# Powerful Outflows and Feedback from Active Galactic Nuclei

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# Understanding the Influence of SMBH

Three Important Equations

1. $M_{SMBH} \sim 10^{-3} \times M_{Bulge}$

2. $M_{SMBH} \approx 3 \times 10^{8} M_{\odot}\, \sigma_{200}{}^{\alpha}$

3. $R_{inf} \approx 8\, M_{8}/\sigma_{200}{}^{2}$ pc

How can this be so?

Significance

1. The mass of the SMBH is almost always a constant fraction of the mass of the bulge

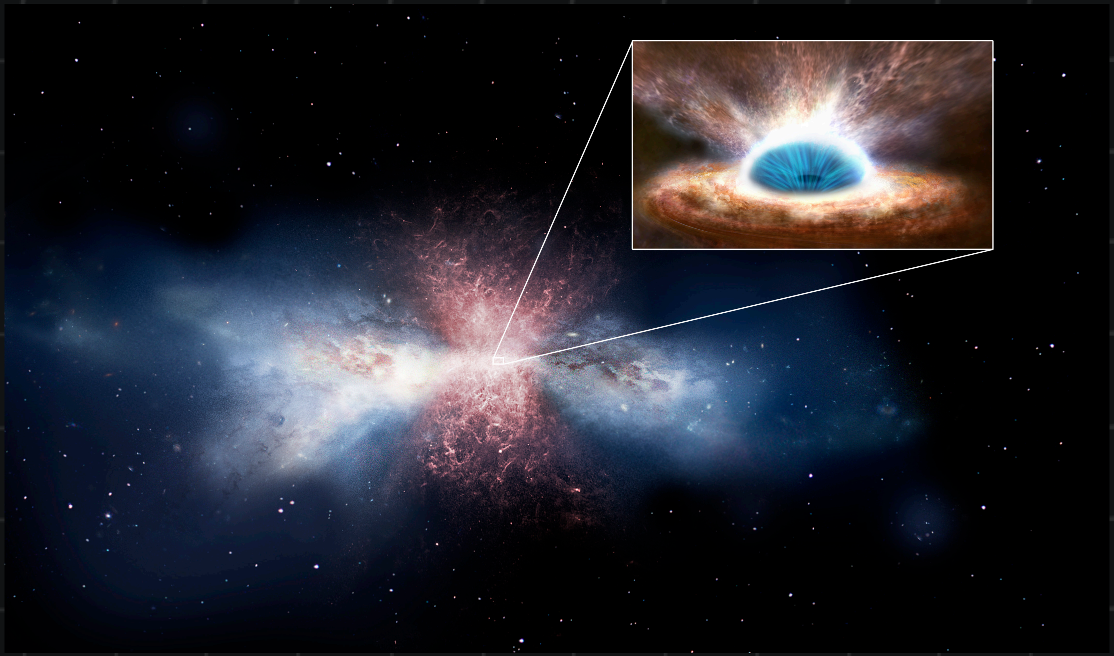
1. The mass of the SMBH is tightly correlated to the velocity dispersion in the bulge

2. Most of the entire galaxy is gravitationally unaware of the SMBH

# Methods of Communication

Radiation: how all the accretion energy is initially released

Mechanical, i.e., literally moving gas around:  huge luminosities drive gas through the galaxy



