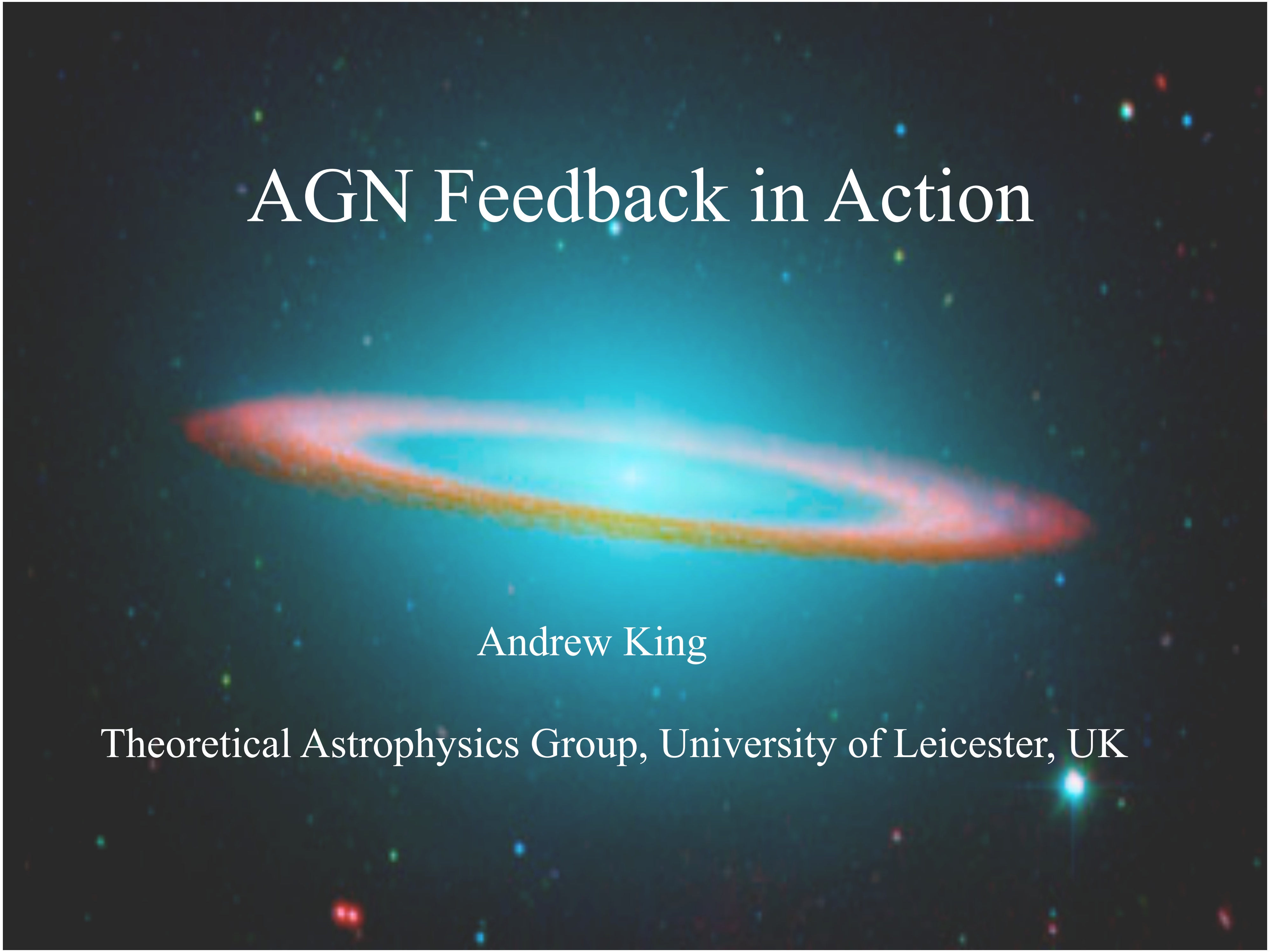

AGN Feedback in Action

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SMBH – host connection

SMBH in every large galaxy, grown by luminous accretion (Soltan)

but only a small fraction of galaxies are AGN

➔ *SMBH should grow at ~ Eddington rate in AGN*

AGN should show outflows

AGN black holes should be underweight

how super—Eddington can AGN be?

