AGN Feedback

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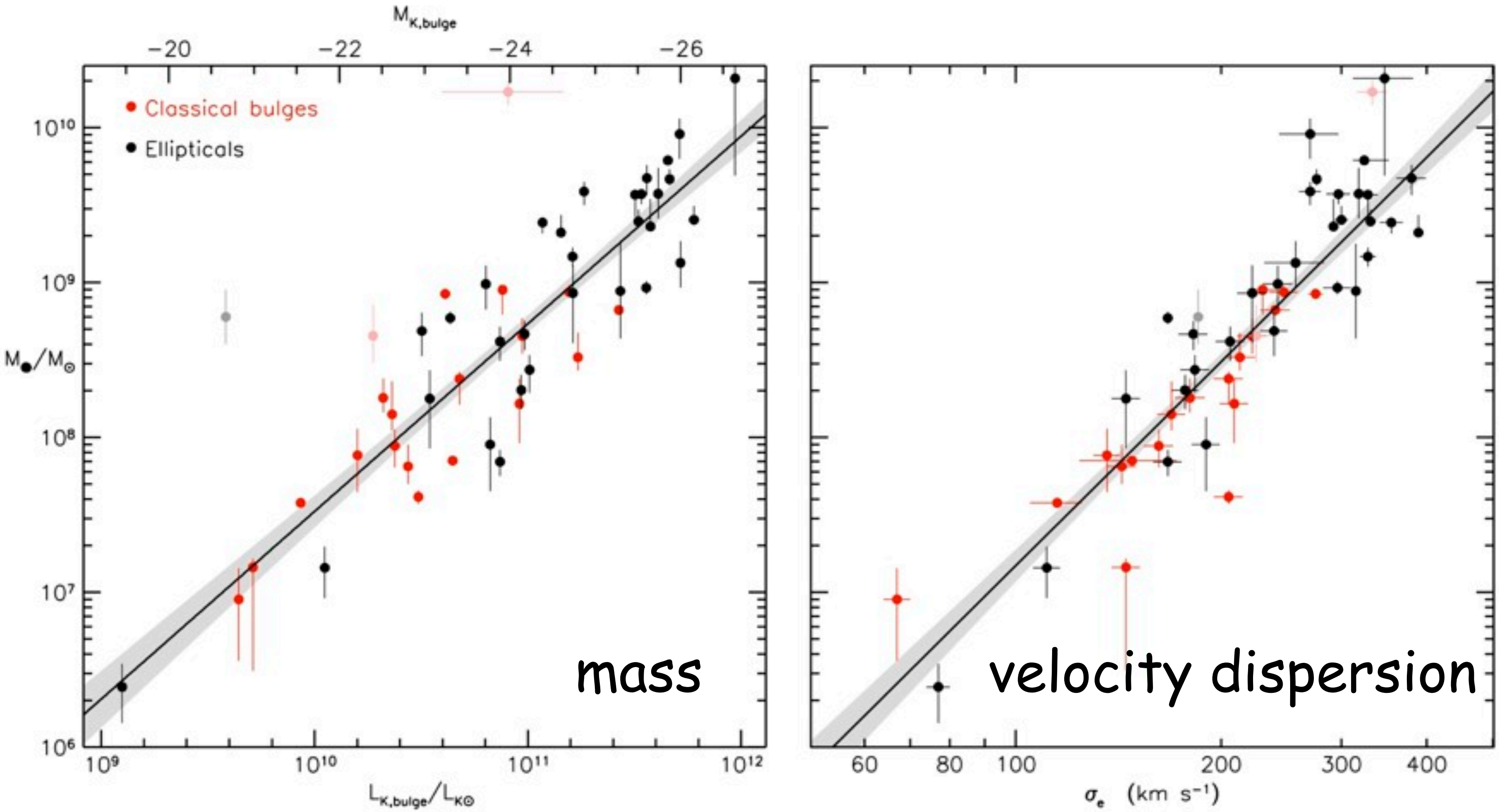
galaxy knows about central SMBH



galaxy bulge →

Kormendy & Ho, 2013

how?

SMBH mass is completely insignificant: $M \sim 10^{-3} M_{\rm bulge}$,

so its gravity affects only a region

$$R_{\rm inf} = \frac{GM}{\sigma^2} \sim 10 \frac{M_8}{\sigma_{200}^2} \text{ parsec}$$

$$\left(M_8 = M/10^8 M_\odot \ , \ \sigma_{200} = \sigma/200 \ {\rm km\,s^{-1}}\right)$$

- far smaller than bulge

why does the galaxy notice the hole?

well....

SMBH releases accretion energy $\sim 0.1 M_{BH} c^2 \sim 10^{61}$ erg
galaxy bulge binding energy $M_b \sigma^2 \sim 10^{58}$ erg

galaxy notices hole through energy release:

`feedback'

SMBH – host connection

SMBH in every large galaxy (Soltan)

