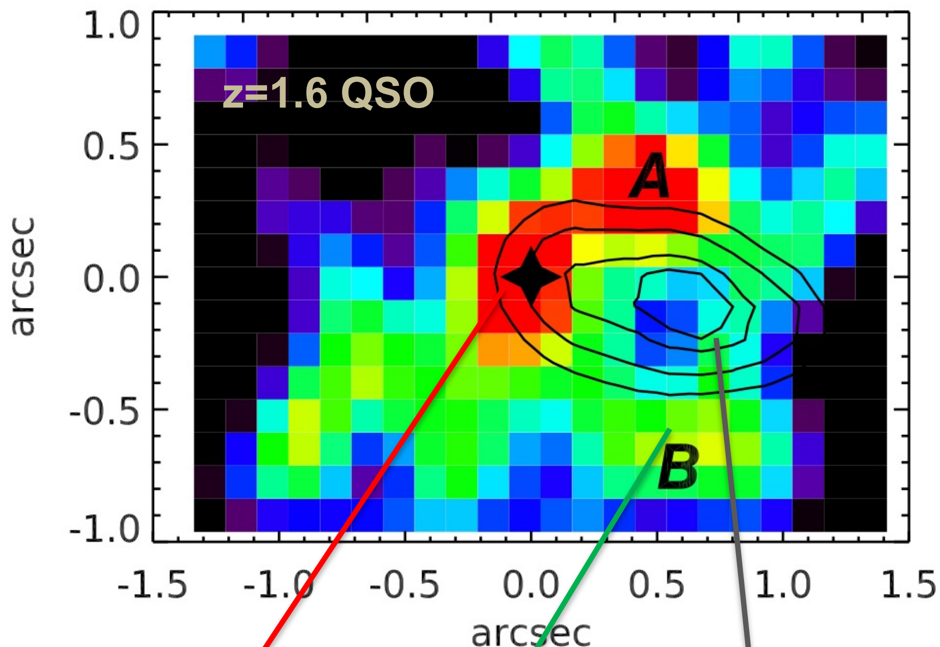


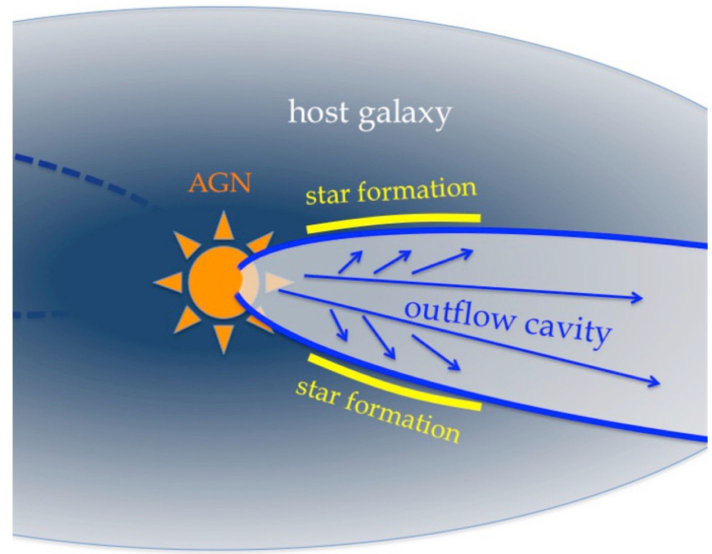
Fabian (2012, review)

An example of outflow-driven feedback

Example of [OIII] outflow in powerful QSO producing positive (SF observed via Hα emission line) and negative (lack of SF) feedback

Cresci et al. (2015)





Contours: [OIII] emission tracing the AGN outflow

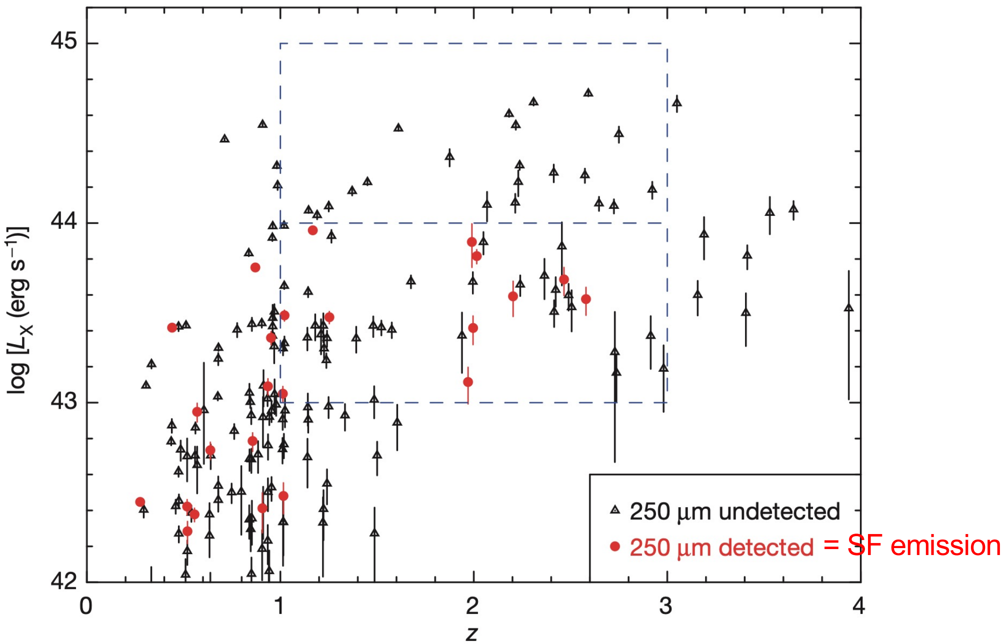
Positive and **negative** **feedback** produced by the outflow observed in [OIII]: $\dot{M}_{out}>1000\ M_{\odot}$/yr, AGN related

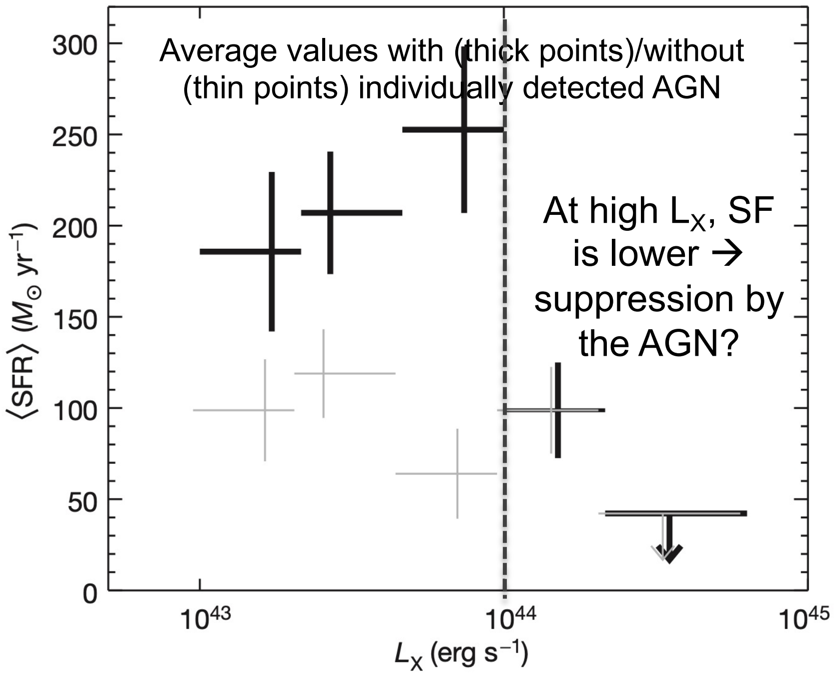
Positive and negative feedback may co-exist in the same system.
To be probed, high-angular resolution facilities (and, possibly IFU) are needed

Suppression of star formation in luminous AGN?

AGN vs. star formation link: can AGN suppress SF?

Page et al. (2012)

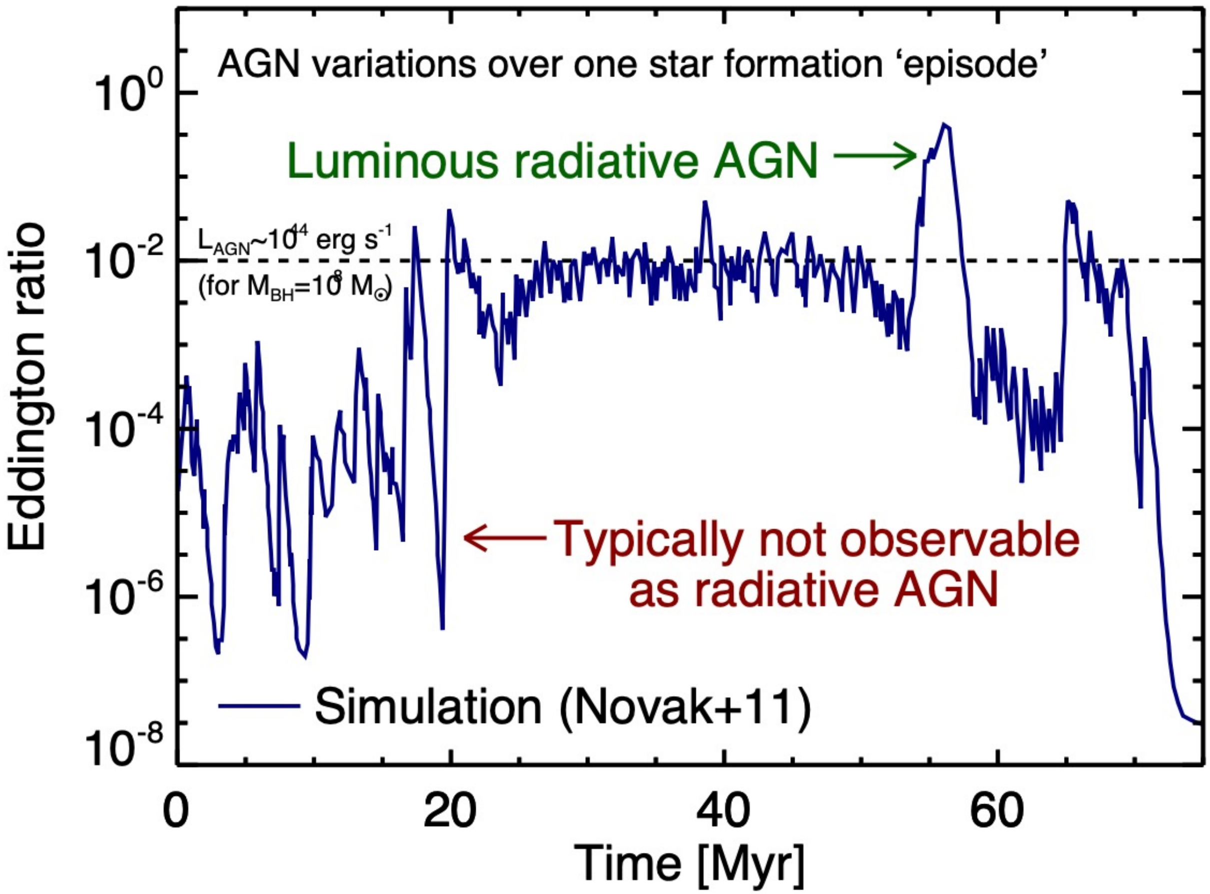




Suppression (quenching) of star formation due to high AGN luminosity

Not all works provide the same results as in Page et al. (2012)

