The physics of AGN-driven galactic outflows

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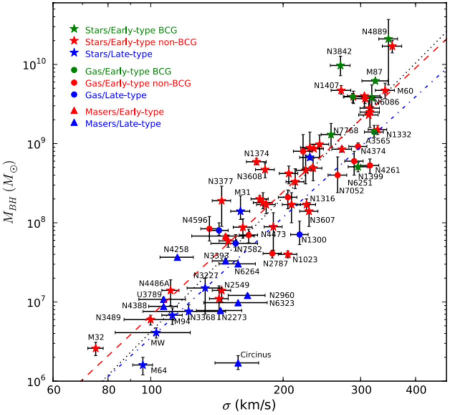
Outline

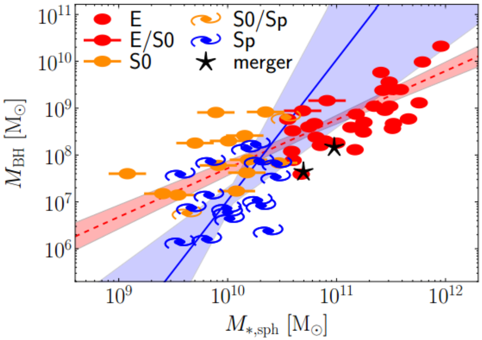
The $M - \sigma$ relation



McConnell & Ma (2013)

- A connection between SMBH mass and galaxy spheroid stellar velocity dispersion
- Power law: $M \propto \sigma^\alpha$, $\alpha \sim 5$
- Value of α decreases when galaxies are separated by morphological type
- Implies co-evolution between SMBH and the host galaxy spheroid

The $M - M_b$ relation



Savorgnan et al. (2016)

- A connection between SMBH mass and bulge stellar mass
- Almost linear (Häring & Rix 2004), at least for ellipticals
- Implies similar growth patterns for SMBH and host galaxies
- Very large scatter

Possible physical SMBH-galaxy connection

- Connection cannot be gravitational:

$$R_{\rm infl} = \frac{GM_{\rm bh}}{\sigma^2} \simeq 10 M_8 \sigma_{200}^{-2}\ {\rm pc} \ll R_{\rm b} \simeq 1\ {\rm kpc} \quad (1)$$

- But can be energetic:

$$E_{\rm accr} \simeq \eta M_{\rm bh} c^2 \simeq 2 \times 10^{61} \eta_{0.1} M_8\ {\rm erg} \gg E_{\rm b} \simeq M_{\rm b}\sigma^2 \simeq 8 \times 10^{58} M_{11} \sigma_{200}^2\ {\rm erg} \quad (2)$$

- The question then becomes how can energy be communicated to the bulge at a $\sim 0.5\%$ efficiency.

Accretion disc wind

- Radiation pressure in the accretion disc drives a wind (King & Pounds 2003):

$$\dot{p}_{\rm w} = \dot{M}_{\rm w} v_{\rm w} = \tau \frac{L_{\rm AGN}}{c}; \quad v_{\rm w} \simeq v_{\rm esc} \simeq \frac{\tau}{\dot{m}} \eta c; \quad \dot{E}_{\rm w} = \frac{\dot{M}_{\rm w} v_{\rm w}^2}{2} = \frac{\tau^2 \eta}{2 \dot{m}} L_{\rm AGN} \quad (3)$$

$$\eta \equiv \frac{L_{\rm AGN}}{\dot{M}_{\rm AGN} c^2}; \quad \dot{m} \equiv \frac{\dot{M}_{\rm w}}{\dot{M}_{\rm acc}} \quad (4)$$

- The wind is quasi-spherical and self-regulates to keep $\tau \simeq 1$ (single-scattering limit) (King 2010)
- Winds likely to be intermittent (e.g. Pounds & Vaughan 2012)

Observed winds (UFOs)

- Winds are detected via blueshifted FeXXV and FeXXVI absorption, indicating very high ionisation parameters $\xi \sim 10^6$
- Observed in $\sim$ 40% of local AGN (Tombesi et al. 2010)
- Wind velocities fall in range $v_{\rm w} = 0.03 - 0.3c$ (Reeves et al. 2003, Tombesi et al. 2010)
- Spatial extent $r_{\rm w} < 1$ pc