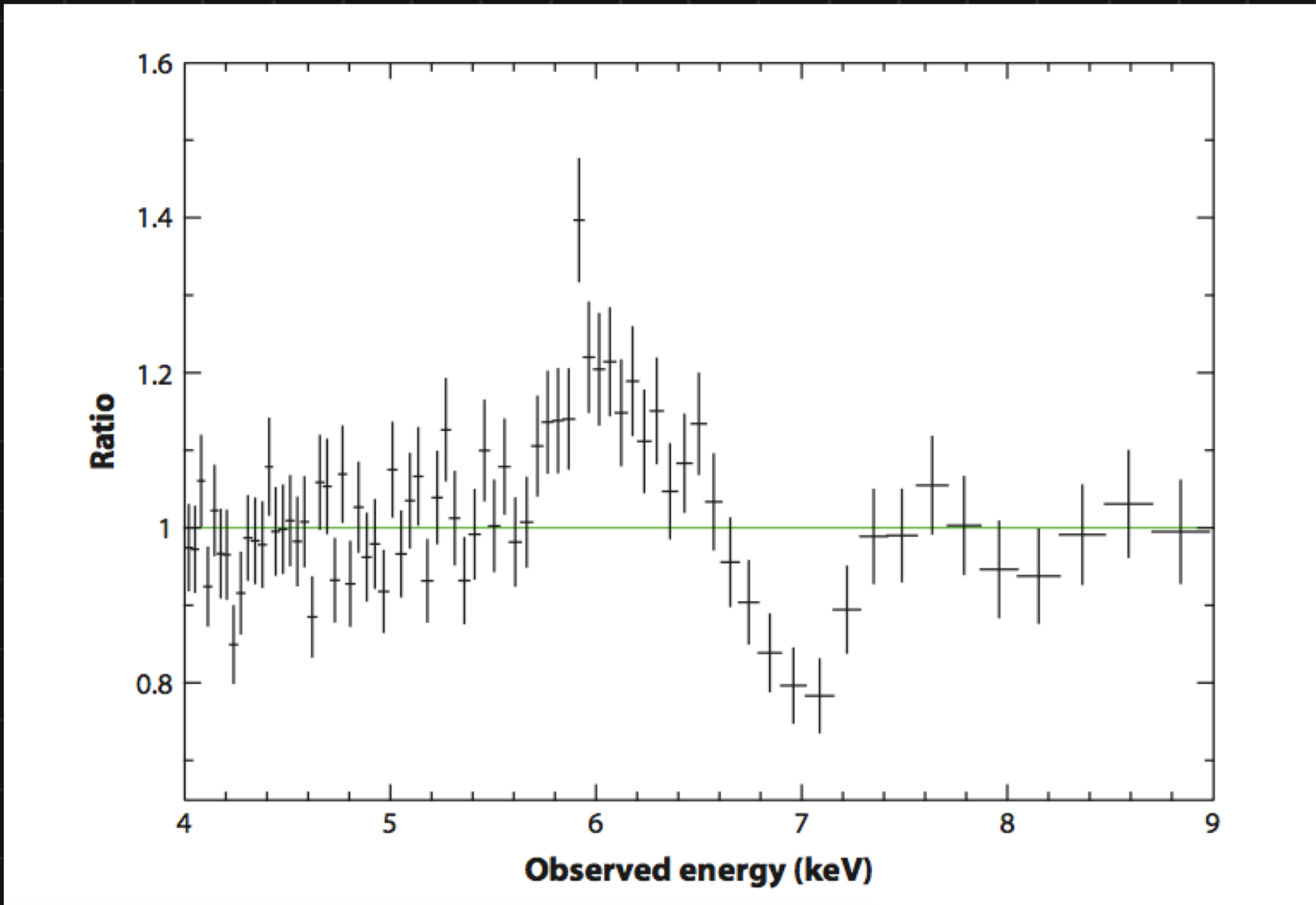
Jets vs. Winds

Jets: highly collimated flows driven from very near the