AGN feedback: timescales

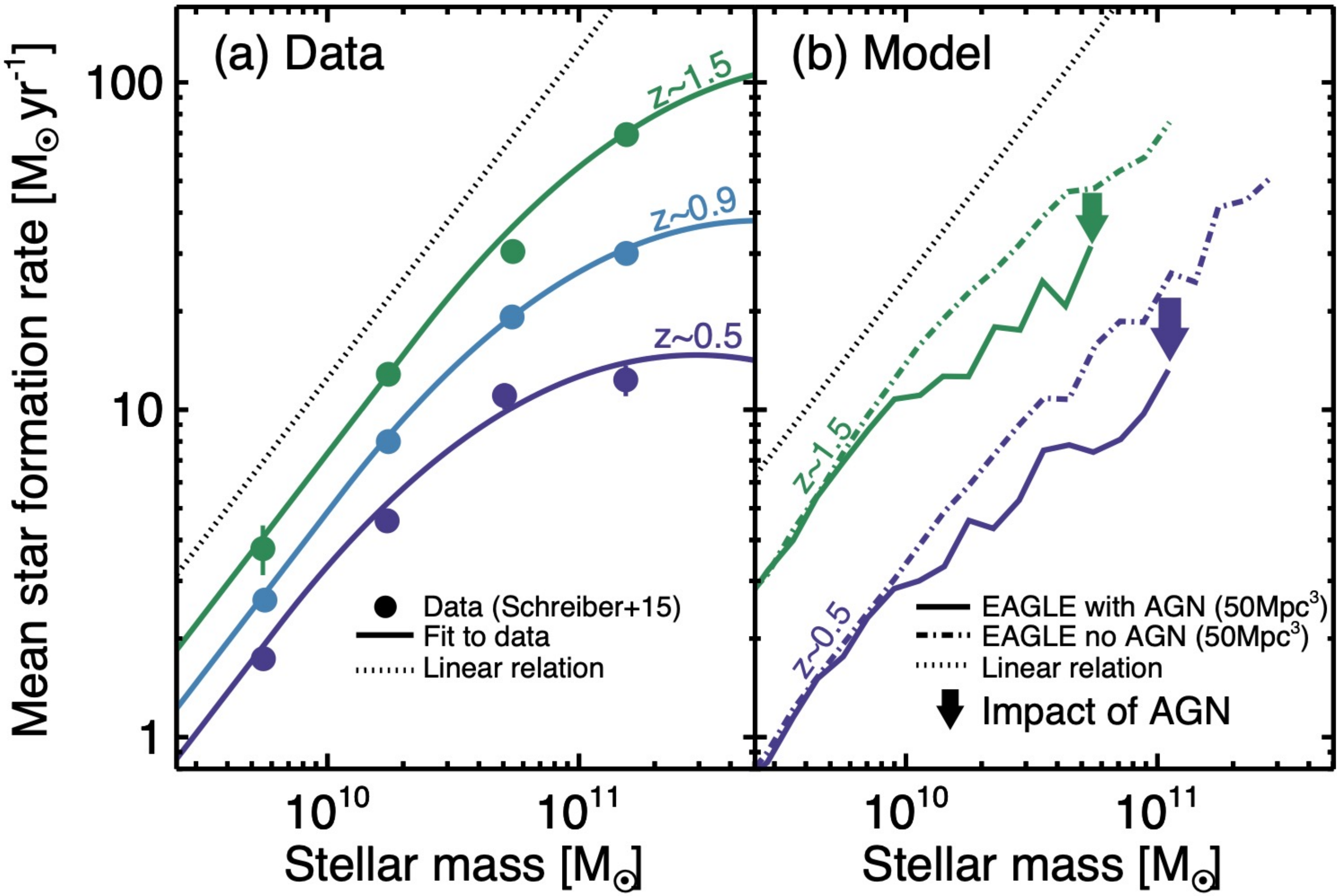


AGN luminosities may vary by orders of magnitude [due, e.g., to a change in the accretion rate on timescales much shorter (<1 Myr) than those associated with SF episodes (>100 Myr)]. Simulations confirm this finding

AGN luminosities may provide limited information on the cumulative energy released over the relevant timescales of SF. Impact of AGN on the SF processes should take the 'unknowns' related to accretion processes and related timescales into account

Harrison (2017, review)

AGN feedback on star-formation activity



Harrison (2017, review)

Data and simulations do actually provide indications that the SF per unit of stellar mass is, on average, reduced in massive galaxies, thus also reducing their number: IT WORKS!

A simple model for AGN feedback

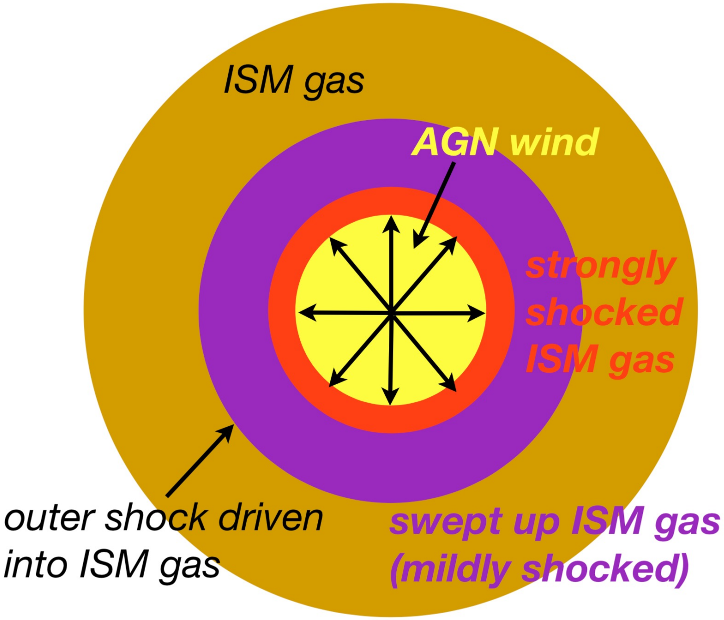
- Assume that AGN emit close to the Eddington limit and there is a radiation-driven outflow from the AGN
- The wind creates a bubble which expands and sweeps the gas in the ISM of the host galaxy. At the interface between outflow and swept material there is a shock propagating outward
- The shocked material either
  - ❑ **Cools**: the wind transfers to the gas only its momentum (ram pressure) and thermal pressure is negligible → **momentum-driven outflow**
  - ❑ **Does not cool**: the wind transfers its energy to the swept-up gas, thermal pressure is larger than ram pressure → **energy-driven outflow**

- **Momentum-driven outflow**

The shocked wind gas is cooled rapidly compared to its flow time: the preshock E_{kin} is lost to radiation and *the postshock gas transmits essentially only its ram pressure to the host ISM*

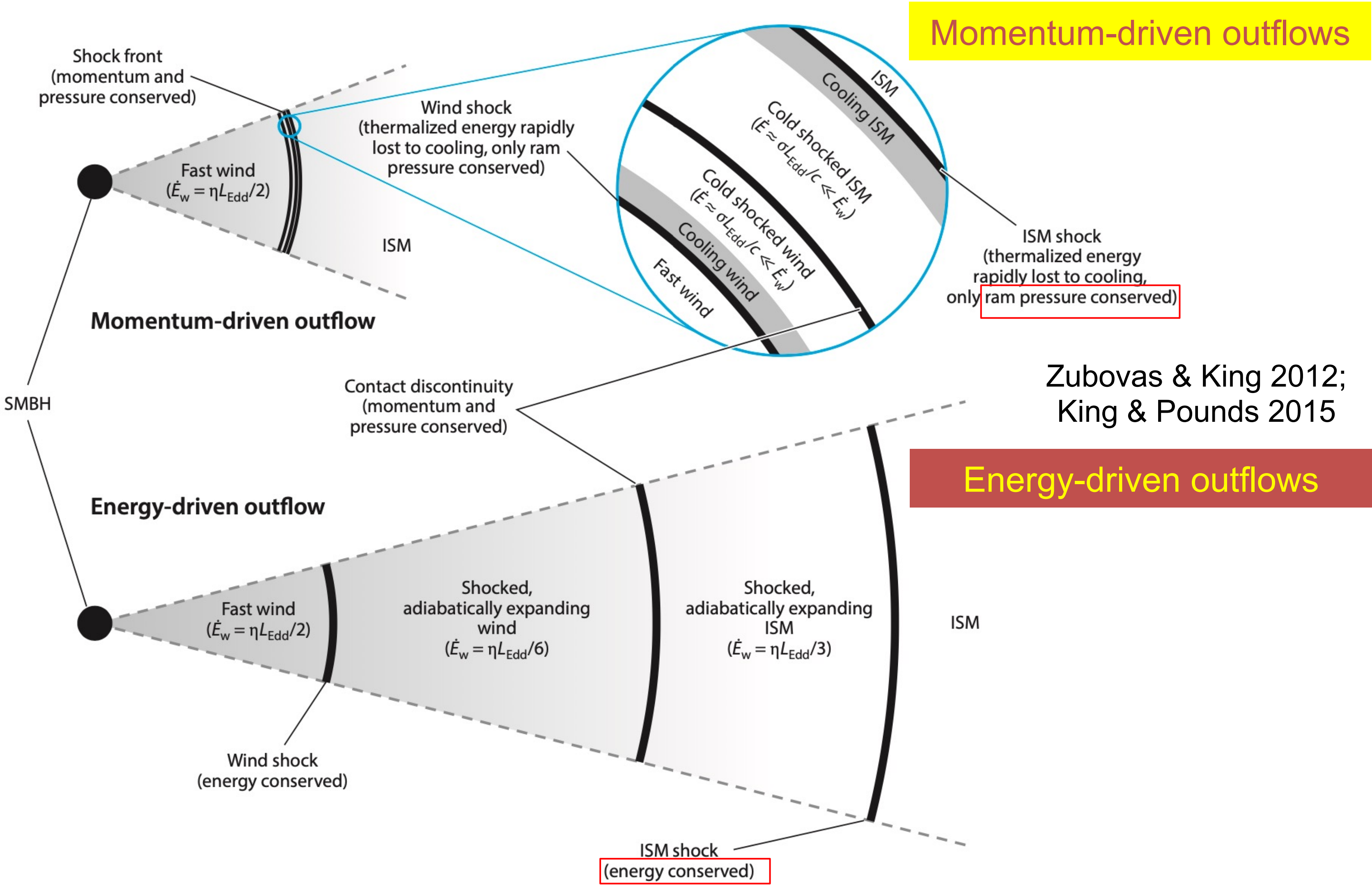
- **Energy-driven outflow**

Cooling is inefficient; *the postshock gas retains most of its original energy* and uses the resulting mechanical luminosity to expand adiabatically (via an inflating bubble) into the ISM. *Much more "violent" than the momentum-driven outflow*