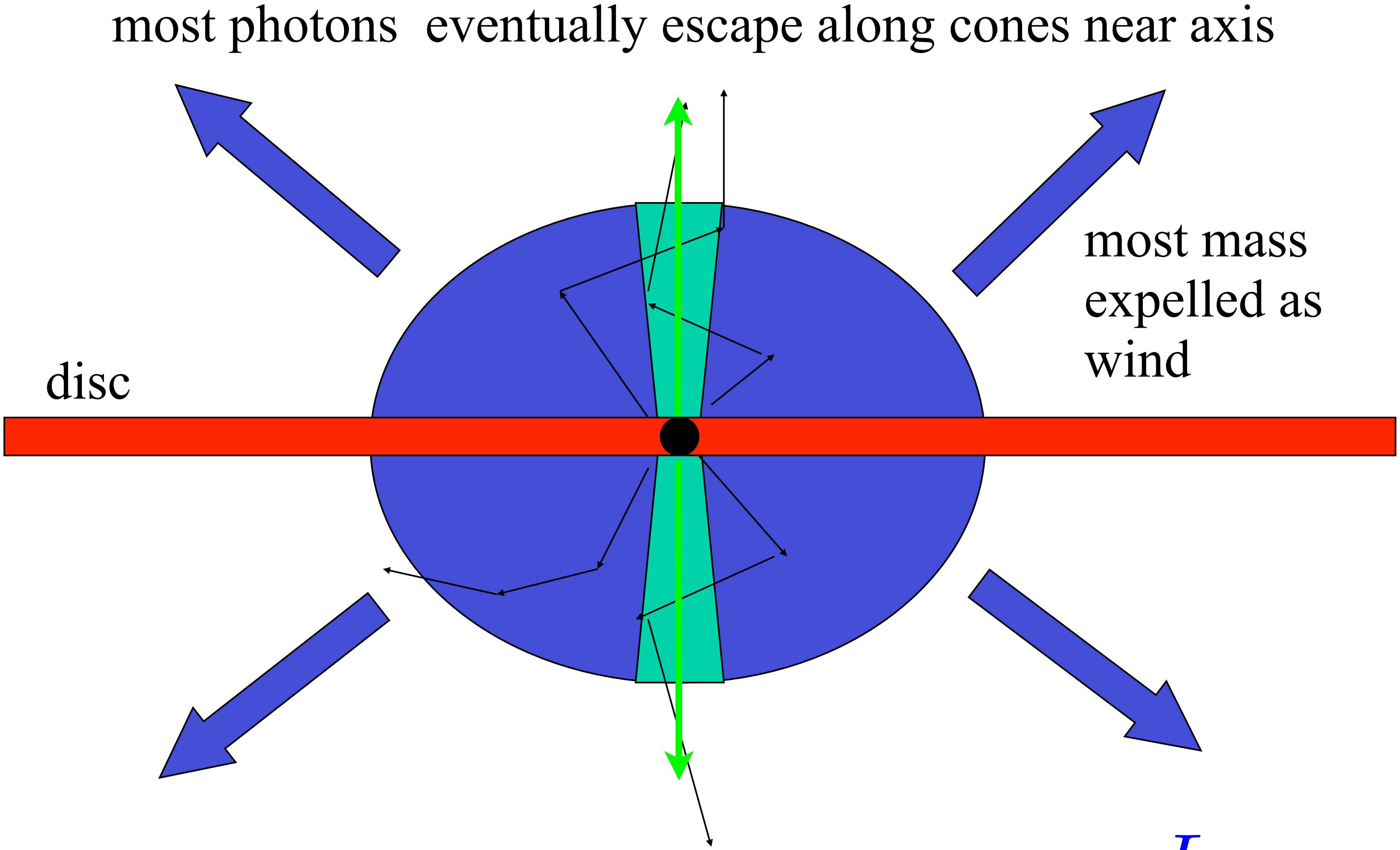
but only a small fraction of galaxies are AGN

➔ SMBH grow at Eddington rate in AGN

$$\eta c^2 \dot{M} = L = L_{\rm Edd} = \frac{4\pi G M c}{\kappa} \quad , \kappa = \text{electron scattering opacity}$$

➔ *AGN should produce Eddington winds*

Super-Eddington Accretion



on average photons give up all
momentum to outflow after ~ 1 scattering

$$\dot{M}v = \frac{L_{\rm Edd}}{c}$$

Eddington winds

momentum outflow rate

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

speed

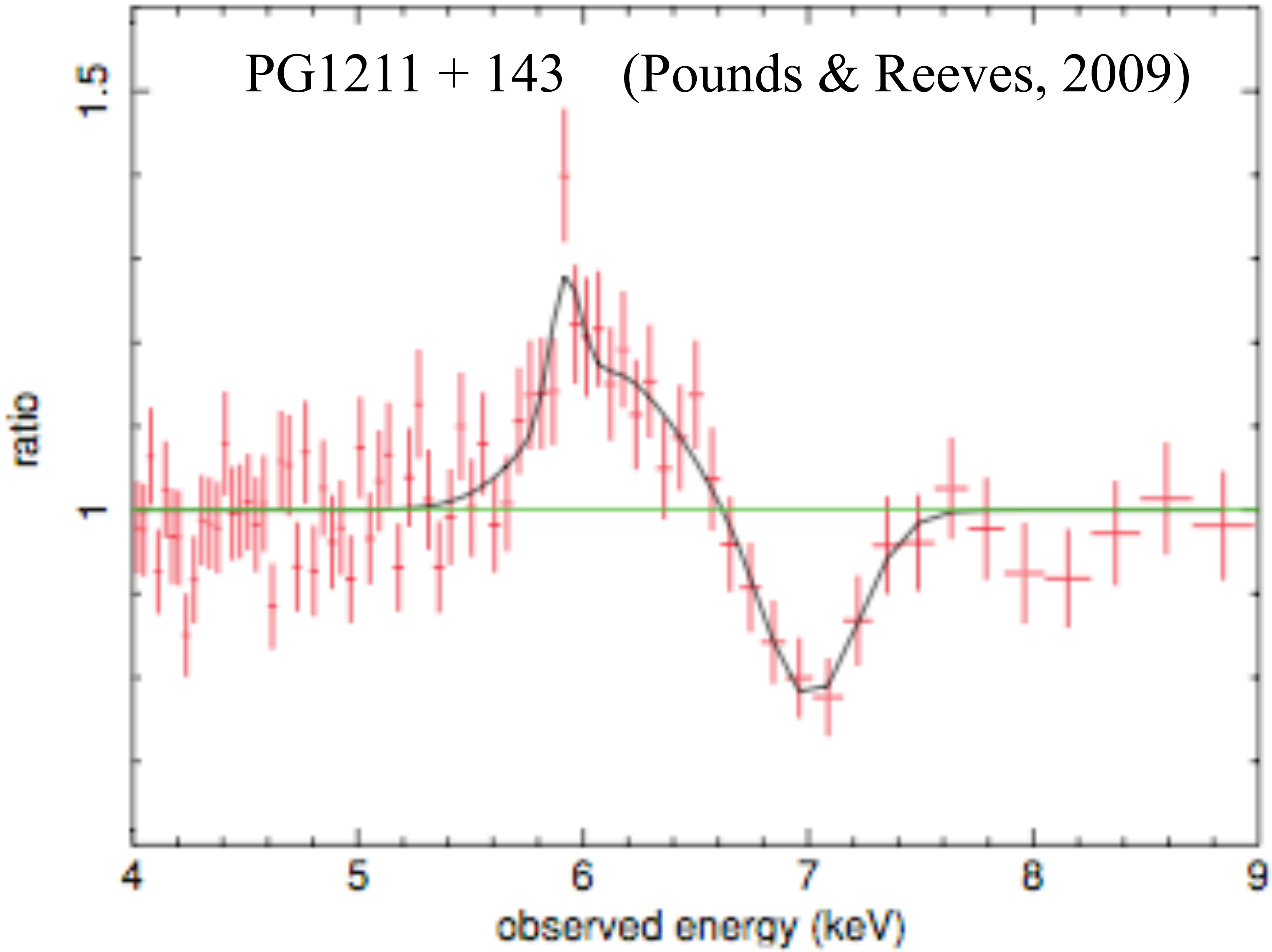
$$v = \frac{\eta c}{\dot{m}} \sim 0.1c$$

where $\dot{m} = \dot{M}_{\rm out}/\dot{M}_{\rm Edd} \sim 1$

energy outflow rate

$$\frac{1}{2}\dot{M}_{\rm out} v^2 = \frac{\eta}{2}.\eta c^2 \dot{M}_{\rm out} = \frac{\eta}{2} L_{\rm Edd} \simeq 0.05 L_{\rm Edd}$$