galaxy bulge ~ isothermal sphere, with mass distribution

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

maximum possible accretion rate: this mass falls in dynamical time

$$t_{\rm dyn} \sim \frac{R}{\sigma}$$

so

$$\dot M_{\rm max} \sim \frac{f_g \sigma^3}{G} \sim 100 \sigma_{200}^3 \ M_\odot \ {\rm yr}^{-1}$$

Eddington rate at $M-\sigma$ mass is

$$\dot{M}_{\rm Edd} = 3\sigma_{200}^{4}\eta_{0.1}^{-1}M_{\odot}\ {\rm yr}^{-1}$$

so Eddington ratio m is modest

$$\dot{m} = \frac{\dot{M}_{\rm out}}{\dot{M}_{\rm Edd}} << 30\frac{\eta_{0.1}}{\sigma_{200}}$$

i.e. we expect $\dot{m} \sim 1$

AGN are never *very* super--Eddington

nature of outflows

outflow has optical depth ~ 1, ➔ outflow momentum is
of order photon momentum: `single scattering limit'

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

[NB: this condition does *not* constitute `momentum—driven' flow!]

thus

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

momentum conservation, modest optical depth ➔ $v \sim 0.1c$

NB: $v \sim 0.1c$ implies large–scale outflow can continue
long after quasar has turned off!

mass conservation equation

$$\dot{M}_{\rm out} = 4\pi b N R^2 m_p v$$

implies ionization parameter

$$\xi = \frac{L_i}{NR^2} = 3 \times 10^4 \eta_{0.1}^2 \left(\frac{l_i}{10^{-2}}\right) \dot{m}^{-2}$$

where L_i = ionizing luminosity, and $l_i = L_i/L$

for a given quasar spectrum, ionizing component l_i must correspond to photon energy implied by ξ

mass conservation ➔ *X—ray lines*

momentum conservation ➔ *lines blueshifted by v ~ 0.1c*

cf observed X—ray outflows: ~ 50 now known

connection between conservation laws and flow speed, ionization works in both directions, i.e.

X—ray lines with $v \sim 0.1c \longleftrightarrow$ Eddington outflow

(unless solid angle of flow << 1)

outflow shock

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

either

(a) shocked gas cools: *this* is `momentum–driven flow'

negligible thermal pressure

or

(b) shocked gas does not cool: `energy–driven flow'