Courtesy of A. Marconi

Momentum- vs. energy-driven winds



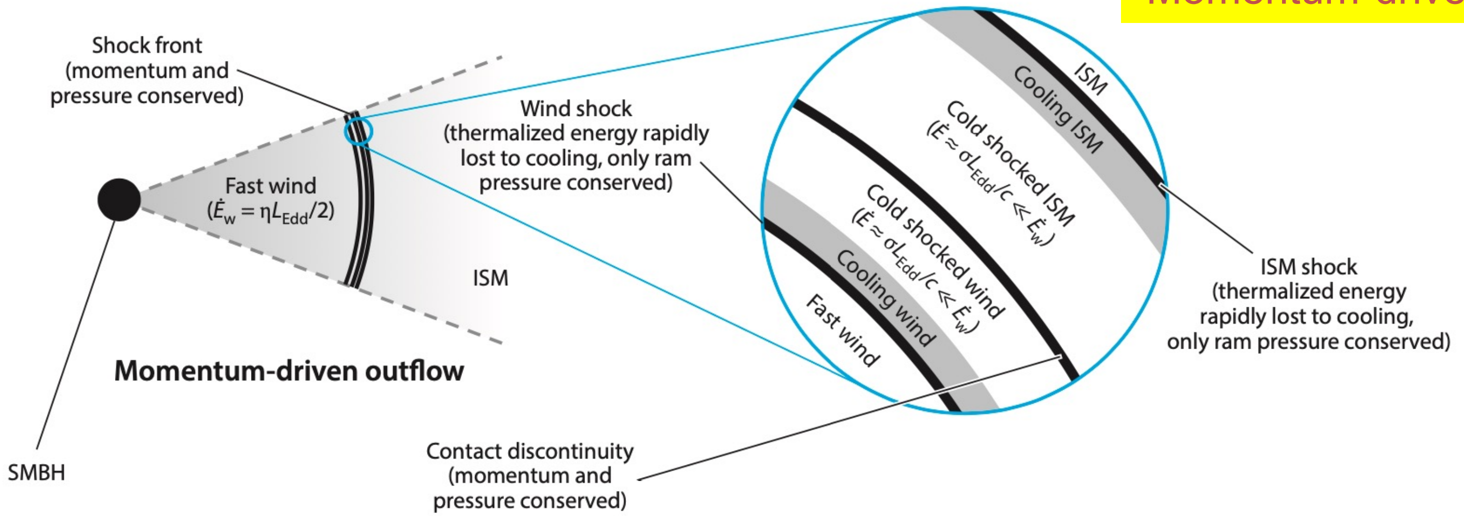
A fast wind (v~0.1c) impacts the interstellar gas of the host galaxy, producing an inner reverse shock, that slows the wind, and an outer forward shock that accelerates the swept-up gas

→ The shocked wind gas acts like a piston, sweeping up the host ISM

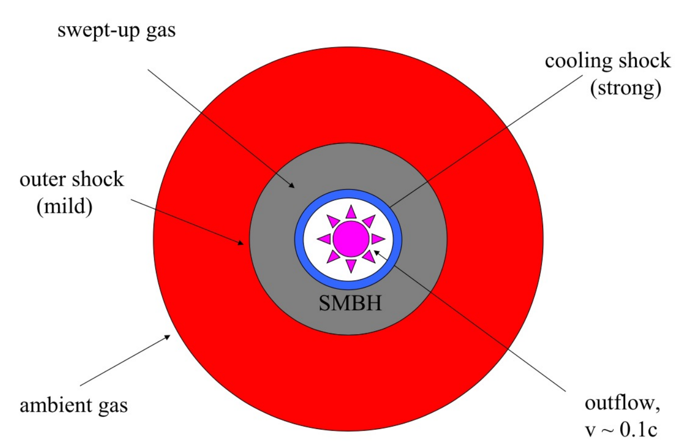
Momentum-driven winds

Momentum-driven winds. I

Momentum-driven outflows



The shocks are very narrow and rapidly cool (via IC and free-free emission) to become effectively isothermal. Only *the ram pressure is communicated to the outflow*: the cooled gas exerts the preshock ram pressure on the galaxy interstellar gas and sweeps it up into a thick shell ('snowplough'), whose motion drives a milder outward shock into the ambient interstellar medium



Momentum-driven conditions hold for shocks confined to within ~1kpc of the AGN and establish the M-σ relation
(see following slides; King 2003, 2005)

Momentum-driven winds. II

Momentum-driven outflows

- The dominant interaction is the reverse shock slowing the BH wind, which injects energy into the host ISM
- *The gas cools through radiation* (IC + free-free), removing significant energy from the hot shocked gas on a timescale shorter than its flow time. If the cooling is strong, most of the preshock kinetic energy is lost
- The very rapid cooling means that the shocked wind gas is highly compressed, making the postshock region geometrically narrow (being idealized as a sort of discontinuity, known as isothermal shock)
- As momentum must be conserved, *the postshock gas transmits just its ram pressure to the host ISM*. This amounts to transfer just a fraction of $\sim\sigma/c\sim 10^{-3}$ of the mechanical luminosity $E_{BH,wind}\sim 0.05\ L_{Edd}$ to the ISM (see calculations reported in the following slides)
- In the momentum-driven wind limit, only about 10% of the bulge binding energy ($f_g M_b \sigma^2$) is injected into the bulge ISM → *momentum-driven flows do not threaten the bulge integrity* → this regime is a stable environment for BH mass growth

Momentum-driven winds. III. Cooling

Cooling: the radiation field of an Eddington accreting SMBH has T~10^7 K. For shocks close to the SMBH, this radiation field is sufficiently intense that IC (see Ciotti & Ostriker 1997) cools the electrons of the postshock wind gas more rapidly than the flow time

Temperature of the shock

$$T_{shock} \sim \frac{3}{16} \frac{\mu \, m_H}{k_B} \, v^2 \sim 1.6 \times 10^{10} \; K$$

μ: mean molecular weight assuming ionized gas (~0.63)
v~0.1c

Radiative (free-free) cooling time for the shocked gas

$$t_{rad} \sim 2 \times 10^{11} \; M_8^{-1} R_{kpc}^2 \; yr$$

Compton cooling time of the shocked gas in the AGN radiation field

$$t_C = \frac{3 m_e c}{8 \pi \sigma_T U_{rad}} \, \frac{m_e c^2}{E}$$

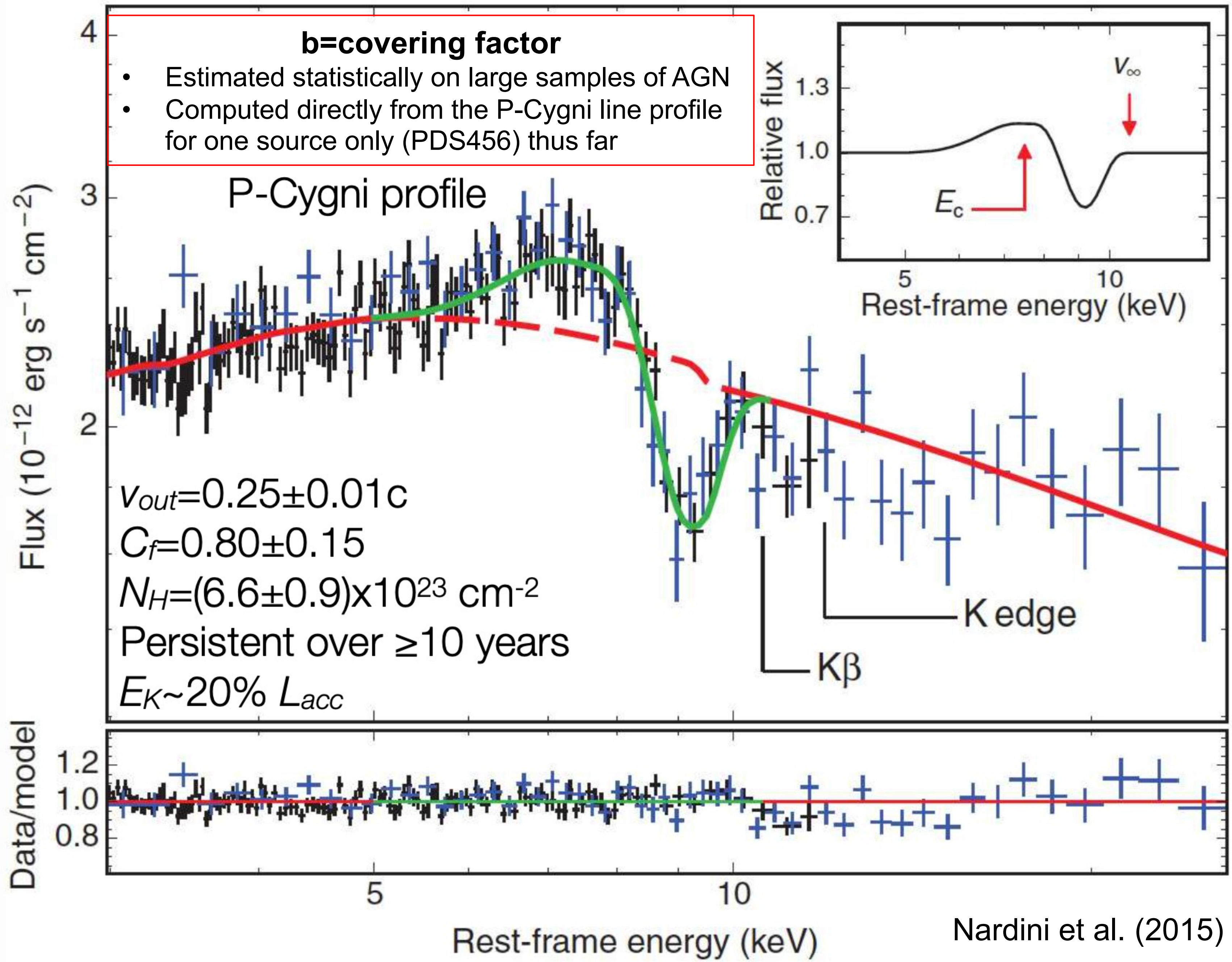
$$U_{rad} = \frac{L_{Edd}}{4 \pi R^2 c b}$$

$$L_{Edd} = \frac{4 \pi G c m_P M}{\sigma_T}$$

U: radiation field at the distance R from the BH
b: ‘geometric’ parameter (‘coverage of the wind’ with respect to 4π ster., hence ≤1)
E: electron energy in the postshock wind gas
v: velocity of the outflow

see next slides to define the covering factor of the wind

PDS456 - XMM-Newton/EPIC + NuSTAR



Nardini et al. (2015)

Assuming mass conservation through a spherical shell (Creenshaw+03)

$$\dot{M}_{\rm out} = 4\pi r N_{\rm H} \mu m_p C_g v_r$$

covering factor **= b**

outflow velocity (measured)

mass of the proton

molecular weight

column density (measured)

Mass outflow rate

location of the outflowing clouds

Momentum-driven winds. IV. Cooling

$$\rightarrow \quad U_{rad} = \frac{4\pi G c m_P M}{\sigma_T} \frac{1}{4\pi R^2 c b} = \frac{G m_P M}{\sigma_T R^2 b}$$

$$E = \frac{3}{16} m_P v^2$$

$$\rightarrow \quad t_C = \frac{3 m_e c}{8\pi \sigma_T U_{rad}} \frac{m_e c^2}{E} = \frac{3 m_e c}{8\pi \sigma_T \frac{G m_P M}{\sigma_T R^2 b}} \frac{m_e c^2}{\frac{3}{16} m_P v^2} \sim$$

$$\sim \frac{2}{3} \frac{c R^2 b}{G M} \left(\frac{m_e}{m_p}\right)^2 \left(\frac{c}{v}\right)^2 \sim 10^7 R_{kpc}^2 b M_8^{-1} \; yr$$

$$t_C = \frac{2}{3} \frac{c R^2}{G M} \left(\frac{m_e}{m_p}\right)^2 \left(\frac{c}{v}\right)^2 b \sim 10^7 R_{kpc}^2 b M_8^{-1} \; yr$$

Momentum-driven winds. V. Cooling

$$t_{flow} = \frac{R}{\dot{R}} = 5 \times 10^6 R_{kpc} \sigma_{200} M_8^{-1/2} \ yr$$

Velocity of the shell

Timescale for a momentum-driven outflow

(further discussion later)

$$\frac{t_C}{t_{flow}} = 2 R_{kpc} \sigma_{200}^{-1} M_8^{-1/2} \ b$$

The Compton cooling is effective only out to few kpc, while the radiative free-free cooling (other mechanism responsible for cooling) is always far longer that the flow timescale

