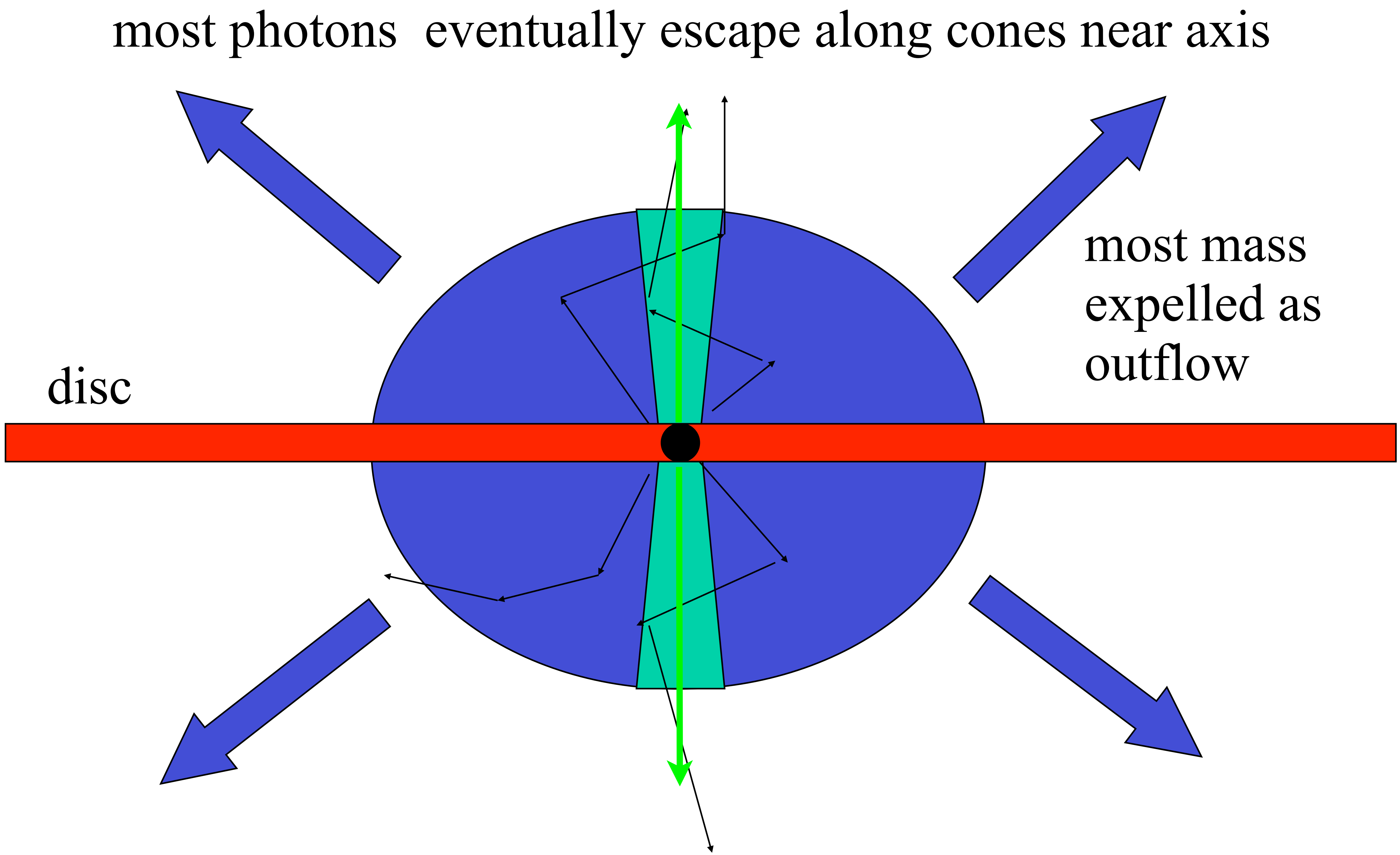
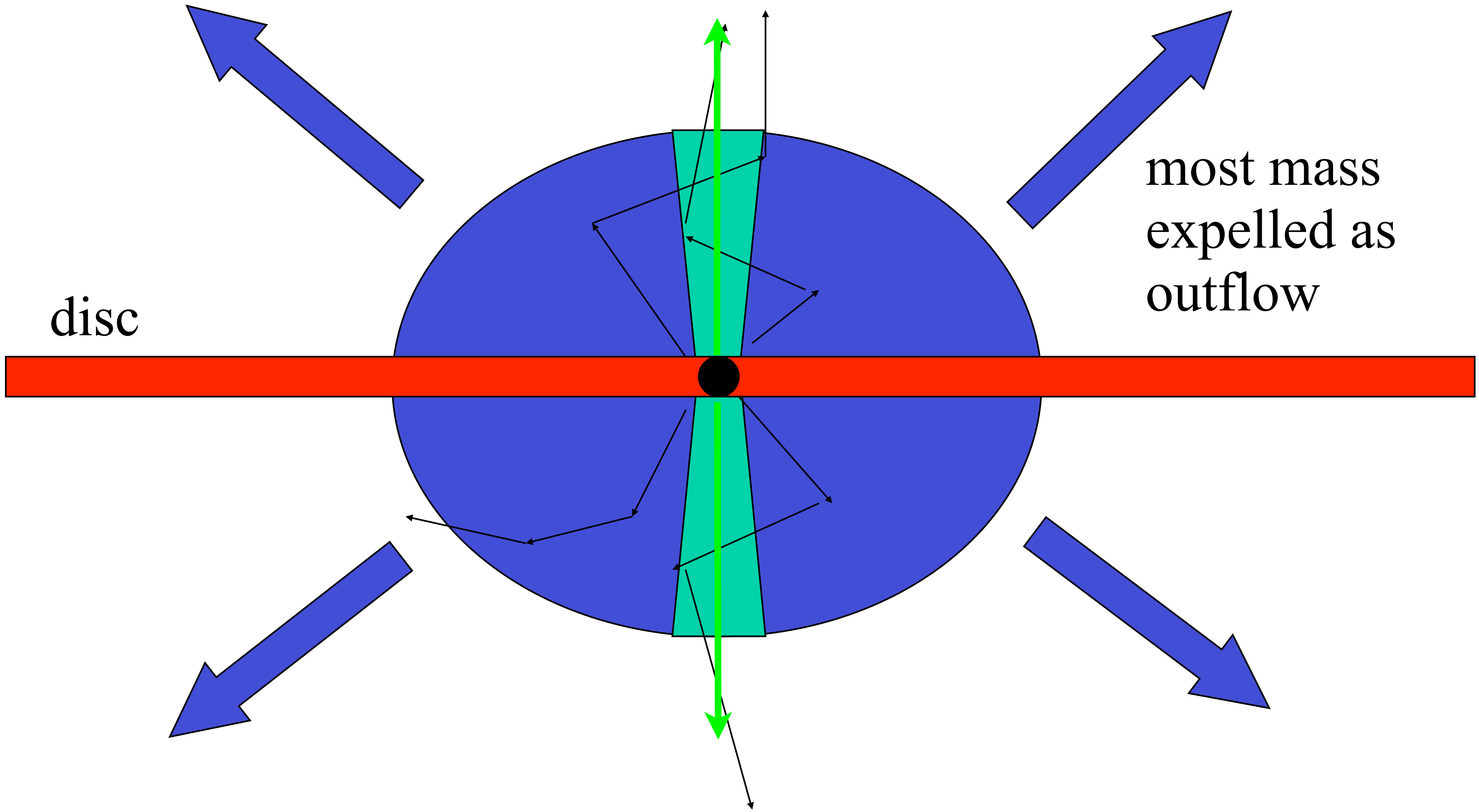
The $M - \sigma$ Relation