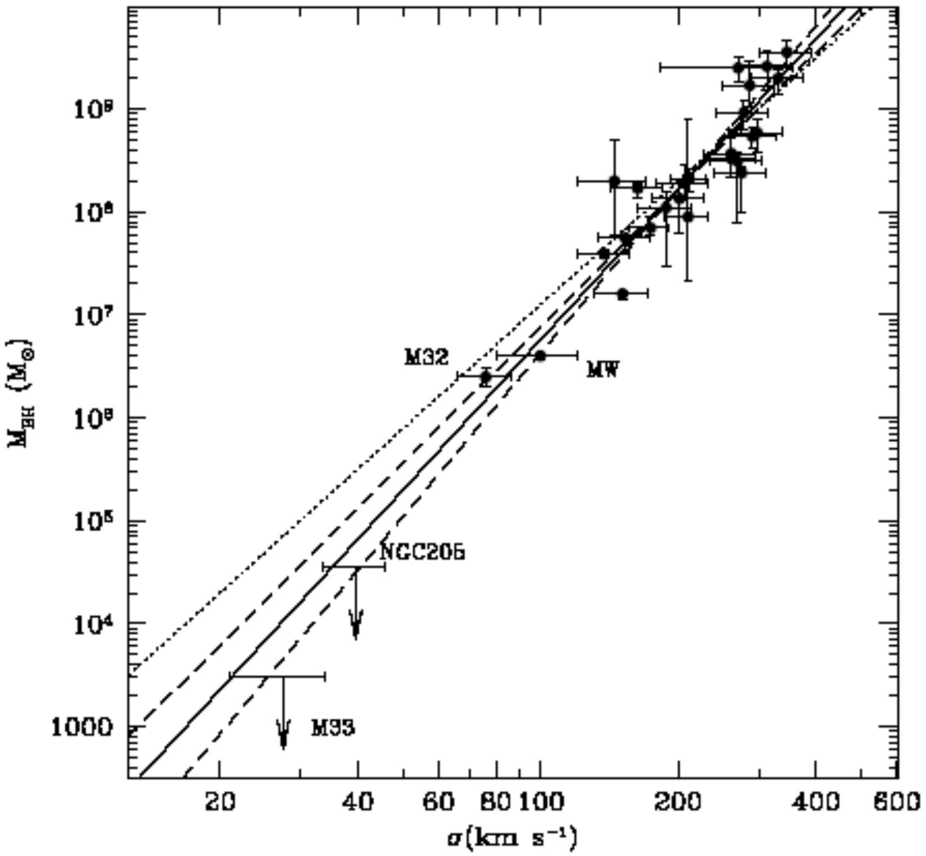
thermal pressure > ram pressure

Compton cooling by quasar radiation field very effective out to bulge radius ~ 1 kpc (cf Ciotti & Ostriker, 1997, 2001)

outflow is momentum-driven inside this radius ➔

$$\boxed{M_{\rm BH} - \sigma \ \text{relation (King, 2003, 2005)}}$$

but energy-driven outside ➔ *sweeps bulge clear of gas*



$$M = 2\times 10^{8}\sigma_{200}^{4} M_{\Theta}$$

need to resolve SMBH sphere of influence $R_{\mathrm{inf}} = 2GM/\sigma^2$

➔relation is *upper limit* to M for given σ (Bacheldor, 2010)

AGN black holes should be below this limit

M – sigma relation

(simple derivation)

matter originally distributed so that

$$\frac{GM_{tot}(R)}{R} = 2\sigma^2$$

with

$$\frac{GM_{gas}(R)}{R} = 2 f_g \sigma^2 \qquad (f_g \approx 0.16)$$

at radius R total *weight* of shell is

$$\frac{GM_{tot}M_{gas}}{R^2} = \frac{4f_g\sigma^4}{G}$$

BH mass grows until Eddington thrust $\frac{L_{\rm Edd}}{c}$ supports this weight, i.e.

$$\frac{4\pi GM_{BH}}{\kappa} = \frac{4f_g\sigma^4}{G}$$

or

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

(King, 2003; 2005)