(King & Pounds, 2003: cf later cosmological simulations)



P Cygni profile of iron K- alpha: *wind* with $v \simeq 0.1c$

`ultrafast outflow' -- `UFO'

outflow affects galaxy bulge

SMBH releases accretion energy $\sim 0.1 M_{BH} c^2 \sim 10^{61}$ erg
galaxy bulge binding energy $M_b \sigma^2 \sim 10^{58}$ erg

even though only a fraction $(\eta/2) \simeq 0.05$ *of accretion energy is in mechanical form, this is more than enough energy to unbind the bulge*

how does the bulge survive?

wind shock

wind must collide with bulge gas, and shock – what happens?

either

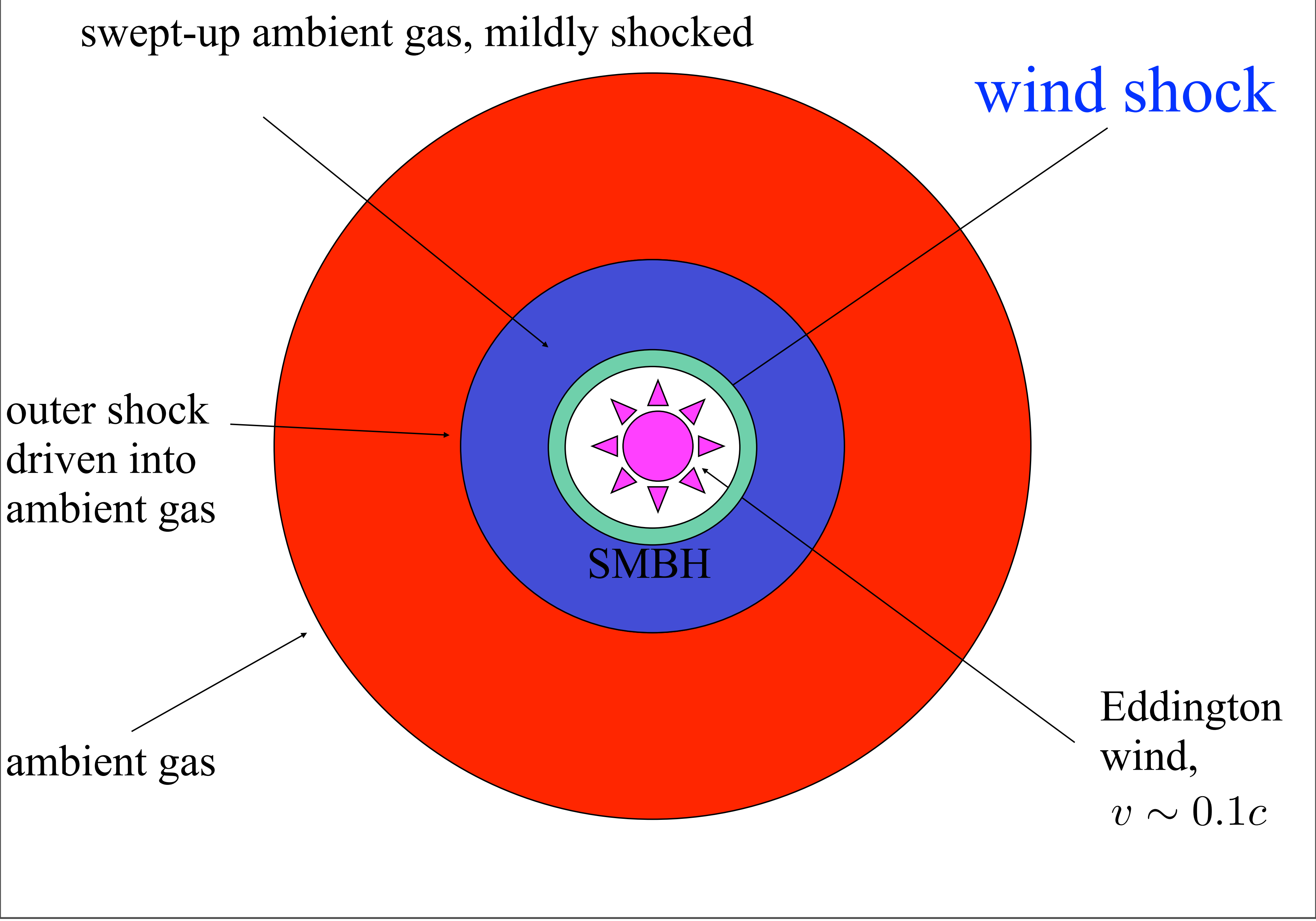
(a) shocked gas cools: `momentum–driven flow'
negligible thermal pressure -
most energy lost

or

(b) shocked gas does not cool: `energy–driven flow'
thermal pressure > ram pressure

Compton cooling by quasar radiation field very effective out to cooling radius $R_C \sim 50 - 500$ pc (cf Ciotti & Ostriker, 1997, 2001)

initial expansion into bulge gas is driven by momentum $\dfrac{L_{\rm Edd}}{c}$ only



swept-up ambient gas, mildly shocked
wind shock
outer shock driven into ambient gas
SMBH
ambient gas
Eddington wind, $v \sim 0.1c$

motion of swept-up shell

total mass (dark, stars, gas) inside radius R of unperturbed bulge is

$$M_{\rm tot}(R) = \frac{2\sigma^2 R}{G}$$

but swept-up gas mass $M(R) = \dfrac{2 f_g \sigma^2 R}{G}$

forces on shell are gravity of mass within R , and wind ram pressure:

since gas fraction f_g is small, gravitating mass inside R is $\simeq M_{\rm tot}(R)$: equation of motion of shell is

$$\frac{{\rm d}}{{\rm d}t}[M(R)\dot{R}] + \frac{GM(R)[M + M_{\rm tot}(R)]}{R^2} = 4\pi R^2 \rho v^2 = \dot{M}_{\rm out} v = \frac{L_{\rm Edd}}{c}$$

where M is the black hole mass

using $M(R), M_{\mathrm{tot}}(R)$ this reduces to

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

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

integrate equation of motion by multiplying through by $R\dot{R}$: then

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

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if $M < M_\sigma$, no solution at large R (rhs < 0)