→ An Eddington outflow is momentum driven very close to the SMBH but likely becomes energy driven outside a typical radius of few kpc

(M_σ, described later, is the key)

Momentum-driven winds. VI. Energetics

$$\dot{M}\ v \sim \frac{L_{Edd}}{c} = \eta\ \dot{M}_{Edd}\ c$$

Momentum rate: AGN active phase, Eddington-limited

$$\dot{m} = \frac{\dot{M}}{\dot{M}_{Edd}} \quad \Rightarrow \quad v = \frac{\eta\ c}{\dot{m}}$$

v~0.1c as often observed in **ultra-fast outflows** (UFOs) in local AGN (via blueshifted highly ionized absorption iron lines)

$$L_{BH,wind} = \frac{1}{2}\dot{M}_W v^2 = \frac{L_{Edd}}{c}\frac{v}{2} = \frac{\eta}{2\ \dot{m}}\ L_{Edd} \sim \frac{\eta}{2}\ L_{Edd} \sim 0.05\ L_{Edd}$$

$\dot{m} \sim 1$ likely η=0.1

$$L_{BH,wind} \sim 0.05\ L_{Edd}$$

$$E_{mom} \sim \frac{\sigma}{c}\ E_{BH,wind} = \frac{\sigma}{c}\frac{\eta}{2}\ M\ c^2 \sim 5 \times 10^{-5}\ M\ c^2 \sim\ 0.1\ E_{gas}$$

σ/c term explained later

Energy injected into the bulge ISM in the momentum-driven limit

Reaching the M-σ relation: the momentum-driven phase

I

Ref: King & Pounds (ARA&A, 2015) + King (2005, 2010, …) + Fabian (ARA&A, 2012), Faucher-Giguere & Quataert (2012), Costa et al. (2014). Original works: Silk & Rees (1998), Haehnelt et al. (1998)

$$M_{BH} \sim \; 3 \times 10^8 M_\odot \sigma_{200}^\alpha$$

σ=velocity dispersion
σ_{200}: in units of 200 km/s
α~4.4 (Ferrarese & Merritt 2000; Gebhardt et al. 2000; see also Kormendy & Ho 2013 for a review)

$$\rho(r) = \frac{\sigma^2}{2\pi G r^2}$$

Density of an isothermal sphere with dispersion σ

$$M(R) = 4\pi \int_0^R \rho r^2 dr = \frac{2\sigma^2 R}{G}$$

Total mass within a radius R (including stars and dark matter)

$$M_g(R) = \frac{2 f_g \sigma^2 R}{G}$$

Mass of the narrow swept-up gas shell at radius R assuming a constant gas fraction $f_g = \Omega_{baryons}/\Omega_{matter} \sim 0.16$

Reaching the M-σ relation: the momentum-driven phase

II

'**Acceleration term**' (change in the momentum of the **swept-up shell**)

'**Gravity term**' (against which the wind works)

Photon momentum rate

Ram pressure

$$\frac{d}{dt}\left[M_g(R)\dot{R}\right] + \frac{GM_g(R)[M + M(R)]}{R^2} = \frac{L_{Edd}}{c} = 4\pi\rho v^2$$

M_{BH}

Equation of motion of the shell

M=mass of the BH

$$\frac{d}{dt}\left[M_g(R)\dot{R}\right] = \frac{d}{dt}\left[\frac{2f_g\sigma^2 R}{G}\dot{R}\right] = \frac{2f_g\sigma^2}{G}\frac{d}{dt}(R\dot{R})$$

$$\frac{GM_g(R)[M + M(R)]}{R^2} = \frac{G\,2f_g\sigma^2 R/G\,(M + 2\sigma^2 R/G)}{R^2} =$$

$$= \frac{2f_g\sigma^2(M + 2\sigma^2 R/G)}{R}$$

Reaching the M-σ relation: the momentum-driven phase

III

$$\Rightarrow \frac{2f_g\sigma^2}{G}\left[\frac{d}{dt}(R\dot{R})+\frac{GM}{R}+2\sigma^2\right]=\frac{L_{Edd}}{c}$$

$$k=\frac{\sigma_T}{m_P}=\frac{6.65\times10^{-25}}{1.7\times10^{-24}}=0.39\ cm^2/g$$

Electron scattering opacity

$$\frac{L_{Edd}}{c}=\frac{4\pi G c m_P M}{\sigma_T c}=\frac{4\pi GM}{k}$$

$$\frac{d}{dt}(R\dot{R})+\frac{GM}{R}=-2\sigma^2+\frac{G}{2f_g\sigma^2}\frac{4\pi GM}{k}=-2\sigma^2+\frac{2\pi G^2}{f_g\sigma^2 k}M$$

$$M_\sigma=\frac{f_g k}{\pi G^2}\sigma^4$$

$$\boxed{\frac{d}{dt}(R\dot{R})+\frac{GM}{R}=-2\sigma^2\left(1-\frac{M}{M_\sigma}\right)}$$

Reaching the M-σ relation: the momentum-driven phase

IV

$$\frac{d}{dt}(R\dot{R}) + \frac{GM}{R} = -2\sigma^2\left(1 - \frac{M}{M_\sigma}\right)$$

$$M < M_\sigma \rightarrow \ddot{R} < 0$$

The shell always decelerates: if the SMBH mass is below M_σ, the swept-up shell of interstellar gas cannot reach large radius because the Eddington thrust ('push') of the BH wind is too small to lift its weight against the galaxy bulge potential.
The SMBH cannot remove the gas from its surroundings and 'goes' on accreting.
Any shell it drives outward eventually becomes too massive and tends to fall back and probably fragments (likely star formation is present in the shell remnants).

For $M>M_\sigma$, the wind drives the swept-up ISM far from the nucleus, quenching its own gas supply and further accretion

$$M_\sigma = \frac{f_g k}{\pi G^2}\sigma^4 \sim 3.2 \times 10^8\ M_\odot\ \sigma_{200}^4$$

Not too dissimilar from $M_{BH} \sim 3 \times 10^8 M_\odot \sigma_{200}^{\alpha}$

Reaching the M-σ relation: the momentum-driven phase

V

The comparison of the two masses suggests that at some point the SMBH growth should stop.
Whatever the bulge geometry is, the BH always communicates its presence mostly via the ram pressure of its wind → strong radial forces in the solid angles exposed to this wind

It is possible that the accretion disc orientation wrt. the host galaxy may change with new episodes of accretion (‘chaotic accretion’; e.g., King & Pringle 2010), which tends to isotropize the long-term effect of momentum feedback

Reaching the M-σ relation: the momentum-driven phase

VI

Far from the BH [i.e., outside the sphere of influence, $R>(GM)/\sigma^2$], the dominant term in the equation of motion is **M(R)**. The condition that the shell should be able to escape to infinity specifies a relation between the black hole mass M and the parameters of the galaxy potential (*in primis*, σ).

The *analytic solution of the motion* equation provides:

$$R^2 = R^2_{shock} = \left[\frac{GL_{Edd}}{2f_g\sigma^2 c} - 2(1-f_g)\sigma^2\right] \; t^2 + 2R_0 v_0 t + R_0^2$$

R0, v0: position and speed of the shell at $t=t_0$ (i.e., boundary conditions corresponding to the flow properties during the transition between the sphere of influence of the BH and large radii)

For large times, the first term (the radiative-driving term) dominates:

$$\rightarrow \;\; R^2 = \frac{GL_{Edd}}{2f_g\sigma^2 c} \; t^2$$

Reaching the M-σ relation: the momentum-driven phase

VII

$$M_\sigma = \frac{f_g k}{\pi G^2}\ \sigma^4$$

Velocity of the momentum-driven flow

$$v_M \sim \ \frac{R}{t} = \left(\frac{G L_{Edd}}{2 f_g \sigma^2 c}\right)^{1/2} = \sqrt{2\frac{M}{M_\sigma}\ \sigma^2} = \sqrt{2}\ \sigma\ \left(\frac{M}{M_\sigma}\right)^{1/2}$$

Timescale of the flow (time for a continuously driven shell to reach a radius R)

$$t_{flow} = \frac{R}{v_M}$$

Energy flow rate = kinetic luminosity: combine the wind momentum outflow rate and the velocity of the flow

'correction' term reported previously

$$\dot{E}_M = \frac{1}{2}\boxed{\dot{p}_W}\boxed{v_M} = \frac{L_{Edd}\ v_M}{2c} = \frac{1}{\sqrt{2}}\boxed{\left(\frac{\sigma}{c}\right)}\ L_{Edd}\ \left(\frac{M}{M_\sigma}\right)^{1/2}$$

Reaching the M-σ relation: the momentum-driven phase

VIII

$$\dot{E}_M = \frac{1}{\sqrt{2}} \left(\frac{\sigma}{c}\right) L_{Edd} \left(\frac{M}{M_\sigma}\right)^{1/2} \sim 5 \times 10^{-4} \sigma_{200} L_{Edd} \left(\frac{M}{M_\sigma}\right)^{1/2}$$

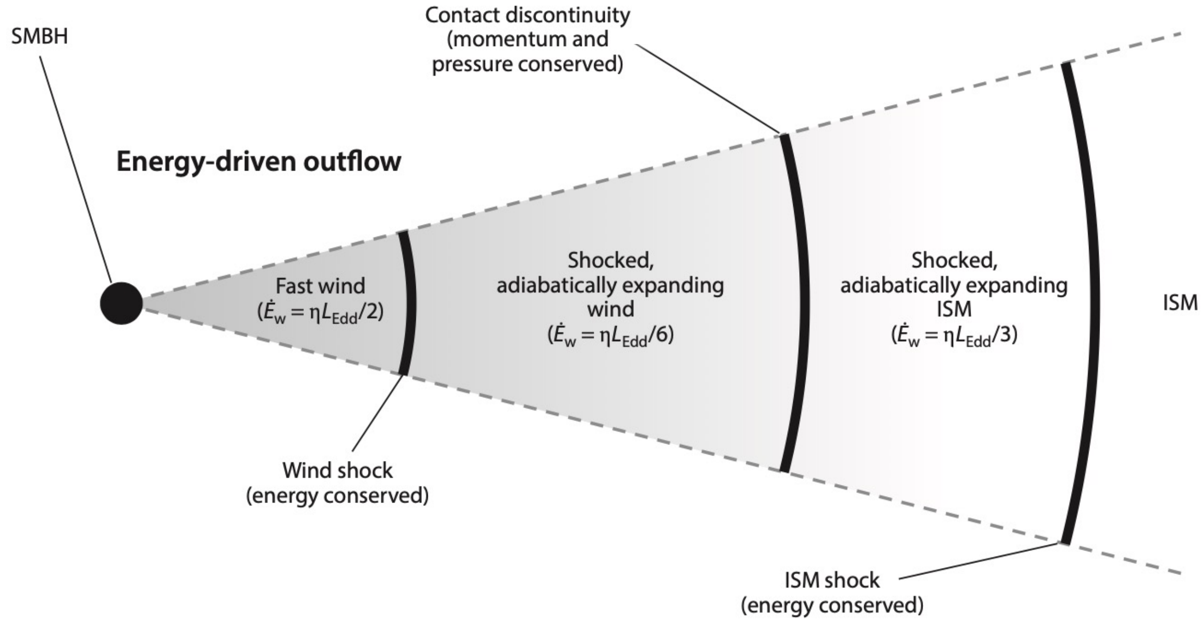
→ *The coupling between the luminosity of the SMBH and the momentum-driven outflow is very inefficient*