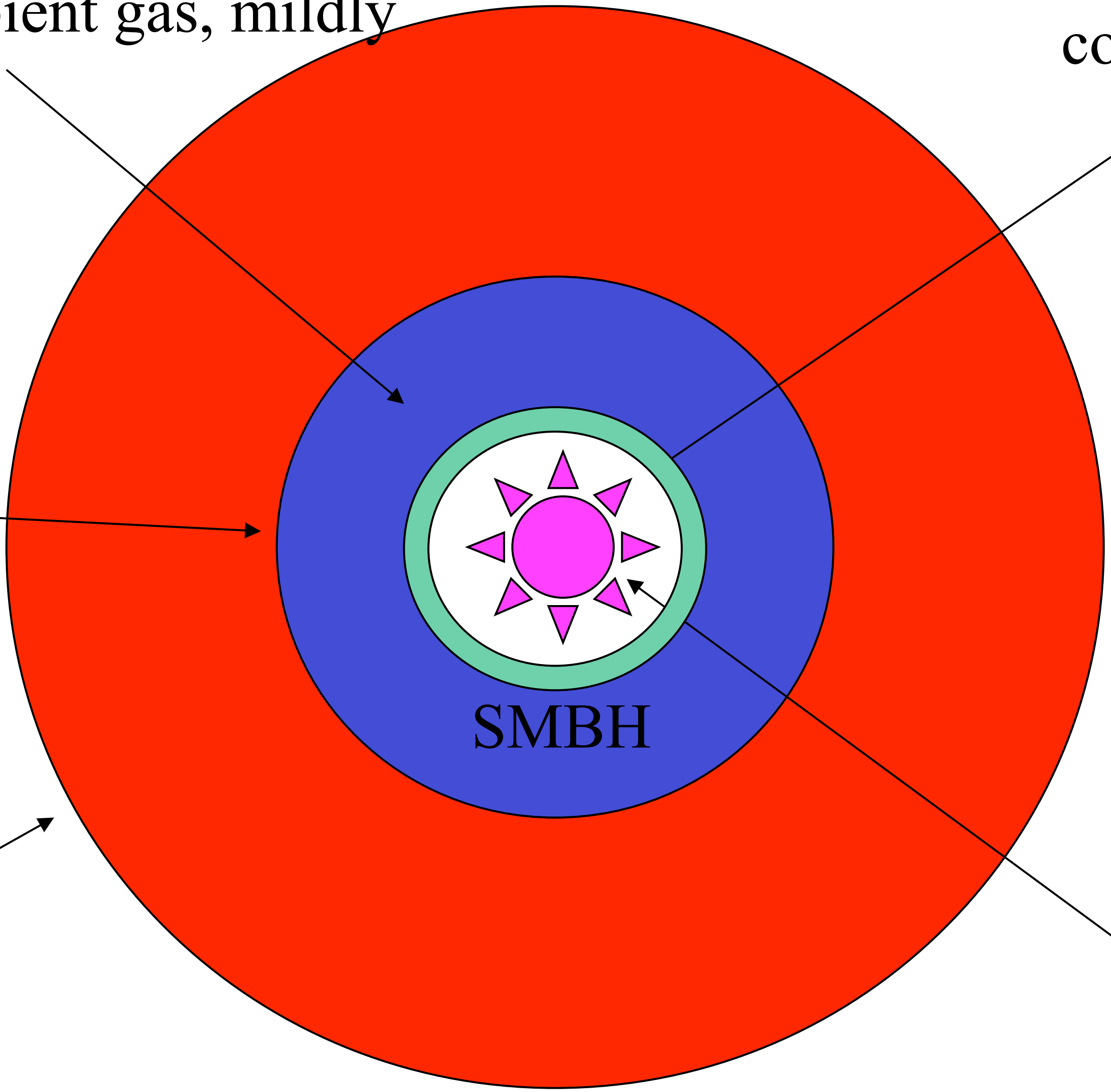
NB: *no free parameter*

total energy communicated to bulge gas to produce
M – sigma relation is just kinetic energy

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

same fraction 0.05 found empirically in cosmological simulations

shock pattern near AGN



swept-up ambient gas, mildly shocked

cooling shocked wind (`momentum – driven’)