Eddington thrust too small to lift swept-up shell using $M(R), M_{\rm tot}(R)$ this reduces to

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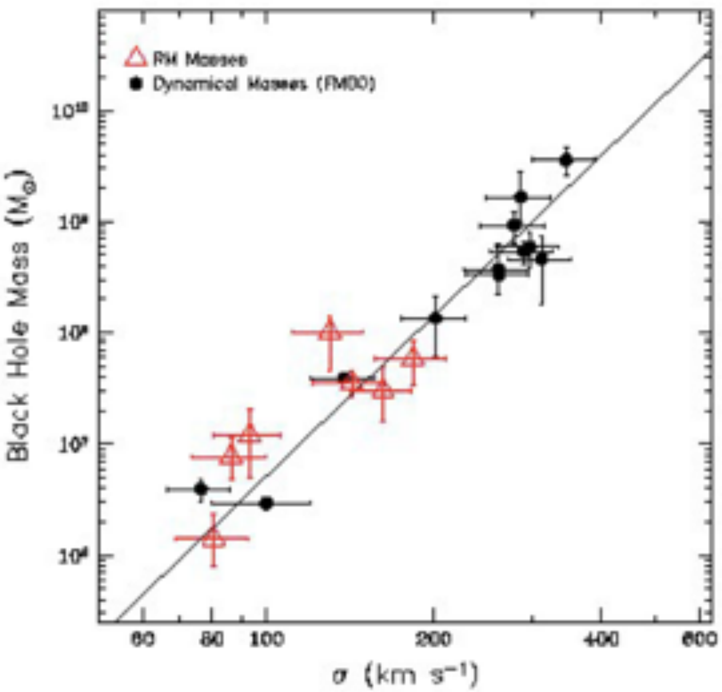
Eddington thrust too small to lift swept-up shell

but if $M > M_\sigma$, $\dot{R}^2 \to 2\sigma^2$, and shell can be expelled completely critical value

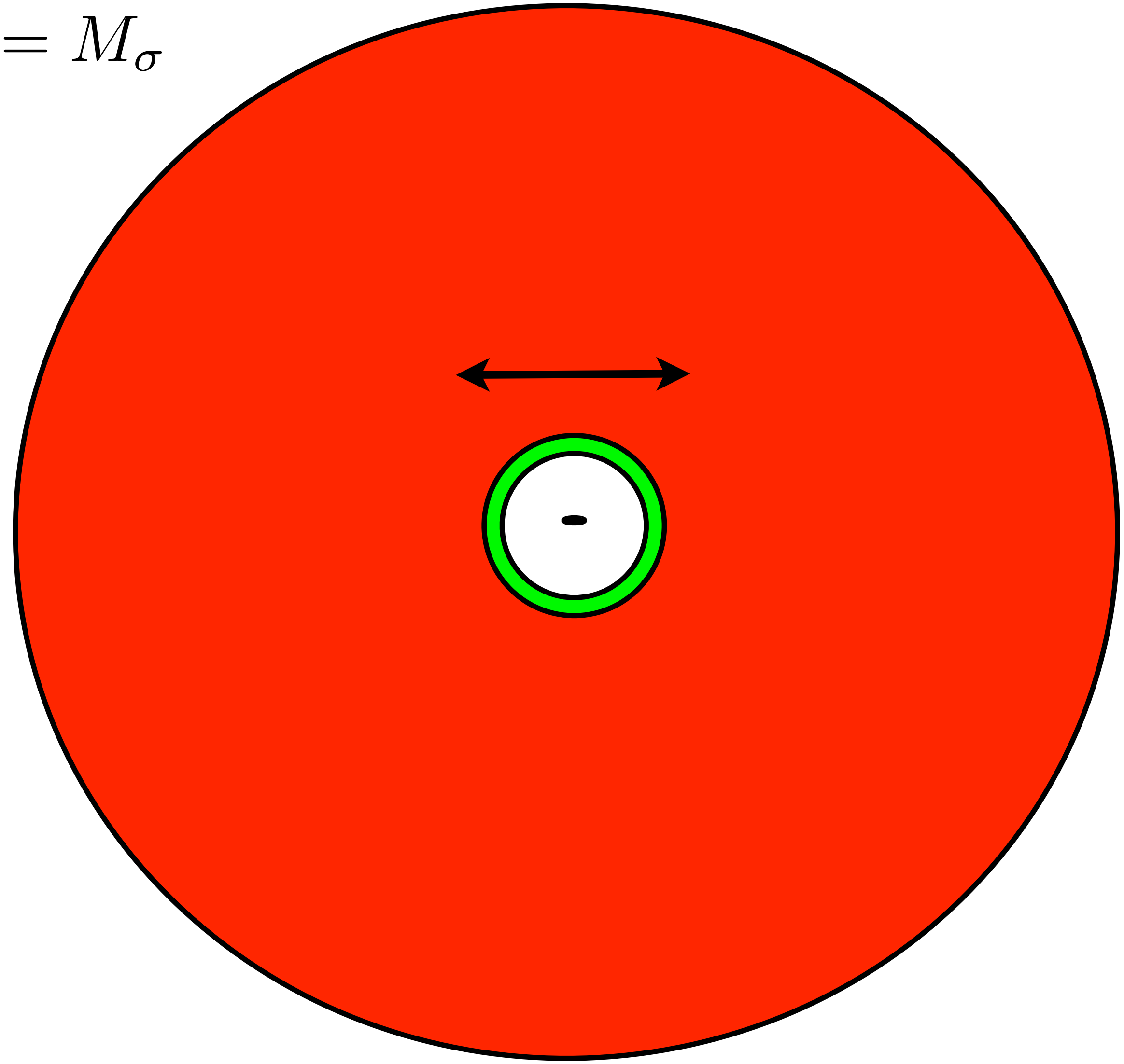
$$M_\sigma = \frac{f_g \kappa}{\pi G^2}\sigma^4 \simeq 2 \times 10^8 M_\odot \sigma_{200}^4$$

remarkably close to observed $M - \sigma$ relation despite effectively no free parameter $(f_g \sim 0.1)$ (King, 2003; 2005)