→ *Limited impact on the host in the end, despite the AGN luminosity*

Energy-driven winds

Energy-driven winds. I

Energy-driven outflows



In an *energy-driven outflow*, the shocked regions are much wider and do not cool. They *expand adiabatically*, communicating most of the kinetic energy of the wind to the outflow. The outflow radial momentum flux is therefore larger than that of the wind (see later calculations)

Momentum-driven conditions hold for the regions within ~1 kpc of the AGN and establish the M-σ relation. Once the SMBH mass attains the critical M-σ value, the shocks move further from the AGN and the outflow becomes energy driven (e.g., large-scale molecular outflows that probably are able, at least at some level, to clear the galaxy from the gas)

Energy-driven winds. II

Energy-driven outflows

- In the opposite (wrt. momentum-driven scenario) limit, the cooling is negligible, therefore the postshock gas retains all of the mechanical luminosity thermalized in the shock and expands adiabatically into the ISM (i.e., not σ/c multiplying term anymore)

$$E_{wind} \sim 0.05\ L_{edd} \sim 100\ E_{gas}$$

- The postshock gas is now geometrically extended, unlike the momentum-driven case

- Multiple scatterings ($\dot{m}>1$) within the outflow means that almost all of the total photon energy is given to the outflow. The outflow shock against the ISM is now not effectively cooled → the total energy rate L_{Edd} now does ($P\,dV$) work against the weight of the swept-up interstellar gas

- *The energy-driven flow is then much more violent than the momentum-driven flow → a BH in an energy-driven environment is unlikely to reach SMBH masses*

Energy-driven winds. Clearing out the galaxy

I

When the black hole mass reaches M_σ, the global change from momentum- to energy-driven has profound implications. The geometry of the outflow changes completely: the shocked wind region is large and expanding adiabatically under the internal gas pressure P

The **equation of motion of the swept-up shell** becomes

$$\frac{d}{dt}\left[M_g(R)\dot{R}\right] + \frac{GM_g(R)M(R)}{R^2} = 4\pi R^2 P$$

The $M=M_{BH}$ term has been neglected because R>>radius of the BH sphere of influence

Energy equation

$$\frac{d}{dt}(V\ U) = \frac{1}{2}\dot{M}_{out}v^2 - P\,\frac{dV}{dt} - \frac{GM_g(R)M(R)}{R^2}\,\dot{R}$$

Variation of internal energy

Rate of injection of energy into the shocked gas

Rate of work against the ambient gas

Rate of work against gravity

Energy-driven winds. Clearing out the galaxy

II

$$V = \frac{4\pi}{3} R^3$$ Volume

$$\frac{d}{dt}(VU) = (\gamma - 1)\frac{d(PV)}{dt}$$

γ=adiabatic index of the gas = 5/3
= heat capacity ratio

$$U = \frac{3}{2} P$$ Internal energy (P=pressure of the gas)

$$\dot{M}_{out} v = \frac{L_{Edd}}{c}$$ Rate by which energy is fed into the shecked gas

$$v = \eta c$$ Wind velocity

Energy equation

$$\frac{d}{dt}\left[\frac{4\pi R^3}{3}\ \frac{3}{2}P\right] = \frac{\eta}{2} L_{Edd} - P\frac{d}{dt}\left[\frac{4\pi R^3}{3}\right] - \frac{G}{R^2}\frac{2f_g\sigma^2 R}{G}\frac{2\sigma^2 R}{G}\dot{R}$$

$$\frac{d}{dt}\left[\frac{4\pi R^3}{3}\ \frac{3}{2}P\right] = \frac{\eta}{2} L_{Edd} - P\frac{d}{dt}\left[\frac{4\pi R^3}{3}\right] - 4f_g\frac{\sigma^4}{G}\dot{R}$$

Energy-driven winds. Clearing out the galaxy

III

First term of Eq.

$$\frac{d}{dt}\left[\frac{4\pi R^3}{3}\ \frac{3}{2}P\right] = 2\pi\frac{d}{dt}(PR^3) = 6\pi PR^2\frac{dR}{dt} = 6\pi PR^2\dot{R}$$

Middle term of Eq.

$$-P\frac{d}{dt}\left(\frac{4\pi R^3}{3}\right) = -4\pi PR^2\dot{R}$$

into energy equation

$$\rightarrow\ \ P = \frac{1}{4\pi R^2}\left[\frac{d}{dt}\ [M_g(R)\dot{R}] + \frac{GM_g(R)M(R)}{R^2}\right] =$$

$$= \frac{1}{4\pi R^2}\left[\frac{d}{dt}\left(\frac{2f_g\sigma^2 R}{G}\dot{R}\right) + \frac{G}{R^2}\frac{2f_g\sigma^2 R}{G}\frac{2\sigma^2 R}{G}\right] =$$

$$= \frac{1}{4\pi R^2}\left[\frac{2f_g\sigma^2}{G}\ \frac{d}{dt}(R\dot{R}) + \frac{4f_g\sigma^4}{G}\right]$$

from equation of motion

Energy-driven winds. Clearing out the galaxy

IV

[......] King et al. (2011) and King (2014) review for detailed calculations

$$\frac{\eta}{2} L_{Edd} = \frac{2 f_g \sigma^2}{G} \left[\frac{1}{2} R^2 \dddot{R} + 3 R \dot{R} \ddot{R} + \frac{3}{2} \dot{R}^3 \right] + 10 f_g \frac{\sigma^4}{G} \dot{R}$$

Equation of motion of the interface (discontinuity) between wind and interstellar gas in the energy-driven case

If $M=M_{BH}=M_\sigma$ in L_{Edd} formula, the solution is $\mathbf{R=v_e t}$ (i.e., $v_e=\dot{R}$)

$$v_e \sim \left(\frac{2 \eta \sigma^2 c}{3} \right)^{1/3} \sim 925 \ \sigma_{200}^{2/3} \ km/s$$

At radii much larger than the 'cooling radius' (the radius at which the wind energy is lost through radiation), Compton cooling is not effective anymore. *The extra gas pressure accelerates the previously momentum-driven gas shell to this new velocity*

Energy-driven winds. Clearing out the galaxy

V

[......]

King et al. (2011) and King (2014) review for detailed calculations

$$M_{\substack{\text{energy}\\\text{driven}}} = \frac{3 f_g k \sigma^2 v_e^3}{\pi G^2 c \eta} \sim \frac{3 f_g k \sigma^5}{\pi G^2 c \eta} = \frac{3\sigma}{\eta c} M_\sigma \sim 6 \times 10^6 M_\odot \sigma_{200}^5$$

$v_e \sim \sigma$: this is physically consistent with the need for the gas to acquire the escape velocity and so continue moving out once the central accretion and, hence, the central energy, turns off

Adiabatically expanding shocked gas pushes the ISM away as a hot atmosphere for any SMBH mass.

Even if the AGN is switches off, the residual gas pressure still drives the outflow for a long time

The SMBH mass above is a sort of critical value (<<observations)

→ *The wind energy-driving solution does not correctly reproduce the M-σ relation*

Energy-driven winds. Clearing out the galaxy

VI

It can be shown (King+, Zubovas+ papers) that most of the wind kinetic energy ultimately goes into the mechanical energy of the outflow in the energy-driven solution

AGN wind **Molecular (kpc-scale) outflow**

$$\frac{1}{2}\dot{M}_w v_w^2 \sim \frac{1}{2}\dot{M}_{out} v_{out}^2$$

$$\frac{\dot{P}_w^2}{2\dot{M}_w} \sim \frac{\dot{P}_{out}^2}{2\dot{M}_{out}}$$

$$\dot{P}_w = \frac{L_{Edd}}{c}$$

$$\dot{P}_{out} \sim \dot{P}_w \sim \frac{L_{Edd}}{c}$$

versus momentum-driven outflow value

f_L=mass-loading factor of the outflow: ratio of the mass flow rate in the shocked ISM to that in the wind

$$\dot{P}_{out} = \dot{P}_w \left(\frac{\dot{M}_{out}}{\dot{M}_w}\right)^{1/2} = \frac{L_{Edd}}{c} f_L \sim 20\ \sigma_{200}^{-1/3} \frac{L_{Edd}}{c}$$

momentum rate of the outflow

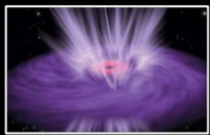
Several molecular-gas observations (e.g., Cicone et al. 2014) are consistent with

$$\dot{P}_{out} = \dot{M}_{out} v_{out} \sim 20\ L_{Edd}/c$$

On the observational side…

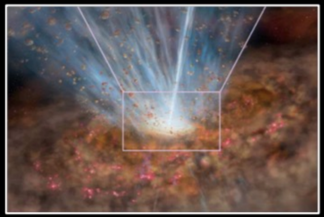
Plenty of literature works in the last decade

Outflows on all scales



BLR/Torus

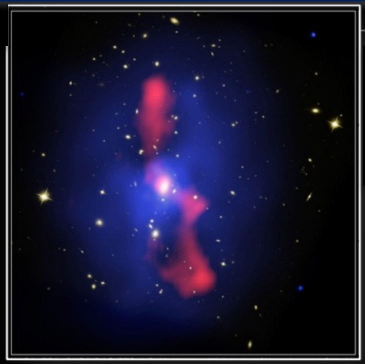
disc winds (UFOs)



ISM

ICM/IGM

Shocked/hot ISM
Galactic ionized/molecular outflows



ICM/IGM

Jets/QSO giant emission regions & nebulae

← + Huge Range in Timescales! →

Log(Temperature)

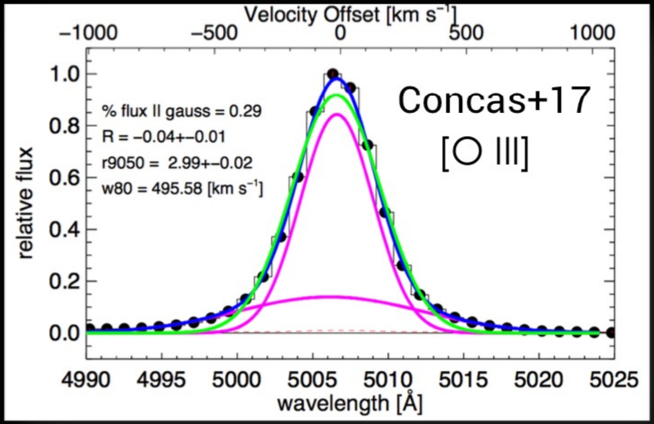
<1pc 10pc 100pc 1kpc 10kpc 100kpc 1Mpc

Log(distance)