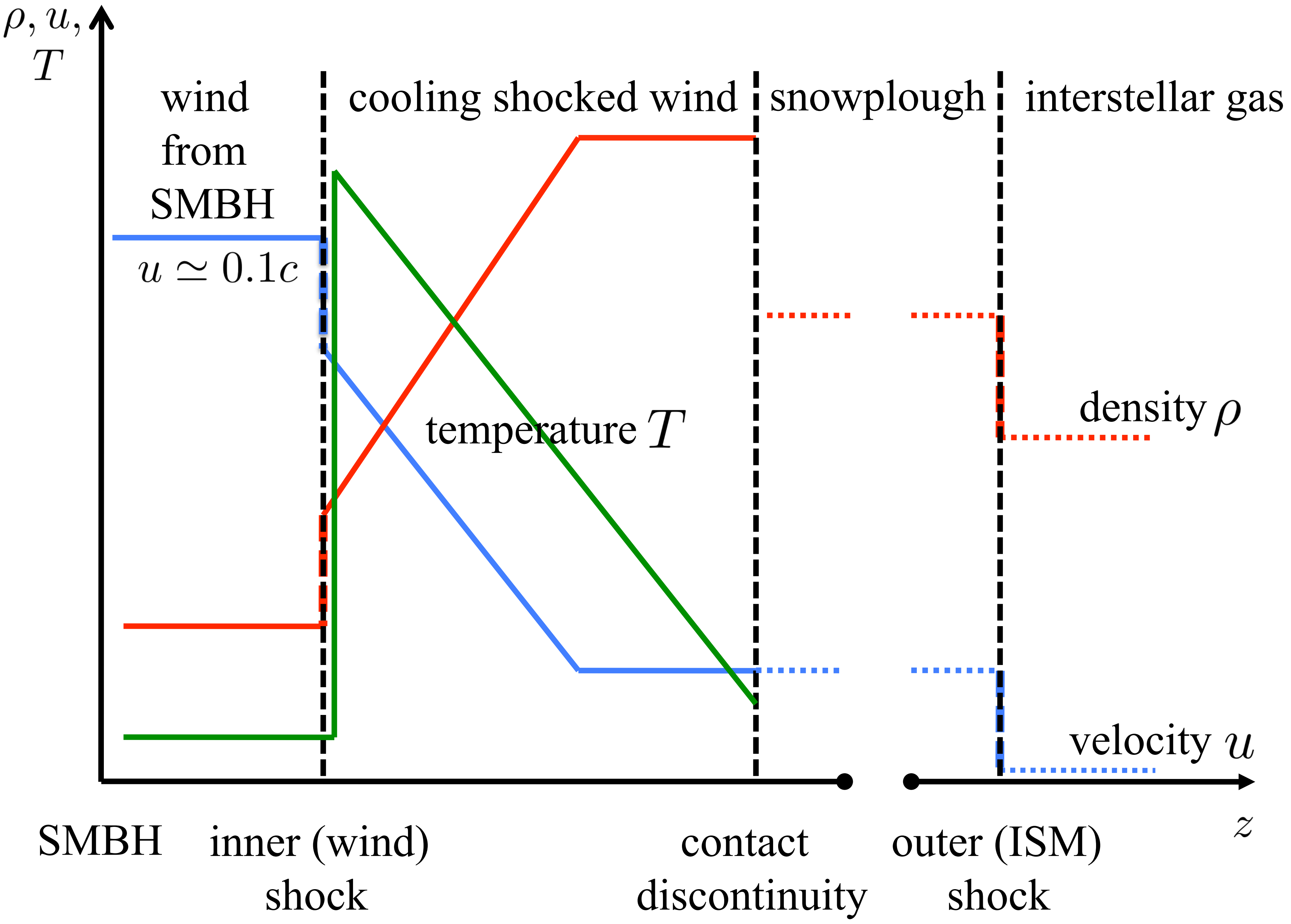
outer shock driven into ambient gas

SMBH

ambient gas

Eddington wind, $v \sim 0.1c$

(single scattering limit)


$\rho, u,$
T
wind
from
SMBH
$u \simeq 0.1c$
cooling shocked wind
snowplough
interstellar gas
temperature T
density ρ
velocity u
SMBH
inner (wind)
shock
contact
discontinuity
outer (ISM)
shock
z

evidence for cooling shock

ionization parameter decreases with outflow velocity as required by mass conservation

$$\dot{M}_{\rm out} \propto \frac{L_i v}{\xi} = {\rm const}$$

NGC4051: 10x decrease in *v*, seen in 14 species (Pounds et al.), correlates with ionization

cf talk by Mat Page

NB: many BH masses estimates use $M - \sigma$

-- tendency to *overestimate* mass and *underestimate* Eddington factor

frequency of Eddington outflows

Tombesi et al 2010 a, b:

22/42 radio—quiet AGN, 3/5 BLRGs show outflows with

$$v \sim 0.1c - 0.3c, \quad \xi \sim 10^4$$

and hence $\dot{M}_{\rm out} \sim 1 - 10 M_{\odot}\,{\rm yr}^{-1}$, with very large momentum rates

high frequency ➔ solid angles large, $b \sim 0.5 - 1$: $\sim$ 50% of sample have super—Eddington episodes with significant duty cycles

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SMBH do grow at ~ Eddington rate in AGN

AGN do show outflows

AGN black holes may be underweight

aside: energy—driven flows?

in *energy—driven* flows (e.g. Silk & Rees, 1998) must equate rate of working vs gravity, i.e.