Super-Eddington Accretion



Super-Eddington Accretion

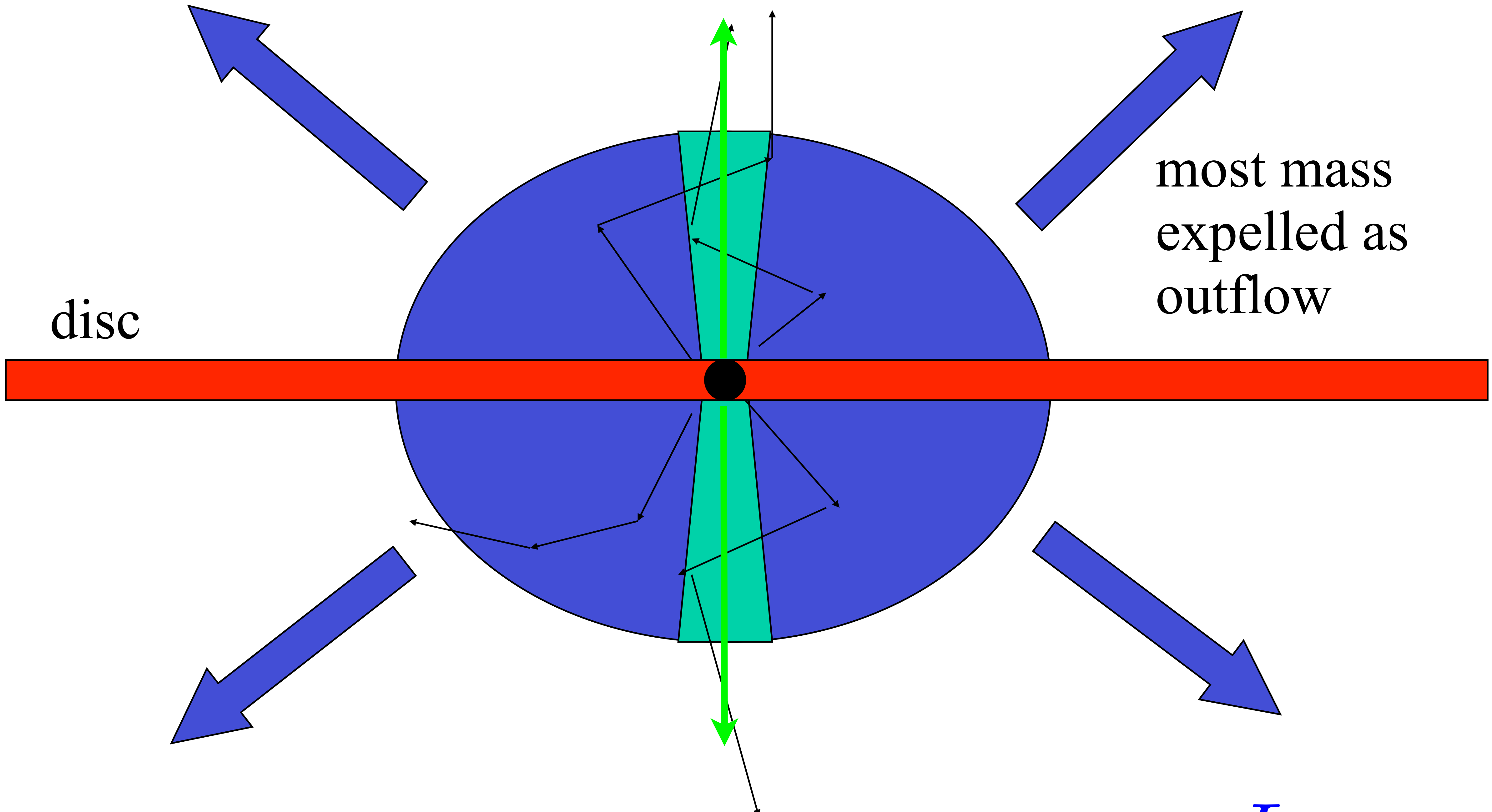
most photons eventually escape along cones near axis