SMBH, somewhat rare

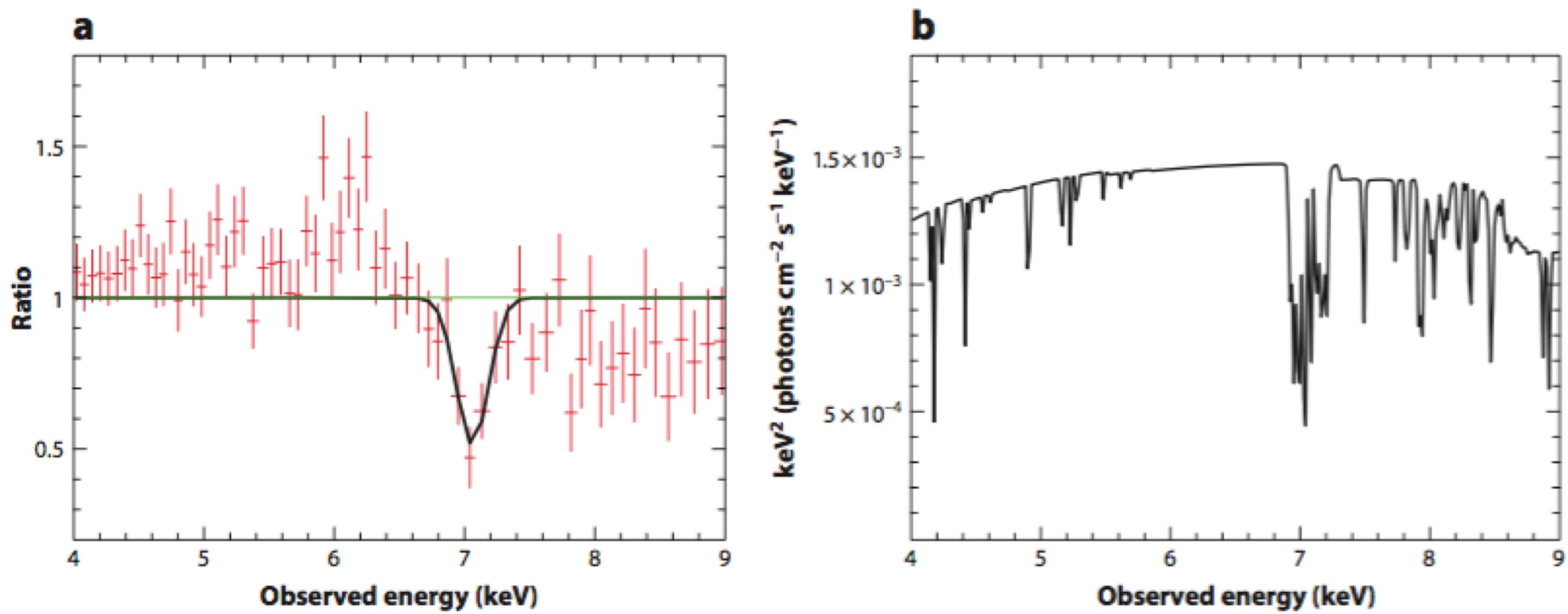
Winds: nearly isotropic outflows, common to many AGN