$$\frac{GM_{\rm tot}M_{\rm gas}}{R^2}\sigma$$

to Eddington *luminosity*, so

$$M_{\rm BH} = \frac{f_g\kappa}{\pi G^2 c}\sigma^5$$

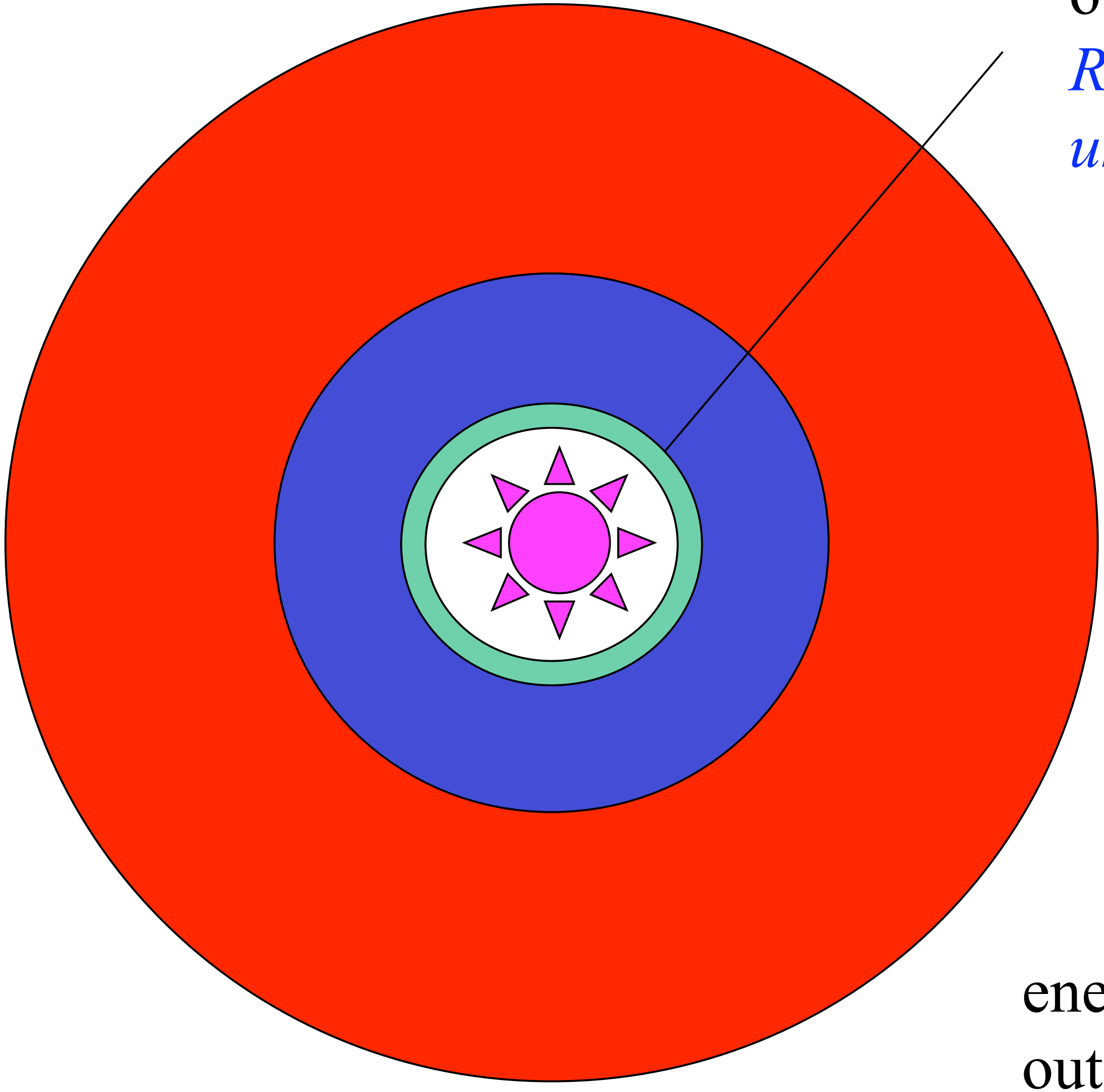
and

$$M_{\rm BH}({\rm energy}) = \frac{\sigma}{c}M_{\rm BH}({\rm momentum}) \simeq 1.3\times 10^5 M_{\odot}\sigma_{200}^5$$