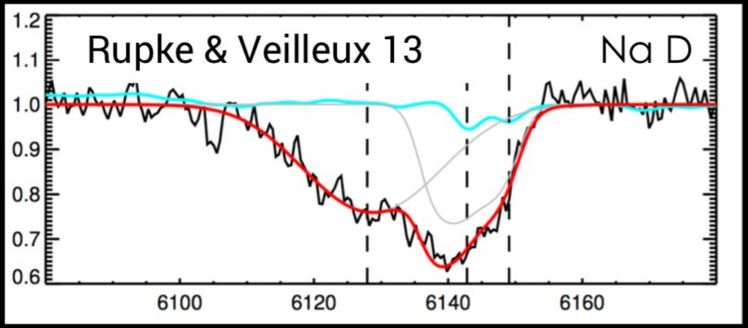
from C. Harrison

Outflows traced by atomic/ionized/molecular transitions

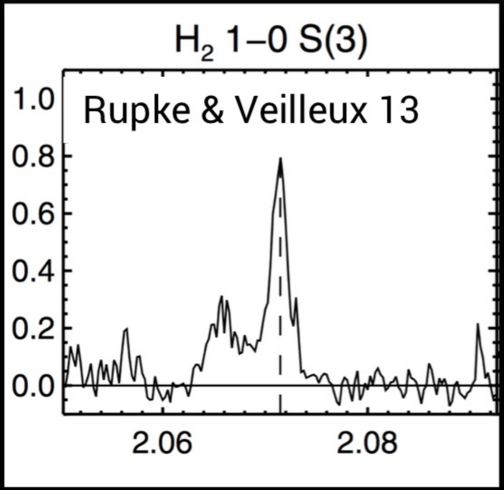
~10^4 K ionised outflows



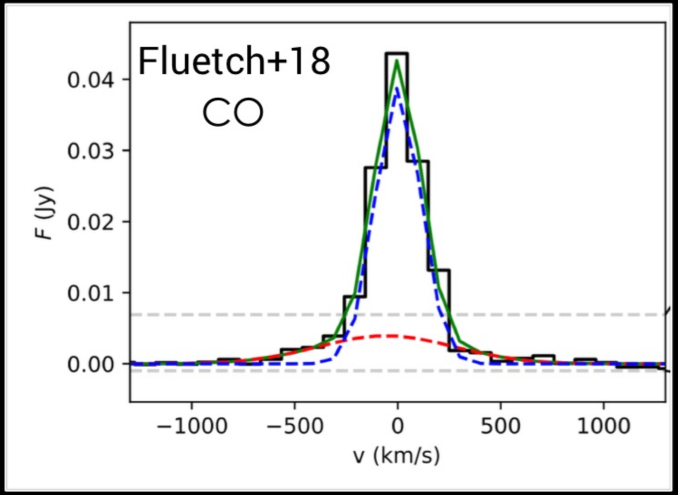
Neutral Atomic outflows



"Warm" molecular outflows



"Cold" Molecular outflows

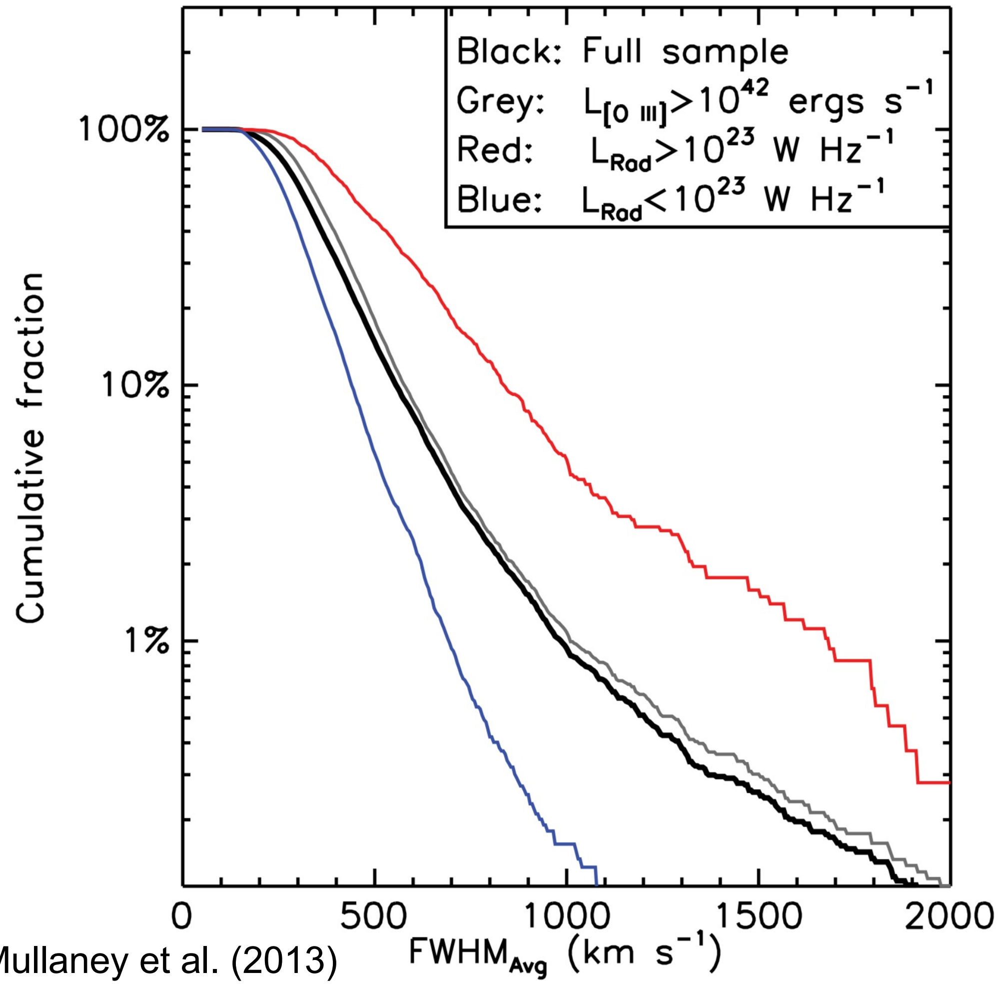


also see: e.g.,Cicone+14,16; Mullaney+13; Bae & Woo+14,16; Balmaverde+16; Harrison+14,16; Zakamska & Greene+14; Talia+17…

from C. Harrison

Outflows in [OIII] – link with radio emission

[OIII] (typically, a narrow line) FWHM distribution from the SDSS



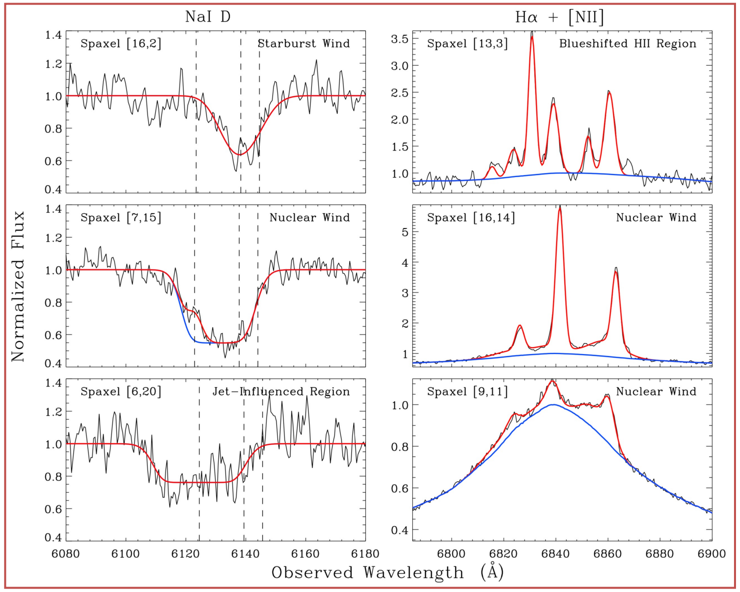
Mullaney et al. (2013)

A connection between the radio luminosity and the presence of outflows has been found also in samples not selected on the basis of their radio properties (SDSS: Mullaney+13, Zakamska & Greene14)

→ presence of faint radio jets or radio emission as by-product of the shocks associated with the outflows? (see Morganti 2017 review)

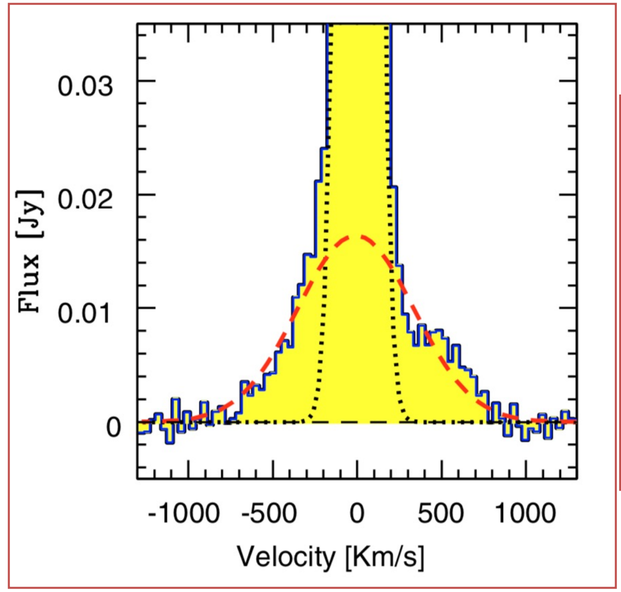
A nearby example: Mrk 231 (ULIRG)

neutral gas   ionized gas

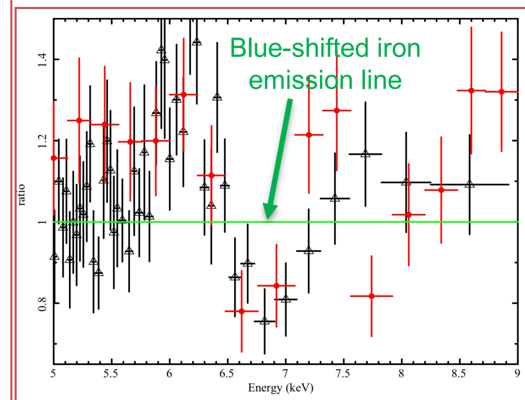


Velocities up to ~1000 km/s, kpc scale (Rupke & Veilleux 2011)

CO (1-0)



Velocity of ~750 km/s, kpc scale; outflow rate~700 $M_\odot$/yr vs SFR~200 $M_\odot$ /yr (Feruglio et al. 2011)



X-ray UFO (*Chandra*+*NuSTAR* data; v~0.1c, Feruglio et al. 2015)

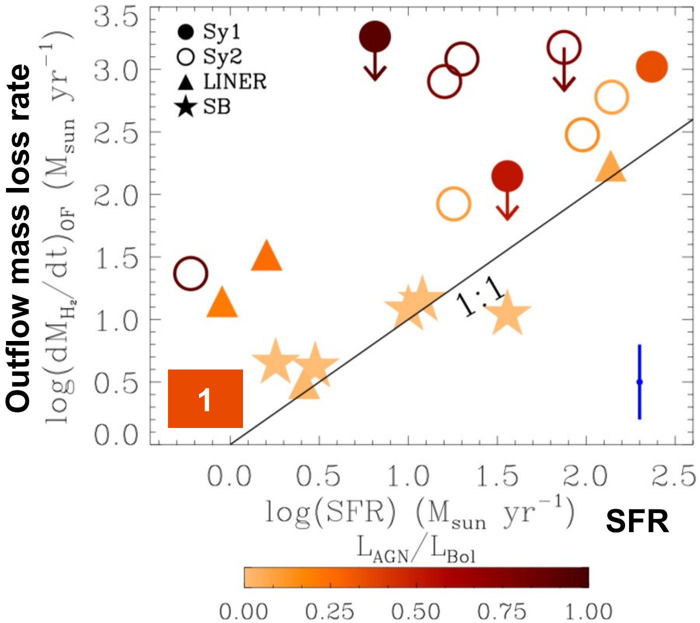
$$\dot{E}_{kin,UFO} \sim \dot{E}_{kin,OF}$$

$$\dot{P}_{out} \sim (30-60)\dot{P}_{(w=UFO)}$$

Energy-driven most likely explanation

Sometimes, a complex line (and continuum) modeling is required to determine the outflow properties