IRAS F11119+3257 artist depiction

# Detecting Winds: Spectrum of PG1211+143



# Modeling Winds: Spectrum of PG1211+143

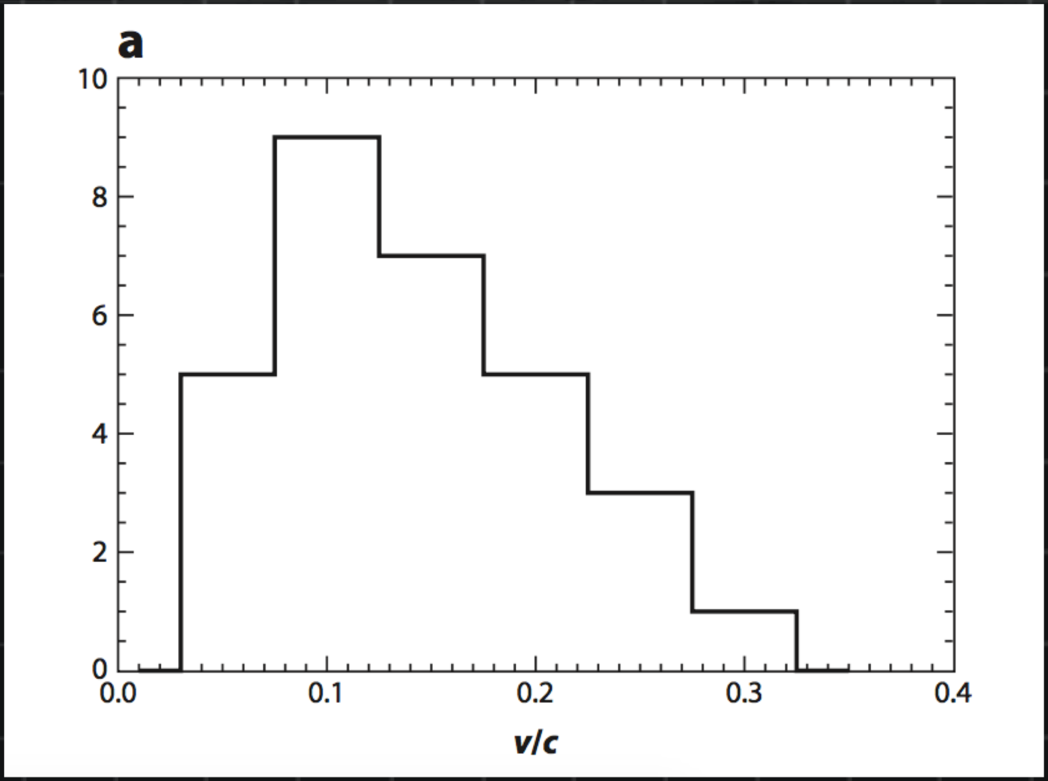



Gaussian fit, v ~ 0.12c

Photoionized gas model, v ~ 0.15c

# Observational Evidence of UFOs

## (Ultra-Fast Outflows)




Cappi 2006 found 7 non-BAL objects with v ~ 0.1c

Tombesi et al. 2010 found outflows in 15/42 radio-quiet objects, v ~ [0.1c,0.3c] (XMM-Newton archive)

Gofford et al. 2013 found similar outflows in 20/51 AGN, also with v ~ [0.1c,0.3c] (Suzaku archive)