SMBH mass grows until Eddington thrust expels gas feeding it

shells confined to vicinity
of BH until $M = M_\sigma$



$$R \lesssim R_{\rm inf} \sim {\rm few} \times \frac{GM}{\sigma^2} \sim 10 - 50\sigma_{200}^2 \ {\rm pc}$$

transition to energy-driven flow once M_σ reached

close to quasar shocked gas cooled by inverse Compton effect (momentum-driven flow)

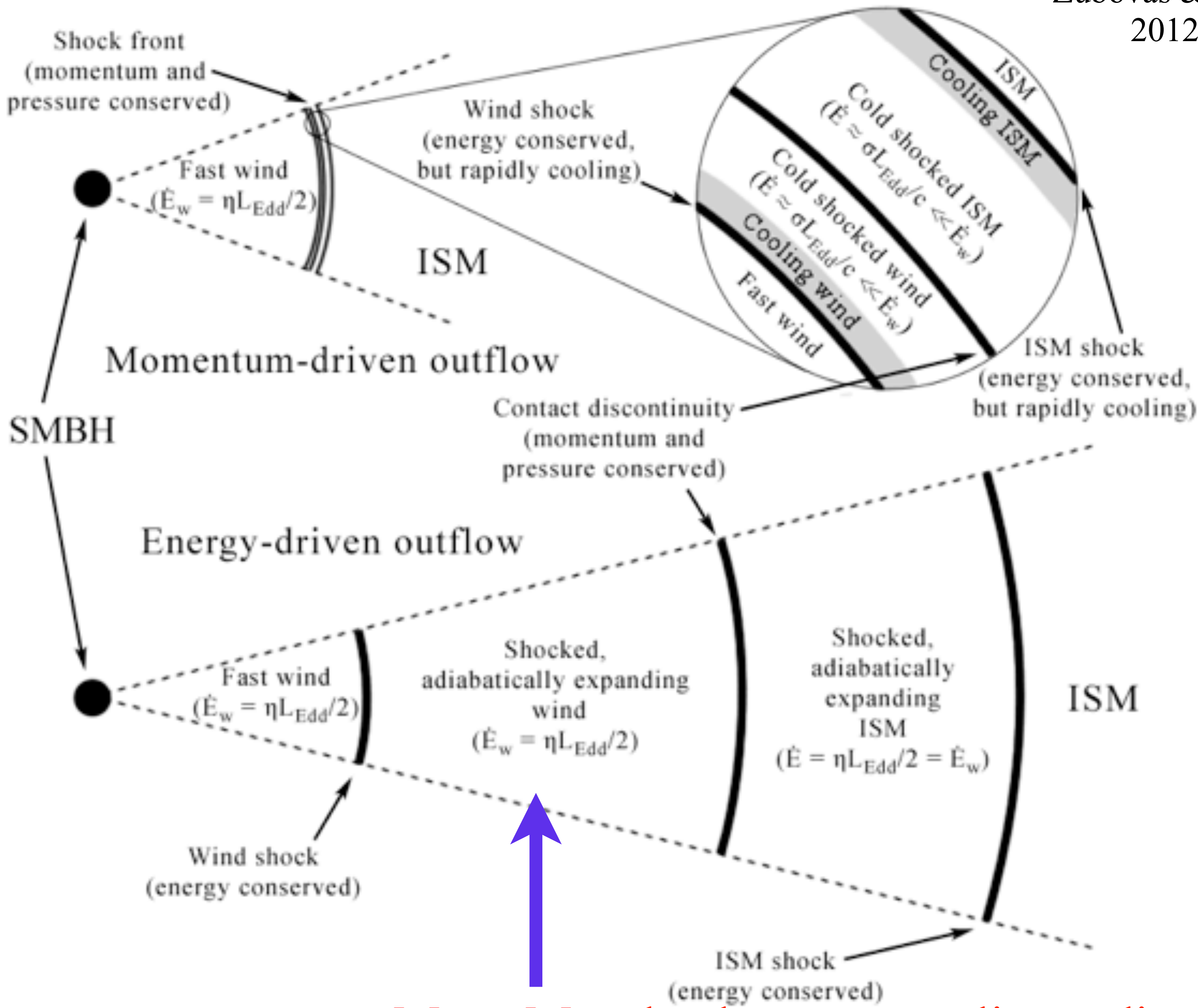
but once $M > M_\sigma$, R can exceed R_C: wind shock no longer cools

wind shock is adiabatic: hot postshock gas does PdV work on surroundings

bulge gas driven out at high speed

$$v_e = \left[\frac{2\eta\sigma^2 c}{3f_g}\right]^{1/3} \simeq 1000\sigma_{200}^{2/3}\ \mathrm{km\,s^{-1}}$$

Zubovas & King, 2012a



once BH grows to $M > M_\sigma$, shock passes cooling radius
=> large-scale energy-driven flow