Molecular outflows and the role of AGN. I

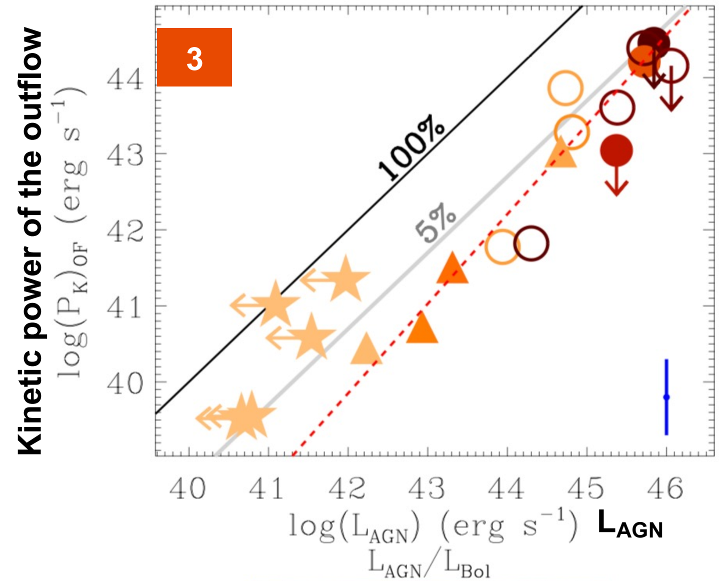


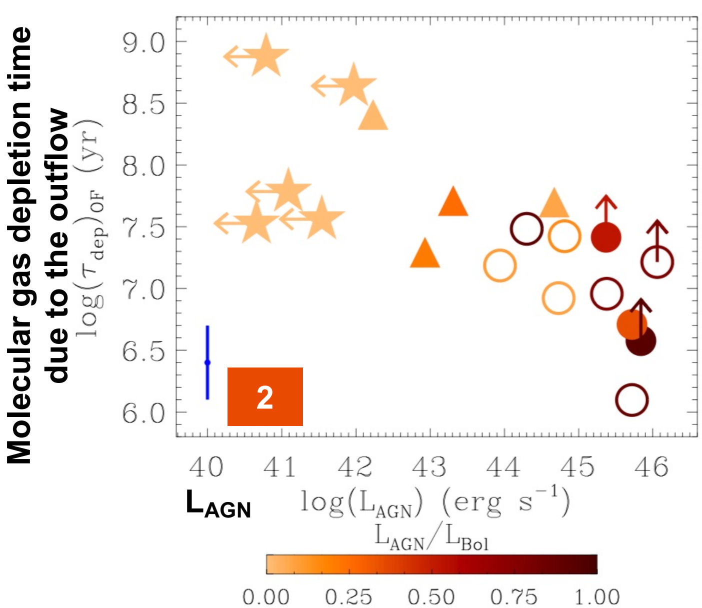
1 The presence of an AGN can boost the **outflow mass loss rate** significantly, depending on AGN strength

2 **Time depletion** ($\mathbf{M_{H2}/\dot{M}_{H2,OF}}$) is lowered in presence of an AGN (a few $\times 10^6$ yr)

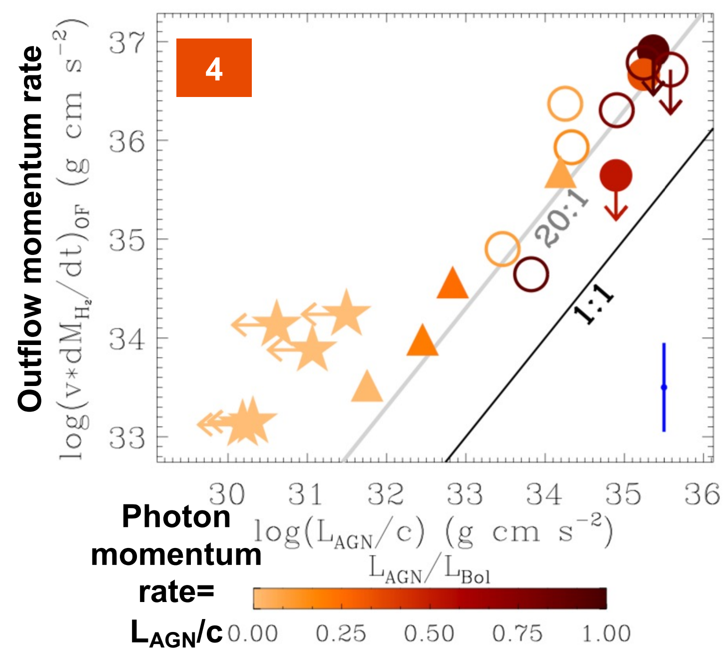
3 The **outflow kinetic power** corresponds to about 5% of L_{AGN} in the most powerful AGN

4 **Outflow momentum rates** are close to ~20 L_{AGN}/c for AGN-dominated systems (favouring AGN-driven scenarios)

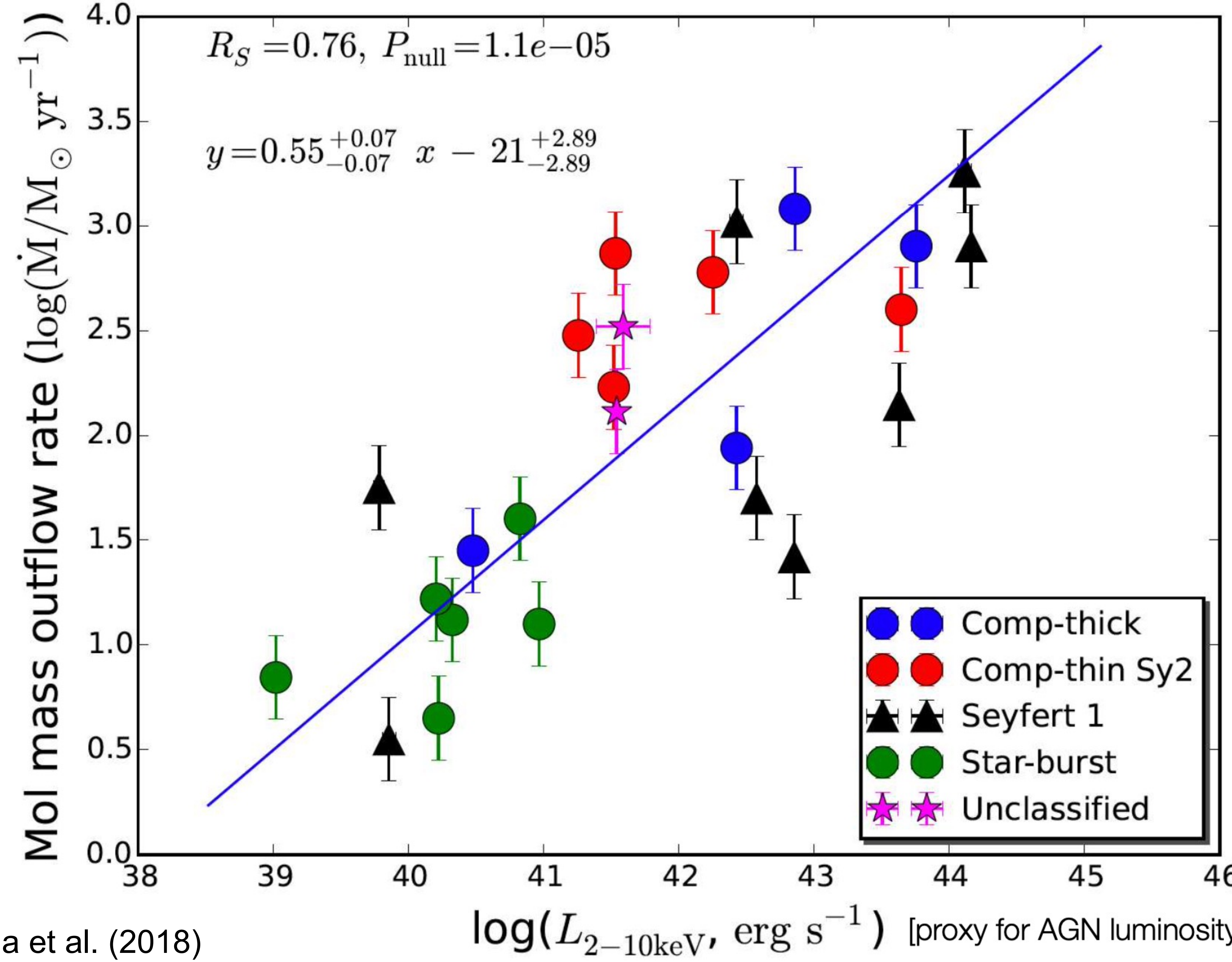




Cicone et al. (2014) - see also Fluetsch+19, […]



Molecular outflows and the role of AGN. II

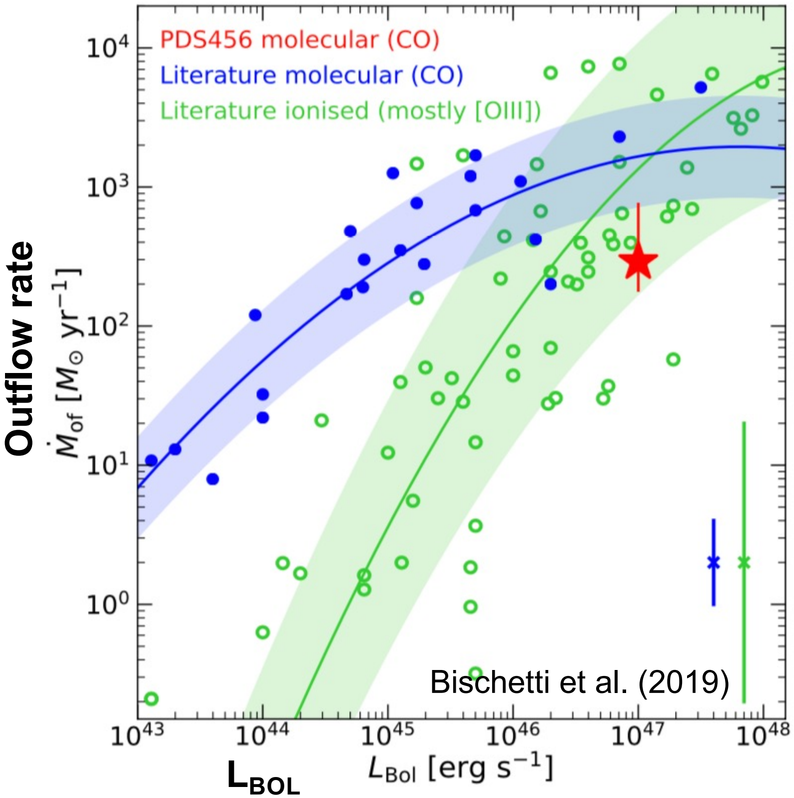


[proxy for AGN luminosity]

Laha et al. (2018)