→ Rather common

# Energy Output and Binding Energies

$$E_{\rm BH} \simeq \eta M c^2 \sim 2 \times 10^{61} M_8 \text{ erg}$$

Black hole mass should be related to galaxy properties that depend on galactic gas, since it is through accretion of this gas that it grows

$$E_{\rm bulge} \sim M_{\rm b}\sigma^2 \sim 8 \times 10^{58} M_8 \sigma_{200}^2 \text{ erg}$$

The important comparison is between $E_{BH}$ and $E_{gas}$

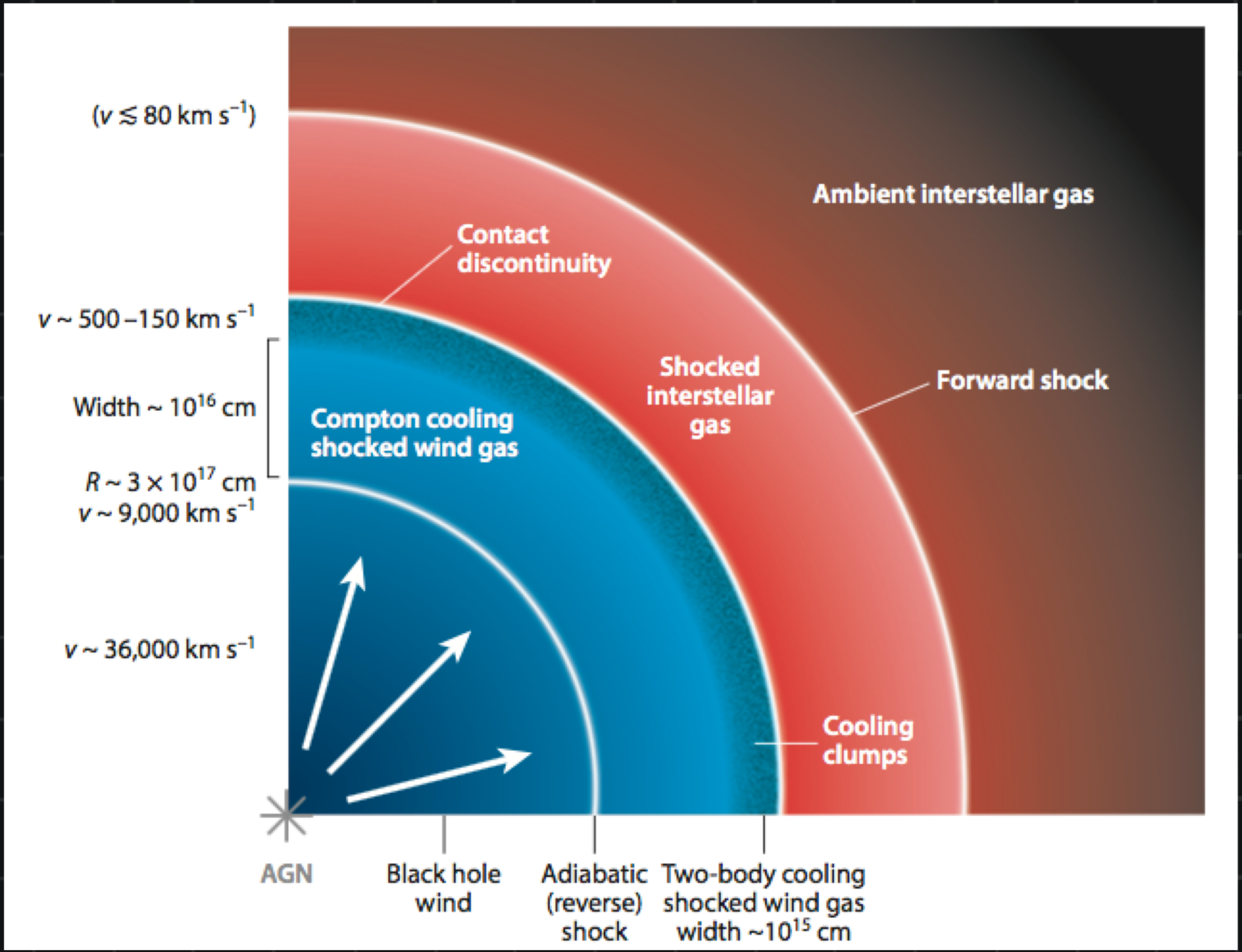
$$E_{\rm gas} = f_{\rm g} E_{\rm bulge},$$