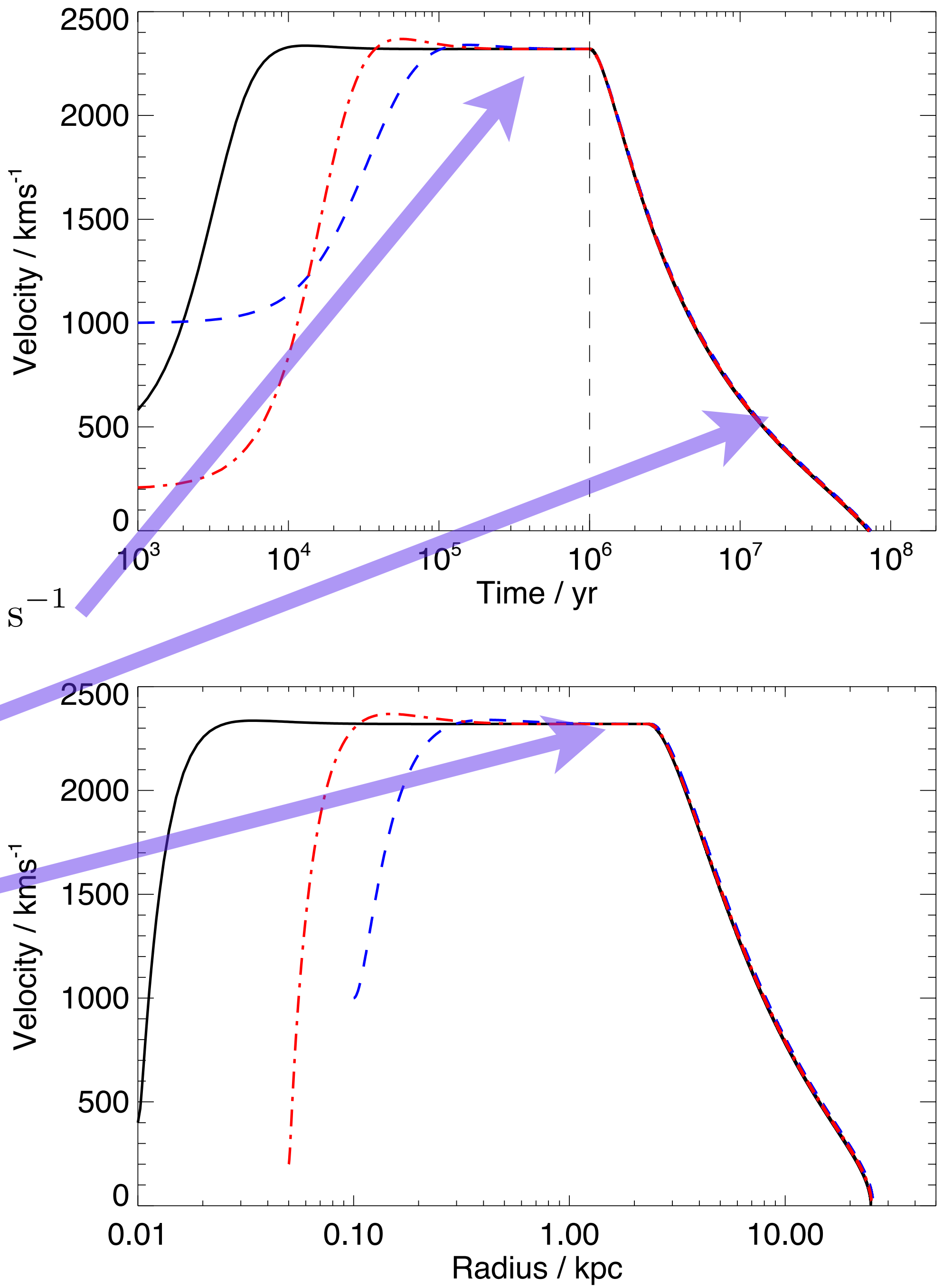
energy--driven outflows rapidly converge to

$$v_e \simeq \left[\frac{2\eta f_c}{3 f_g}\sigma^2 c\right]^{1/3} \simeq 925\sigma_{200}^{2/3}(f_c/f_g)^{1/3} \text{ km s}^{-1}$$

and persist even after central quasar turns off

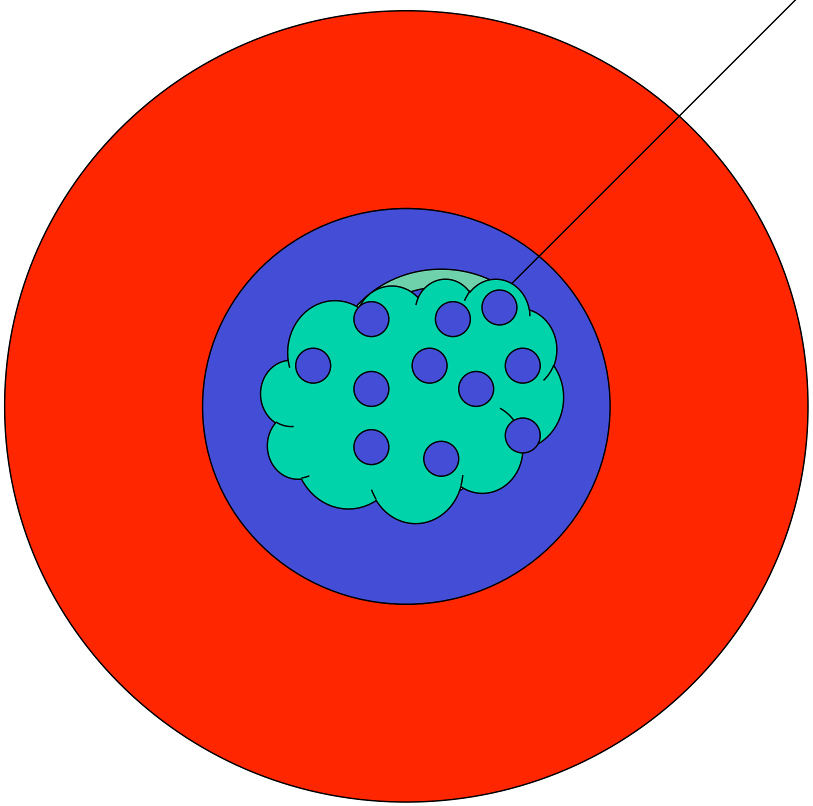
high velocity outflow at large radius

also for other potentials: Zubovas & King, 2012b



density contrast => energy-driven outflow

shock may be *Rayleigh-Taylor unstable*



two—phase medium: gamma—rays and molecular emission mixed

large--scale high speed molecular outflows, e.g. Mrk 231:

galaxy bulge should produce gamma-ray emission outer shock runs ahead of contact discontinuity into ambient ISM: velocity jump across it is a factor $(\gamma + 1)/(\gamma - 1)$: fixes velocity as

$$v_{\rm out} = \frac{\gamma + 1}{2}\dot{R} \simeq 1230\sigma_{200}^{2/3}\left(\frac{lf_c}{f_g}\right)^{1/3} \ \mathrm{km\ s^{-1}}$$

and radius as

$$R_{\rm out} = \frac{\gamma + 1}{2}R$$

outflow rate of shocked interstellar gas is

$$\dot{M}_{\rm out} = \frac{{\rm d}M(R_{\rm out})}{{\rm d}t} = \frac{(\gamma + 1)f_{\rm g}\sigma^2}{G}\dot{R}$$

$$\dot{M}_{\rm out} \simeq 3700\sigma_{200}^{8/3}l^{1/3} \ M_\odot\,{\rm yr}^{-1}$$