i.e. *far too small*, and σ^5, not σ^4

this results because for observed SMBH masses,

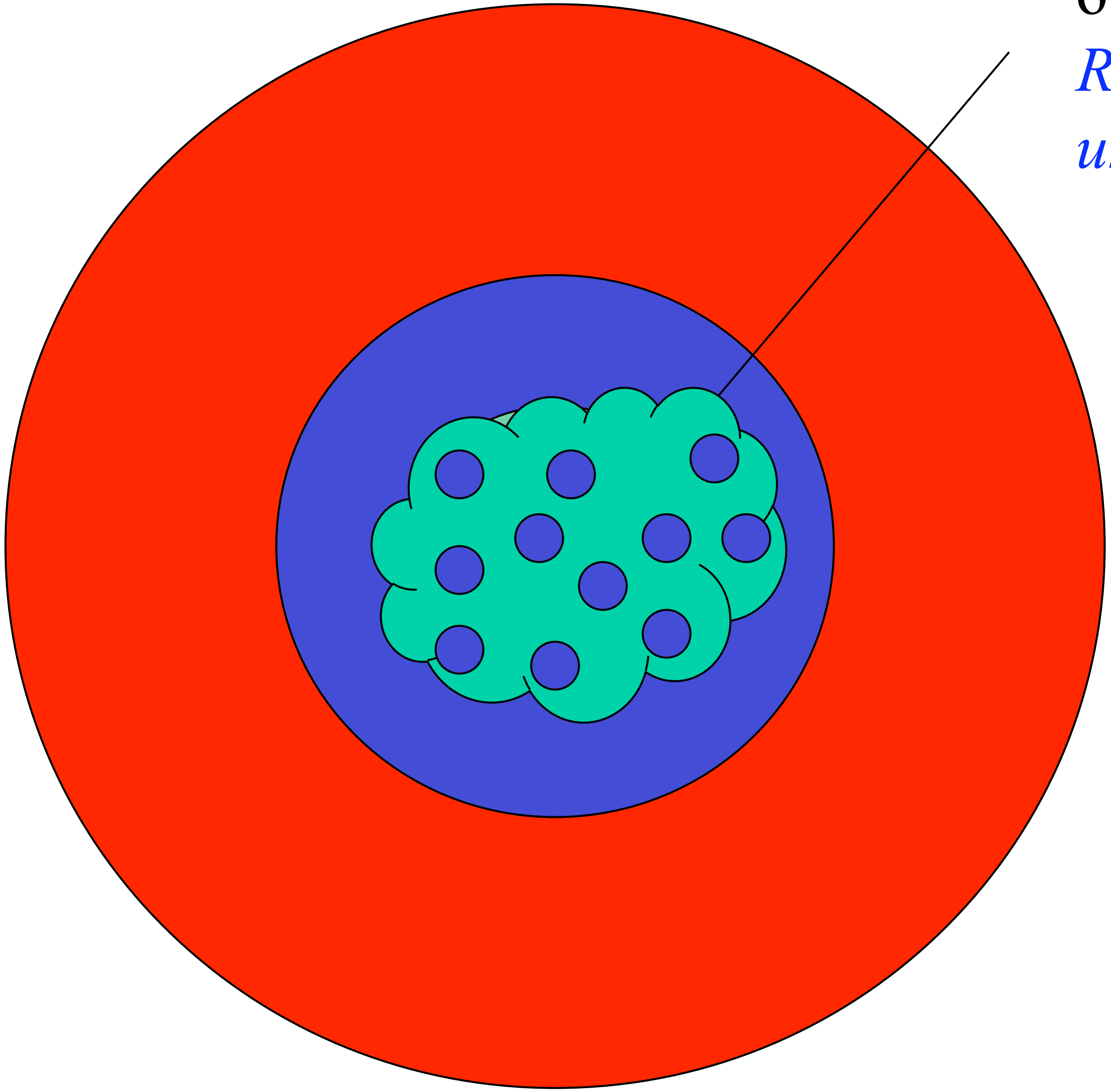
BH binding energy >> bulge binding energy – outflow must cool!



outflow shock is
Rayleigh-Taylor
unstable unless

$$M \sim M_\sigma$$

energy-driven
outflows always
R – T unstable



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BH masses in AGN are probably $\sim M_\sigma/\mathrm{few}$