$$E_{\rm BH} \sim 2 \times 10^3 E_{\rm gas}$$

The energy is more than enough to disrupt all of the gas in the bulge of galaxy, so it must not be communicated efficiently → slowed outflows

# Shocked Outflows

$$E_{\rm mom} \sim \frac{\sigma}{c} E_{\rm BH\ wind} \sim \frac{\sigma}{c}\frac{\eta^2}{2} Mc^2 \sim 5\times10^{-5} Mc^2 \sim 0.1 E_{\rm gas}$$




Significant Inverse Compton cooling

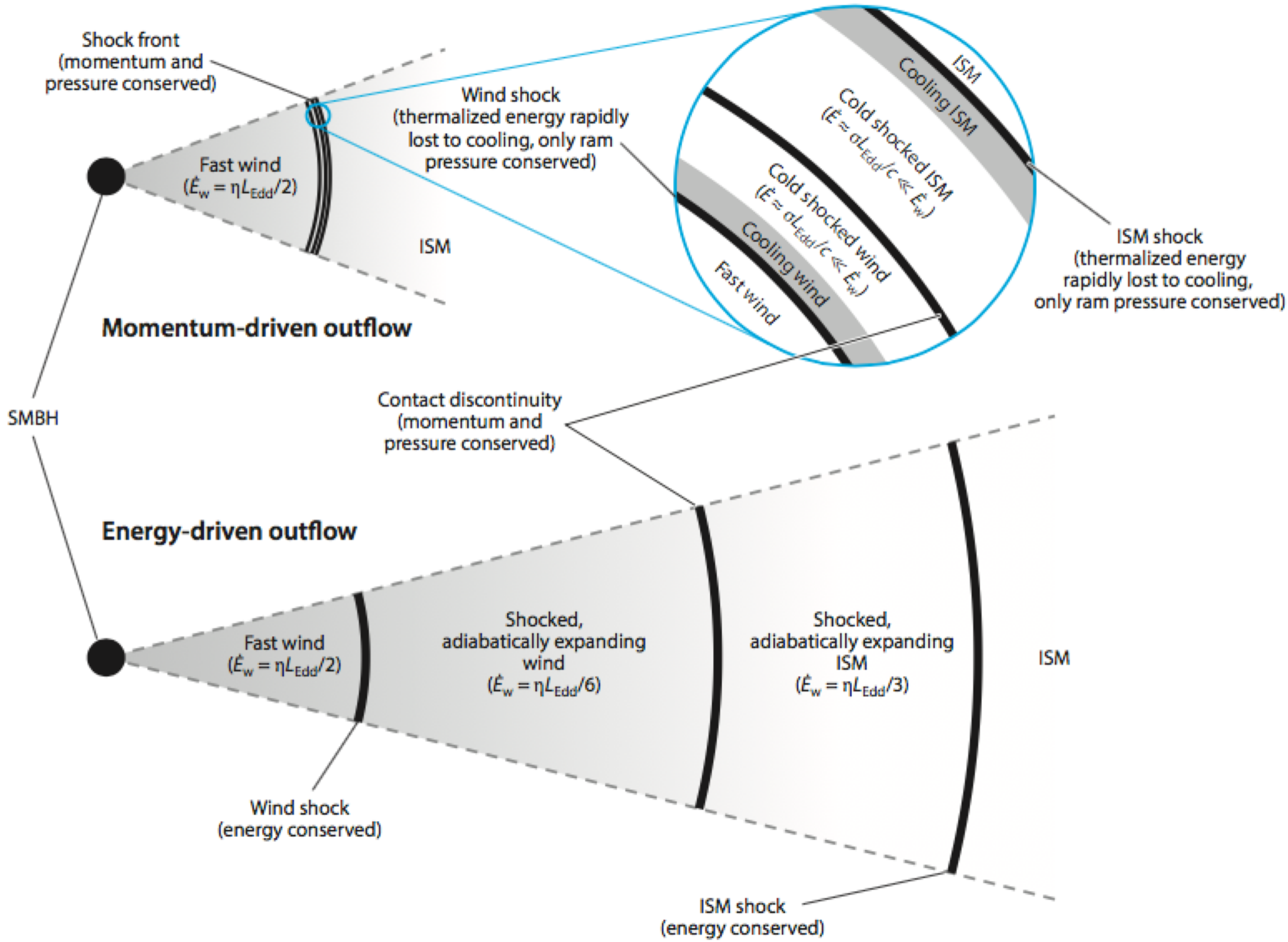
# Energy Dominated Flows

•Cooling time is not significant

$$E_{\mathrm{wind}} \simeq 0.05 L_{\mathrm{Edd}} \simeq 100 E_{\mathrm{gas}}$$

•Expansion is adiabatic so it retains its heat, and at greater distances the cooling time begins to increase, confining momentum flows to smaller radii and allowing energy dominated flows to extend much further

•Could not be supported long term because this would blow out all of the gas that the SMBH feeds on → couldn't reach observed masses


Shock front
(momentum and
pressure conserved)
Wind shock
(thermalized energy rapidly
lost to cooling, only ram
pressure conserved)
Fast wind
($\dot{E}_w = \eta L_{Edd}/2$)
ISM
Momentum-driven outflow
ISM
Cooling ISM
Cold shocked ISM
($\dot{E} \approx \sigma L_{Edd}/c \ll \dot{E}_w$)
Cold shocked wind
($\dot{E} \approx \sigma L_{Edd}/c \ll \dot{E}_w$)
Cooling wind
Fast wind
ISM shock
(thermalized energy
rapidly lost to cooling,
only ram pressure conserved)
SMBH
Contact discontinuity
(momentum and
pressure conserved)
Energy-driven outflow
Fast wind
($\dot{E}_w = \eta L_{Edd}/2$)
Shocked,
adiabatically expanding
wind
($\dot{E}_w = \eta L_{Edd}/6$)
Shocked,
adiabatically expanding
ISM
($\dot{E}_w = \eta L_{Edd}/3$)
ISM
Wind shock
(energy conserved)
ISM shock
(energy conserved)

# The M-σ Relation

A quick derivation that leads to a qualitatively similar M-σ relation

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

$\rightarrow$

$$M(R) = \frac{2\sigma^2 R}{G}.$$

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

$\rightarrow$

$$\frac{\mathrm{d}}{\mathrm{d}t}[M_g(R)\dot{R}] + \frac{GM_g(R)[M + M(R)]}{R^2} = \frac{L_{\mathrm{Edd}}}{c},$$

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

where

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

$$R^2\dot{R}^2 = -2GMR - 2\sigma^2\left[1 - \frac{M}{M_\sigma}\right]R^2 + \text{constant}.$$

$\rightarrow$

$$\dot{R}^2 \simeq -2\sigma^2\left[1 - \frac{M}{M_\sigma}\right],$$

What if $M < M_\sigma$?