Mrk 231 – OH Outflow

terminal velocity (obs): ~1.100 km/s

R_{out} (model) ~1.0 kpc

outflow rate (dM/dt): ~1.200 $M_\odot$/yr

SFR: ~100 $M_\odot$/yr

gas mass (from CO): 4.2 x 10^9 $M_\odot$

depletion time scale ($M_{gas}/\dot{M}$): ~4 x 10^6 yr

mechanical energy: ≥ 10^{56} ergs

$$T = \frac{1}{2} M_{\mathrm{gas}} v^2$$

mechanical luminosity: ≥ 1% L_{IR}

$$P = \frac{T}{t_{\mathrm{dyn}}}$$

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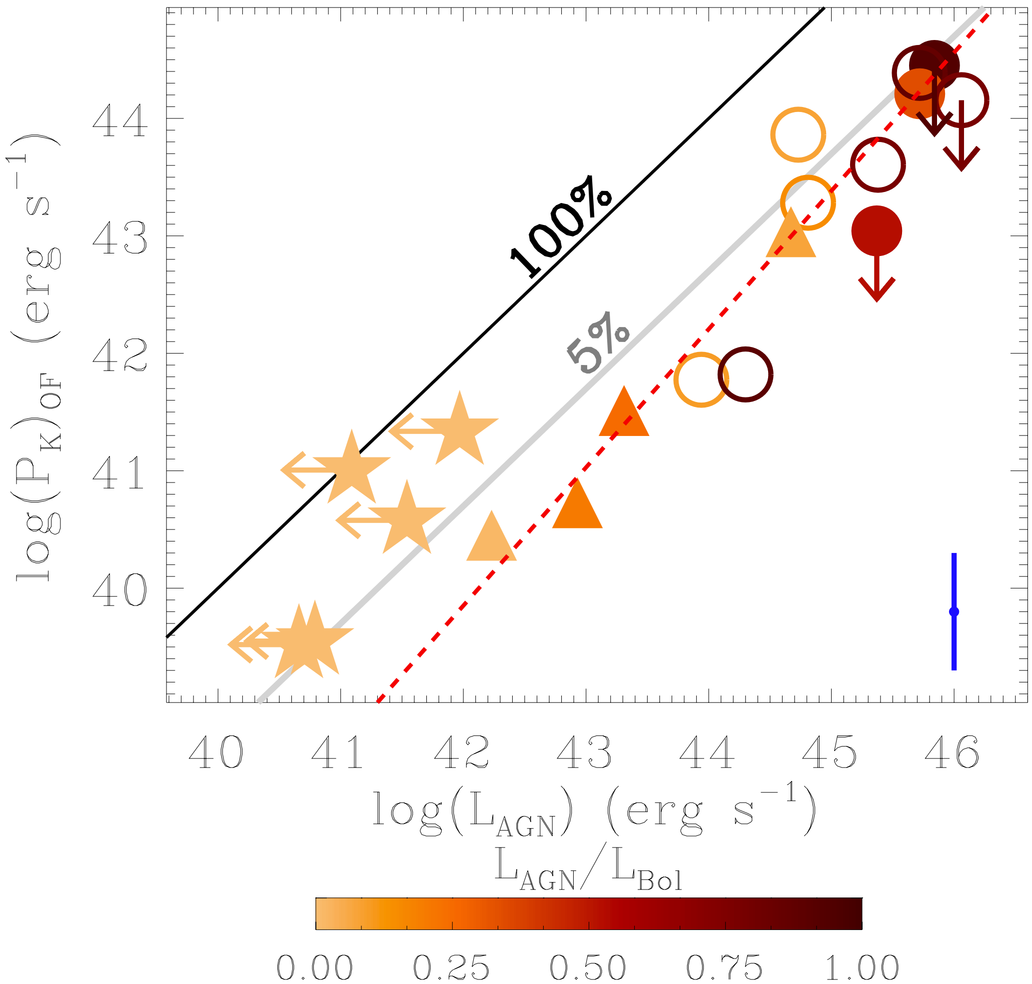
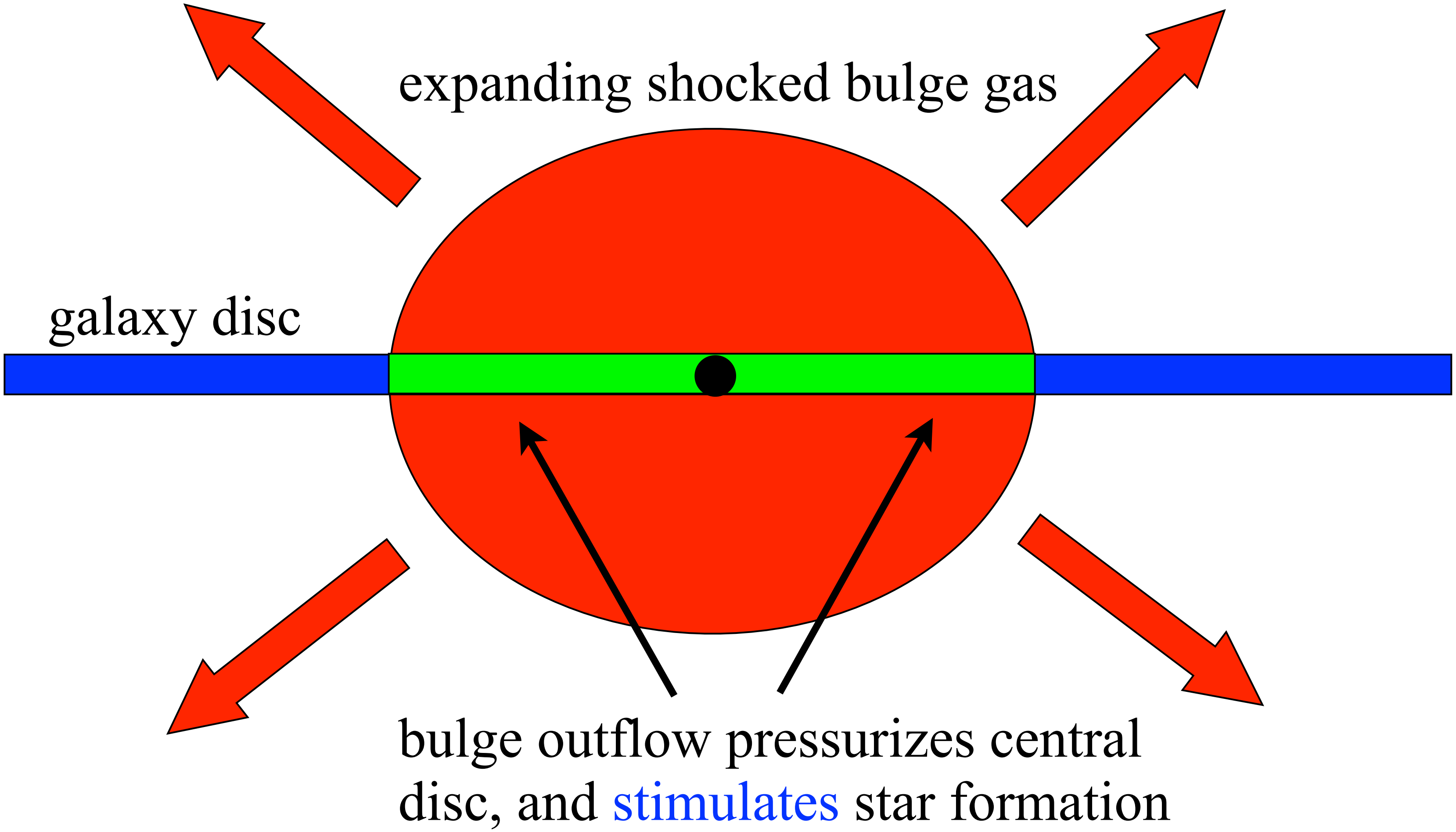