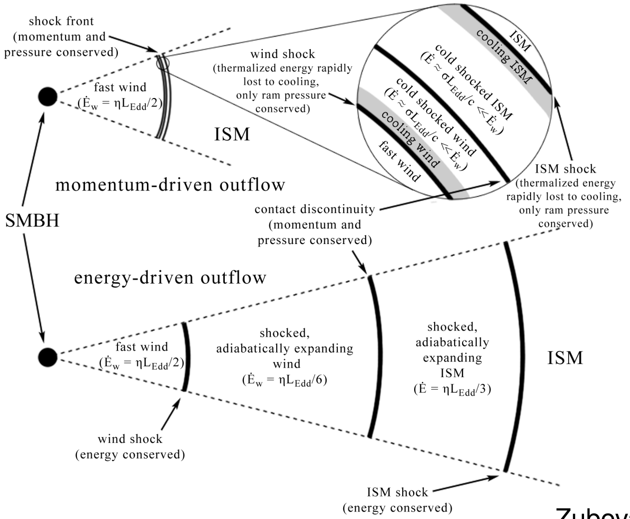
Wind shock

- Wind shocks against the surrounding ISM; post-shock temperature (assumed uniform)

$$T_{\rm sh} = \frac{3\mu m_{\rm p} v_{\rm w}^2}{16 k_{\rm B}} \simeq 1.3 \times 10^{10} v_{0.1}^2 \ {\rm K} \qquad (5)$$

- Shocked wind cools by inverse Compton scattering against the AGN radiation field, with a cooling time $t_{\rm C}$
- Hot wind bubble pushes against the surrounding gas and causes it to expand on a timescale $t_{\rm exp}$
- $t_{\rm C}/t_{\rm exp}$ increases with radius, determines type of outflow:
  - Close to the AGN, $t_{\rm C}/t_{\rm exp} < 1$, cooling is efficient, outflow is driven by wind momentum
  - Far from the AGN, $t_{\rm C}/t_{\rm exp} > 1$, cooling is inefficient, outflow is driven by wind energy
  - The transition radius at which $t_{\rm C}/t_{\rm exp} = 1$ is known as the cooling radius

AGN winds and outflows



Zubovas & King (2012)

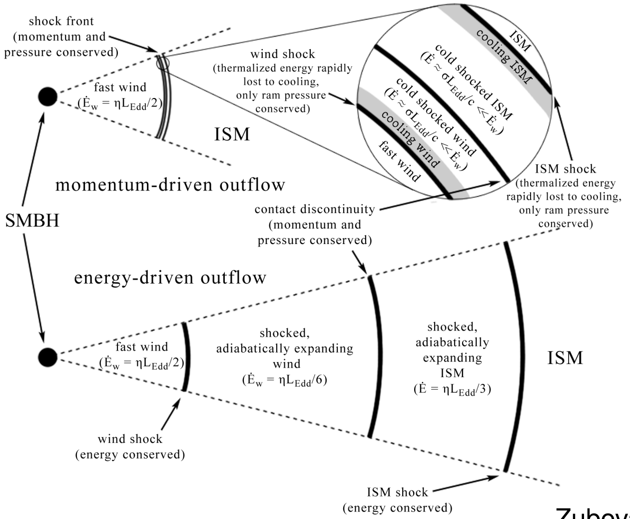
Cooling radius

- If the shocked wind is treated as a uniform plasma, $R_C \simeq 500$ pc (King 2003)
- More realistically, the wind is a two-temperature plasma (Faucher-Giguère & Quataert 2012):
  - Electrons cool down very rapidly
  - Most of the energy is in protons
  - Electron-proton energy exchange inefficient, cooling also inefficient
  - Effective $R_C < 1$ pc

Wind shock in clumpy medium

- A realistic ISM has uneven density
- Most of the wind energy escapes through low-density channels (Zubovas & Nayakshin 2014)
- Dense clouds, which can feed the SMBH, are affected mostly by the AGN wind momentum
- Two types of outflow still occur:
    - Dense gas experiences a momentum-driven outflow and evaporation in the surrounding hot diffuse plasma
    - Diffuse gas and evaporating dense clouds experience an energy-driven outflow

AGN winds and outflows



Zubovas & King (2012)

Momentum-driven outflow

- Small-scale outflow, $\dot{E} < 10^{-3} L_{\rm AGN}$
- Can only escape to large distances if AGN wind momentum rate is higher than the weight of the dense gas clouds
- This condition gives a required luminosity:

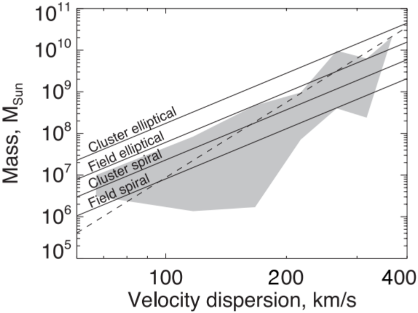
$$L_{\rm AGN} > L_{\rm crit} = \frac{4 f_{\rm g} c}{G} \sigma^4 \simeq 4.6 \times 10^{46} \sigma_{200}^4 \ {\rm erg\ s^{-1}} \qquad (6)$$

- Assuming that this is the Eddington luminosity, this translates to a critical mass

$$M_{\rm SMBH} > M_{\rm crit} = \frac{f_{\rm g} \kappa}{\pi G^2} \sigma^4 \simeq 3.7 \times 10^8 \sigma_{200}^4 \ M_\odot \qquad (7)$$

- The calculated $M_{\rm crit}(\sigma)$ is rather similar to, but with a lower exponent value than, the observed $M - \sigma$ correlation

$M - \sigma$ relation



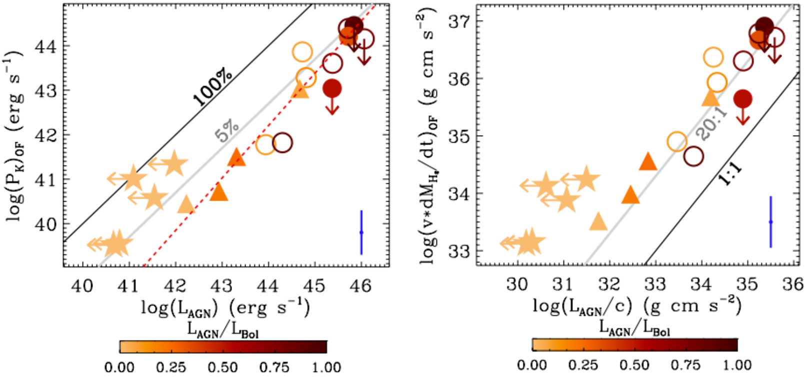
Zubovas & King (2013)

- Galaxies of different morphological types and in different environments have different ISM and different requirements for the AGN luminosity:
    - The constant factor in the $M_{\rm crit}(\sigma)$ expression is higher in ellipticals than in spirals and in cluster galaxies than in field galaxies
    - The same is true for σ
- The resulting correlation has a steeper slope, closer to observed (Zubovas & King 2013)

Energy-driven outflow

- Once the black hole mass $M_{\rm SMBH} > M_{\rm crit}$, or if there is sufficiently diffuse gas close to the SMBH, the outflow becomes large-scale
- Shocked wind is adiabatic, $\dot{E}_{\rm out} \simeq \dot{E}_{\rm w} \simeq 0.05 L_{\rm AGN}$
- Typical outflow velocities $v_{\rm out} \sim 10^3$ km s^{-1}, mass flow rates $\dot{M}_{\rm out} \sim 10^3 M_{\odot}$ yr^{-1}
- Outflow momentum $\dot{p}_{\rm out} \sim 20 L_{\rm AGN}/c$
- These predictions (Zubovas & King 2012) agree very well with observations (Cicone et al. 2014)

Observed outflow properties



Cicone et al. (2014)

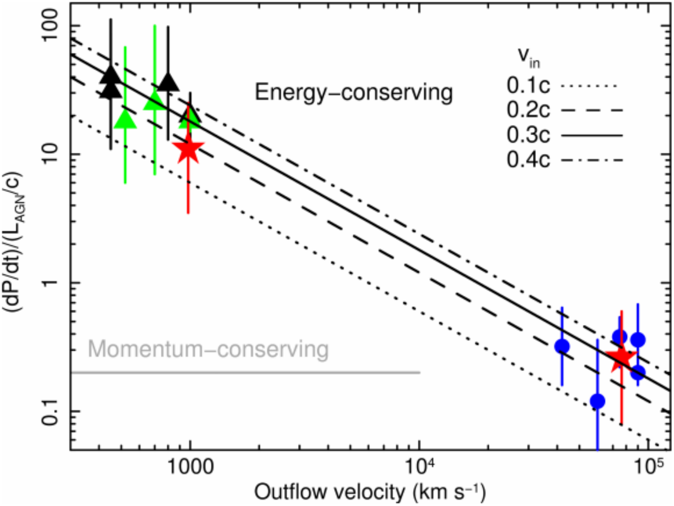
Effect on galactic scales

- Outflow is powerful enough to remove most gas from galaxy spheroid on timescales shorter than star formation timescale (Feruglio et al. 2010, Cicone et al. 2014)
- Outflowing gas cools rapidly (Zubovas & King 2014, Richings & Faucher-Giguère), $t_{\rm cool} \ll t_{\rm dyn}$, forms molecular clumps, might lead to star formation within the outflow (Maiolino et al. 2017)
- Outflow has very high pressure:

$$\frac{P_{\rm out}}{P_{\rm disc}} \sim \left(\frac{v_{\rm out}}{\sigma}\right)^2 \left(\frac{R_{\rm d}}{R_{\rm out}}\right)^2 \sim 25 \left(\frac{R_{\rm d}}{R_{\rm out}}\right)^2; \qquad (8)$$