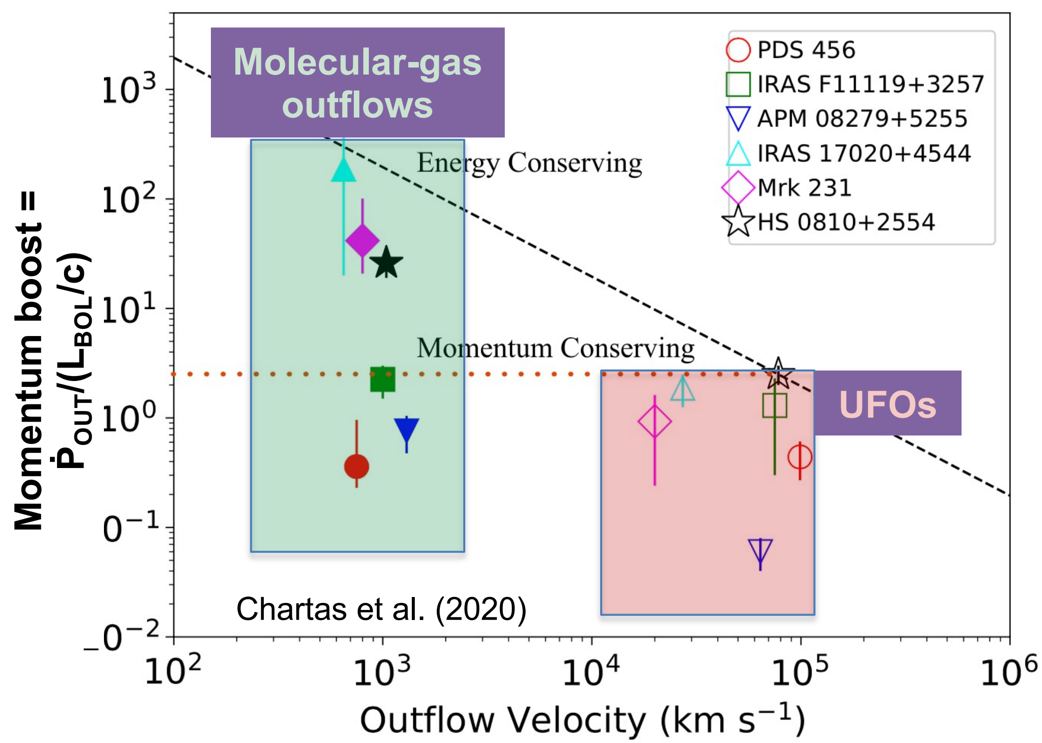
Molecular vs. ionized outflows. Momentum vs. Energy-conserving scenario

see also Fiore et al. (2017), Laha et al. (2018), Smith et al. (2019), […]



Indications of a flattening of the molecular mass outflow rate at $L_{BOL}>10^{46}$ erg/s, while the ionized mass outflow rate still increases up to $L_{BOL}\sim10^{48}$ erg/s.

→ *in luminous quasars the ionized gas phase cannot be neglected to properly evaluate the impact of AGN-driven feedback*



Connecting the properties of small-scale high-velocity winds (ultra-fast outflows in X-rays) with those of lower-velocity large-scale (kpc) molecular outflows should shed light on *momentum- vs. energy-driven scenarios*.

Paucity of sources with both outflow components, selection biases → situation not clear yet

Some calculations: momentum boost of Mrk231

Mrk 231 case (updated values from Feruglio et al. 2015; magenta point below)

$$L_{BOL,AGN} \sim 5 \times 10^{45}\ erg/s$$

Molecular outflow (out)

$$\dot{M}_{out} \sim 1000\ M_{\odot}/yr$$

$$v_{out} \sim 800\ km/s$$

X-ray wind (UFO)

$$\dot{M}_{UFO} \sim 1.2\ M_{\odot}/yr$$

$$v_{UFO} \sim 20000\ km/s$$

$$\dot{P}_{out} = \dot{M}_{out} \times\ v_{out} \sim 5.4 \times 10^{36}\ \frac{g\ cm}{s^2}$$

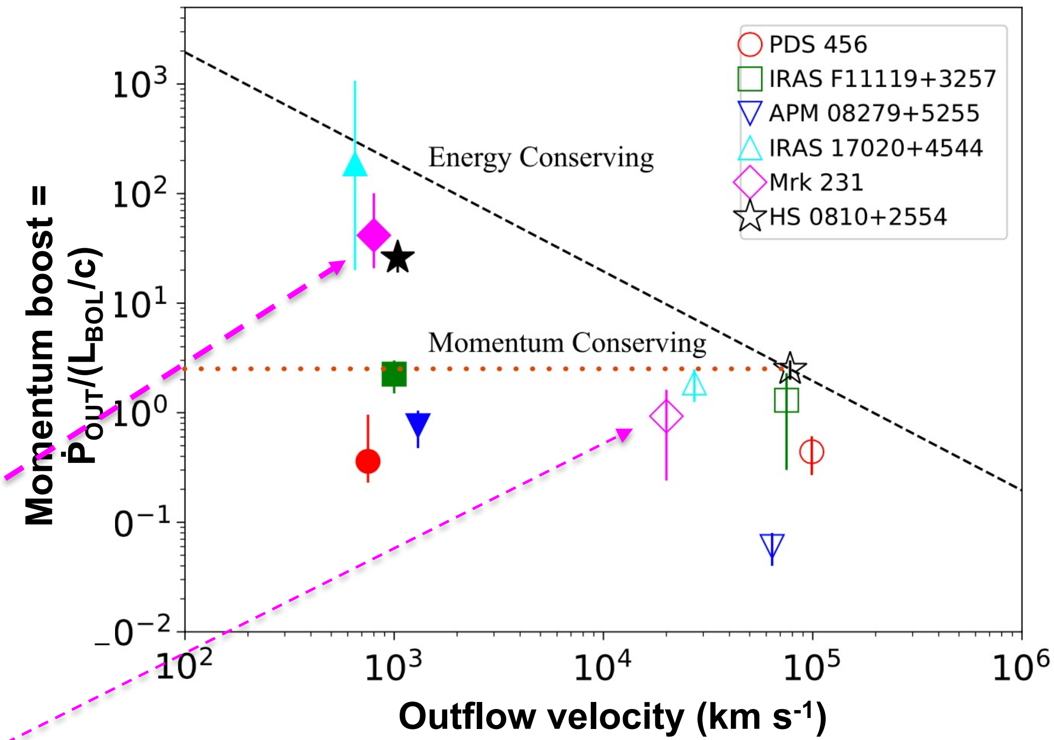
Momentum boost

$$\frac{\dot{P}_{out}}{L_{BOL}/c} \sim 32$$

$$\dot{P}_{UFO} = \dot{M}_{UFO} \times\ v_{UFO} \sim 1.5 \times 10^{35}\ \frac{g\ cm}{s^2}$$

$$\frac{\dot{P}_{UFO}}{L_{BOL}/c} \sim 0.9$$

$$\frac{\dot{P}_{out}}{\dot{P}_{UFO}} \sim 36$$



Some calculations: energy conservation in Mrk231

Molecular outflow (out)

$$\dot{M}_{out} \sim 1000\ M_\odot/yr$$
$$v_{out} \sim 800\ km/s$$

X-ray wind (UFO)

$$\dot{M}_{UFO} \sim 1.2\ M_\odot/yr$$
$$v_{UFO} \sim 20000\ km/s$$

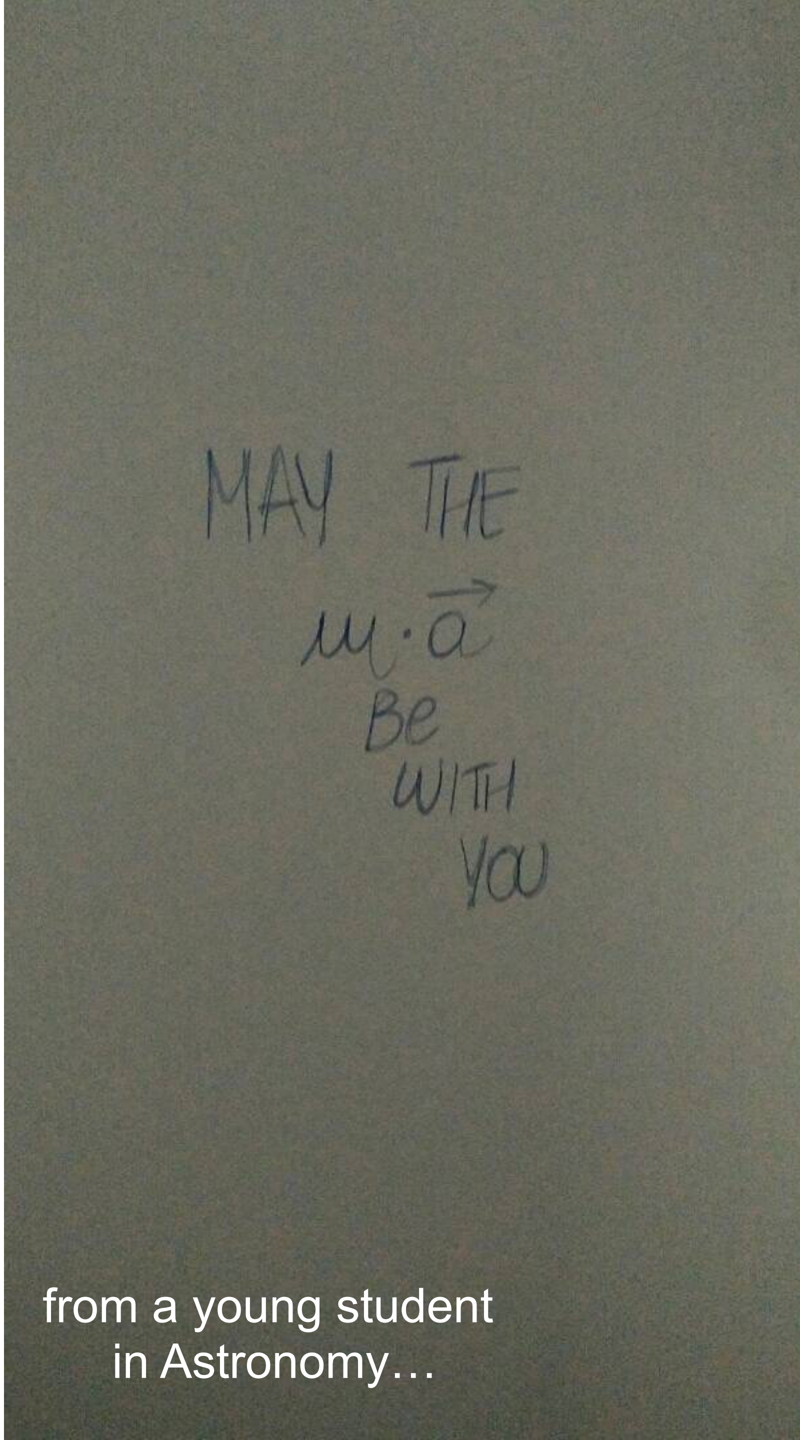
$$\frac{1}{2}\dot{M}_{out}v_{out}^2 = \frac{1}{2}10^3 \times \frac{2\times10^{33}}{365\times24\times3600}(8\times10^7)^2\ \left[\frac{g}{s}\frac{cm^2}{s^2}\right] =$$

Kinetic energy of the outflow

$$\rightarrow\ \frac{1}{2}\dot{M}_{out}v_{out}^2 \sim 2\times10^{44}\ [cgs]$$

$$\frac{1}{2}\dot{M}_{UFO}\ v_{UFO}^2 = \frac{1}{2}1.2 \times \frac{2\times10^{33}}{365\times24\times3600}(2\times10^9)^2\ \left[\frac{g}{s}\frac{cm^2}{s^2}\right] =$$

$$\rightarrow\ \frac{1}{2}\dot{M}_{UFO}\ v_{UFO}^2 \sim 1.5\times10^{44}\ [cgs]$$



from a young student
in Astronomy…

Summary of outflow pending issues

cf. Gaspari et al., 2020, Nature Astronomy, 4, 10

- Geometry of accretion and ejection flow near the BH?
- Outflow ejection and acceleration mechanisms?
- Partition of kinetic power into outflows and jets
- Relation between accreted and ejected mass rate?
- How much energy/momentum rate are needed for feedback?
- Connection between ionised, neutral and molecular phases
- Distribution function of basic observables in complete samples?
- How does the molecular outflows form in hot outflows?