Maiolino et al., 2013

Fig. 12. Correlation between the kinetic power of the outflow and the AGN bolometric luminosity. Symbols and colour-coding as in Fig. 8. The grey line represents the theoretical expectation of models of AGN feedback, for which $P_{K,OF} = 5\% L_{AGN}$. The red dashed line represents the linear fit to our data, excluding the upper limits. The error bar shown at the bottom-right of the plot corresponds to an average error of ±0.5 dex.

spirals: bulge outflow pressure => disc star formation



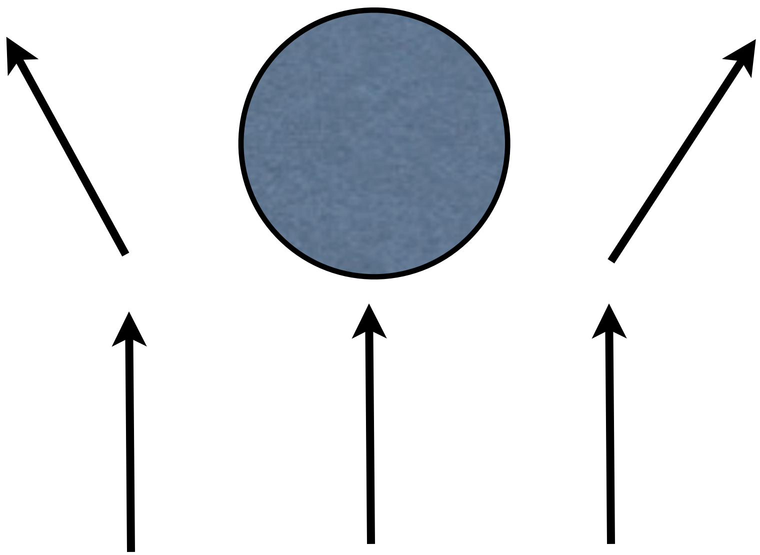
bulge quenched, disc briefly fired up?

inhomogeneous ISM?

if ISM is patchy, of two-temperature effects important, not obvious that wind shocks always cool

could outflows be energy-driven at all radii? (Faucher-Giguere & Quataert, 2012, Bourne & Nayakshin 2013, 2014)

if most of mass in dense blobs, these feel only *drag* of wind

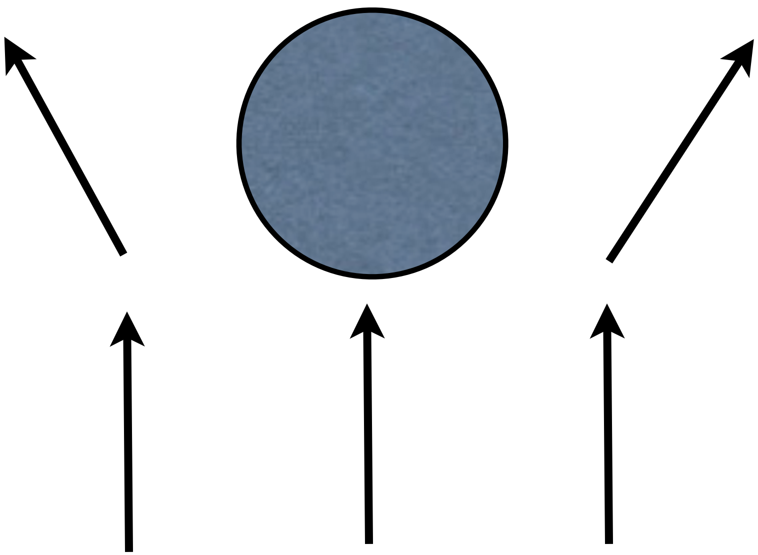


inhomogeneous ISM?

if most of mass in dense blobs, these feel only *drag* of wind

in simple cases this is dimensionally ~ ram pressure - maybe M-sigma OK?

but not obvious -- e.g. D’Alembert’s paradox -- no drag on smooth objects



inhomogeneous ISM?

calculation of drag => boundary layer; unstable, numerically difficult

instabilities producing blobs also numerically difficult

two-fluid effects on Compton cooling also difficult!

but *observational distinction* is clear:

momentum-driven = small-scale

energy-driven = large-scale

evidence for localised behaviour?

1. super--solar QSO abundances
same gas swept up, turned into stars, recycled => enrichment in very centre of galaxy

2. removal of DM cusps: repeated small--scale (momentum-driven) outflow and fallback very effective (cf Pontzen & Governato 2012, who used SNe (less mass, less effective)

3. inner parts of most galaxy discs do not show enhanced star formation => no energy-driven outflow most of the time

4. metals produced by stellar evolution in galaxy eventually expelled to large radii by energy--driven outflow -- CGM

SMBH feedback: summary

AGN have Eddington winds, $\dot{M}v = L_{\rm Edd}/c$, $v \sim 0.1c$

Compton cooling by AGN radiation field effective out to $R_C \lesssim 0.5$ kpc

resulting momentum-driven flow establishes $M - \sigma$ relation

once $M > M_\sigma$ shock passes R_C and flow become energy-driven,
with $v \sim 1000\ {\rm km\,s^{-1}}$ and $\dot{M}_{\rm out} \sim$ few $1000{\rm M_\odot\,yr^{-1}}$(molecular)

galaxy bulge becomes `red and dead', but can stimulate disc SF

$M - \sigma$ divides localised from global behaviour:
super-solar abundances in AGN, removal of DM cusps (local)
metal pollution of CGM (local to global)

for more details see King & Pounds, ARAA, 2015