# What happens at $M_\sigma$ and Beyond

$M_{SMBH} \approx 3 \times 10^8 M_\odot \, \sigma_{200}{}^{\alpha}$

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

Something must happen to halt black hole growth at this point → The black hole must expel all the gas

For $M \gg M_\sigma$, the solution to -------------------------->
allows for R to grow very large,
larger than the critical radius at which cooling takes place.

$$\dot{R}^2 \simeq -2\sigma^2 \left[1 - \frac{M}{M_\sigma}\right],$$

For $M \gg M_\sigma$, the shock wave becomes energy driven, and can extend for kpc scales
→ Clear out

# The Effects of a "Clear out" Considering Galactic Morphology

Disk Galaxies, e.g. spirals

Eventually the outflow must encounter the galactic disk. The resistance causes the flow proceed above and below the disk, however, $P_{outflow} >> P_{disk}$

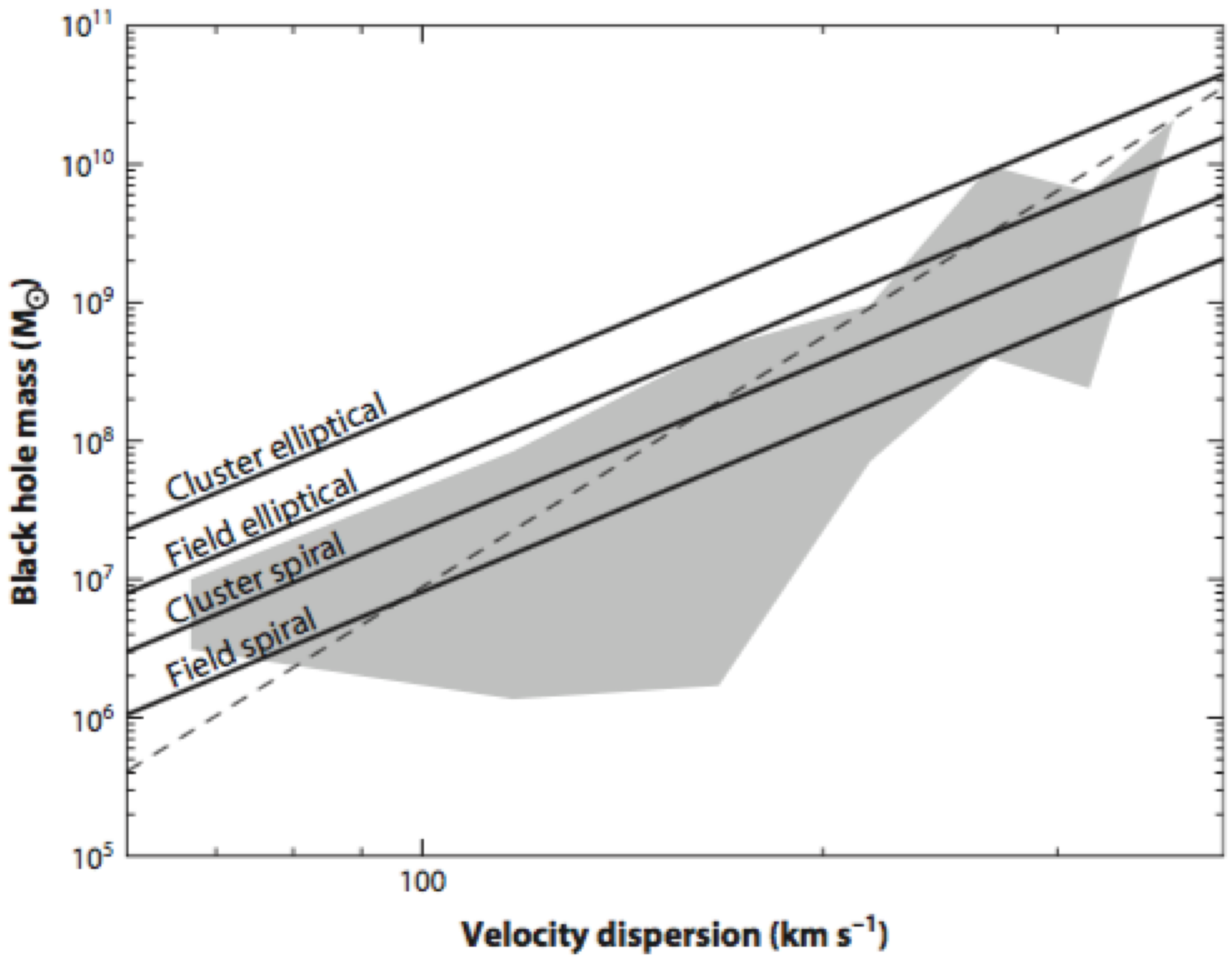
→ Triggered star formation

Elliptical Galaxies

In the absence of a disk, the energetic outflows proceed more or less uninterrupted, leaving spherical galaxies "red and dead"

Different morphologies and locations in which galaxies are found will yield different interactions between galaxies and their environments → Three (four) *M*-σ relationships

# Three (Four) M-σ Relationships



# Black Hole Mass – Bulge Mass Relation

Our previous discussion asserts that σ determines $M_{SMBH}$, so we cannot say that $M_{bulge}$ independently determines $M_{SMBH}$.

$$L_* \sim 2 \times 10^{10}\ \mathrm{L}_\odot\ \sigma_{200}^4.$$

M/L ~ 5 (Faber-Jackson is empirical)

Additionally, $M_{SMBH}$ cannot determine $M_{bulge}$ because it is in the form of stars

$$M_* \sim 1 \times 10^{11}\ \mathrm{M}_\odot \sigma_{200}^4 \sim 10^3 M.$$