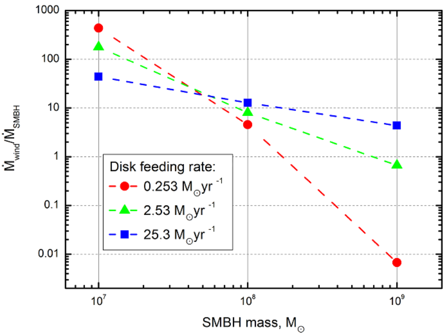
this compresses gas in the galactic disc and can trigger or enhance star formation there (Zubovas et al. 2013)

Wind-outflow connection



Tombesi et al. (2015)

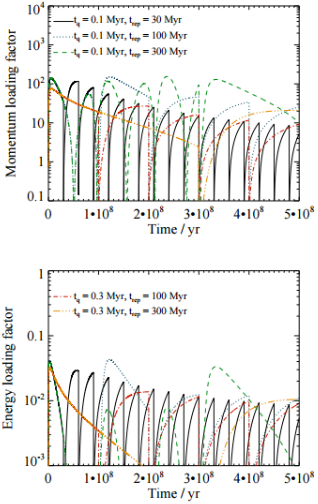
Wind mass flow rate



Naujalis, Zubovas & Semionov (in prep)

- Model assumption: $\dot{m} \equiv 1$, i.e. $\dot{M}_{\rm w} \equiv \dot{M}_{\rm acc}$
- This isn't true in general: disc feeding process doesn't know about the central SMBH mass
- Preliminary 1.5D simulation results suggest that $\dot{m} \sim 10$; winds have lower $v_{\rm w}$, but higher $\dot{p}_{\rm w}$ and $\dot{E}_{\rm w}$
- However, parts of the wind might 'fail' and become the torus, so the escaping wind may have $\dot{M}_{\rm w}$ similar to $\dot{M}_{\rm acc}$

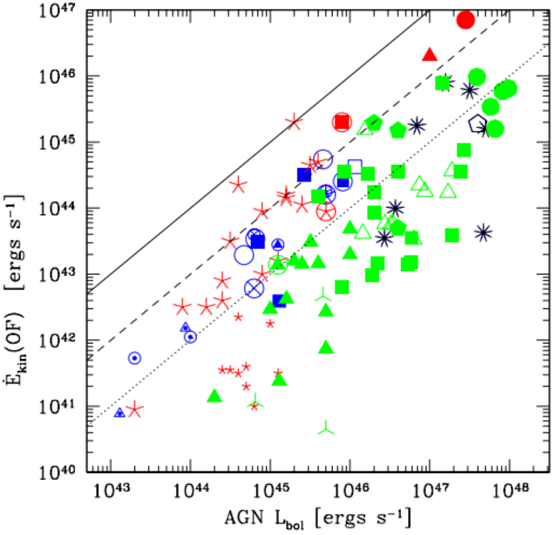
Multiple AGN episodes



Zubovas (2017, submitted)

- AGN episodes are short ($t_{\rm AGN} \sim 10^5$ yr), outflow lifetimes are long ($t_{\rm out} > 1$ Myr)
- Outflow correlations might be broken as the AGN fades
- Correlations preserved if $L_{\rm AGN}(t) \propto t^{-\alpha}$ with exponent $\alpha \sim 1$
- Later AGN episodes can illuminate the outflow, but do not break correlations either
- Observed correlations might be an upper limit to outflow properties

Correlations as upper limits



Fiore et al. (2017)

Summary

- AGN winds are a powerful source of energy affecting galaxy evolution:
  - AGN wind momentum establishes the $M - \sigma$ relation by cutting off the SMBH gas supply
  - Energy-driven AGN outflows clear gas out of galaxies and affect star formation
- Theoretical predictions agree very well with observed wind and outflow properties
  - But there are certain complications and outstanding issues