Hypothesis: Whatever determines $M_{bulge}$ also makes it proportional to $\sigma^4$ (and therefore $M_{SMBH}$). Why?

$$M_\mathrm{b} \sim \frac{0.14 f_\mathrm{g} t_\mathrm{H} \sigma^4}{\epsilon_* c\, G},$$

Star Formation & Stellar Feedback

$$M \simeq M_\sigma \sim \frac{1.8 \kappa \epsilon_* c}{\pi G t_\mathrm{H}} M_\mathrm{b} \sim 10^{-3} M_\mathrm{b},$$

# A Statistical Interpretation

The Less Accepted Hypothesis:

Jahnke & Maccio (2011) argue that the observed scaling relationships are the consequence of repeated mergers

$M_{SMBH}$ is proportional to $M_{bulge}$ simply due to the central limit theorem, i.e., a value that centers more and more closely on the mean of the system for increasing numbers of mergers.

Counter-Argument:

1. This hypothesis does not determine the ratio of $M_{SMBH}/M_{bulge}$

2. This doesn't simultaneously explain both $M_{SMBH}$-$M_{bulge}$ and $M_{SMBH}$-σ

3. It would be incredible coincidence that this "chance" collision process produces the same $M_{SMBH}$-σ relation needed to balance the weight of the bulge gas

# Summarizing Wind-Momentum Driving Effects ~ Small Scale

1. Super-solar elemental abundances in observed AGN spectra

2. Dark matter cusp removal

3. Quiescence of AGN hosts

# Summarizing Wind-Energy Driving Effects ~ Large Scale

1. Metals in the circumgalactic medium
2. Mechanical luminosities of galaxy-scale molecular outflows
3. Suppression of cosmological infall

# Closing Remarks

Remaining Question at Hand:

What mechanism can produce such a ready supply of gas with very small angular momentum, such that it can accrete onto the central SMBH fast enough for it to grow relatively quickly?

→ Not gravity

→ Perhaps feedback from SMBH can cause this?