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

Super-Eddington Accretion

most photons eventually escape along cones near axis

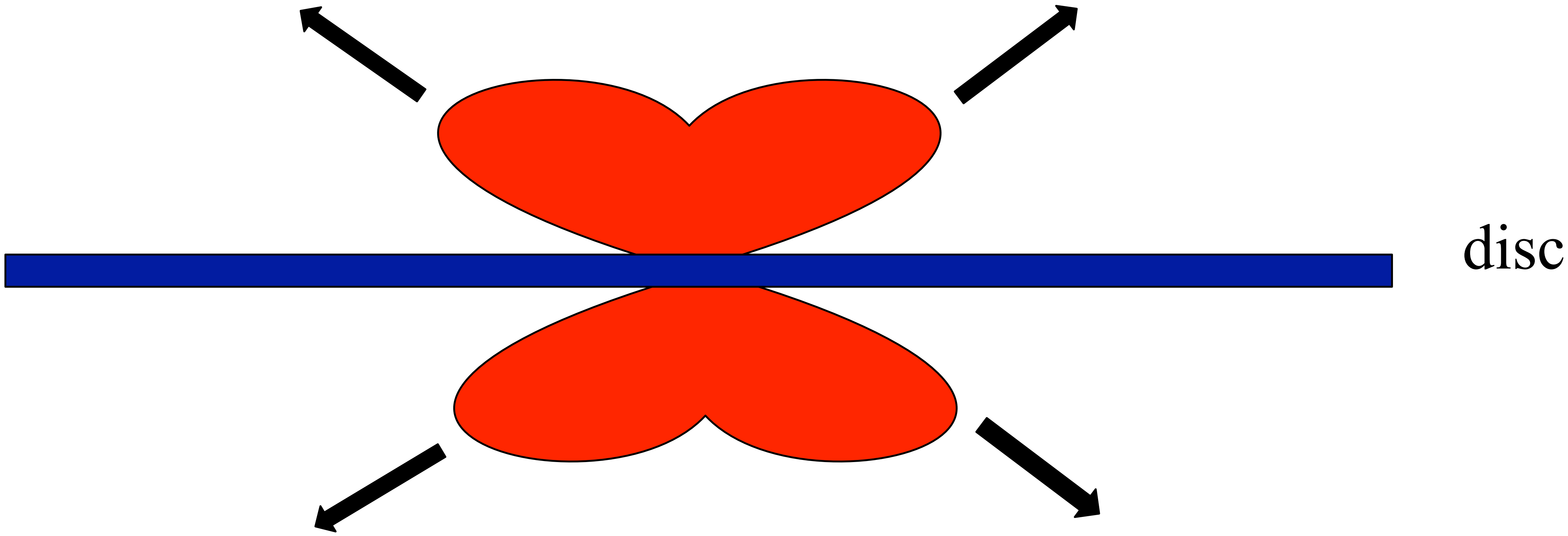


on average photons give up all
momentum to outflow after ~ 1 scattering

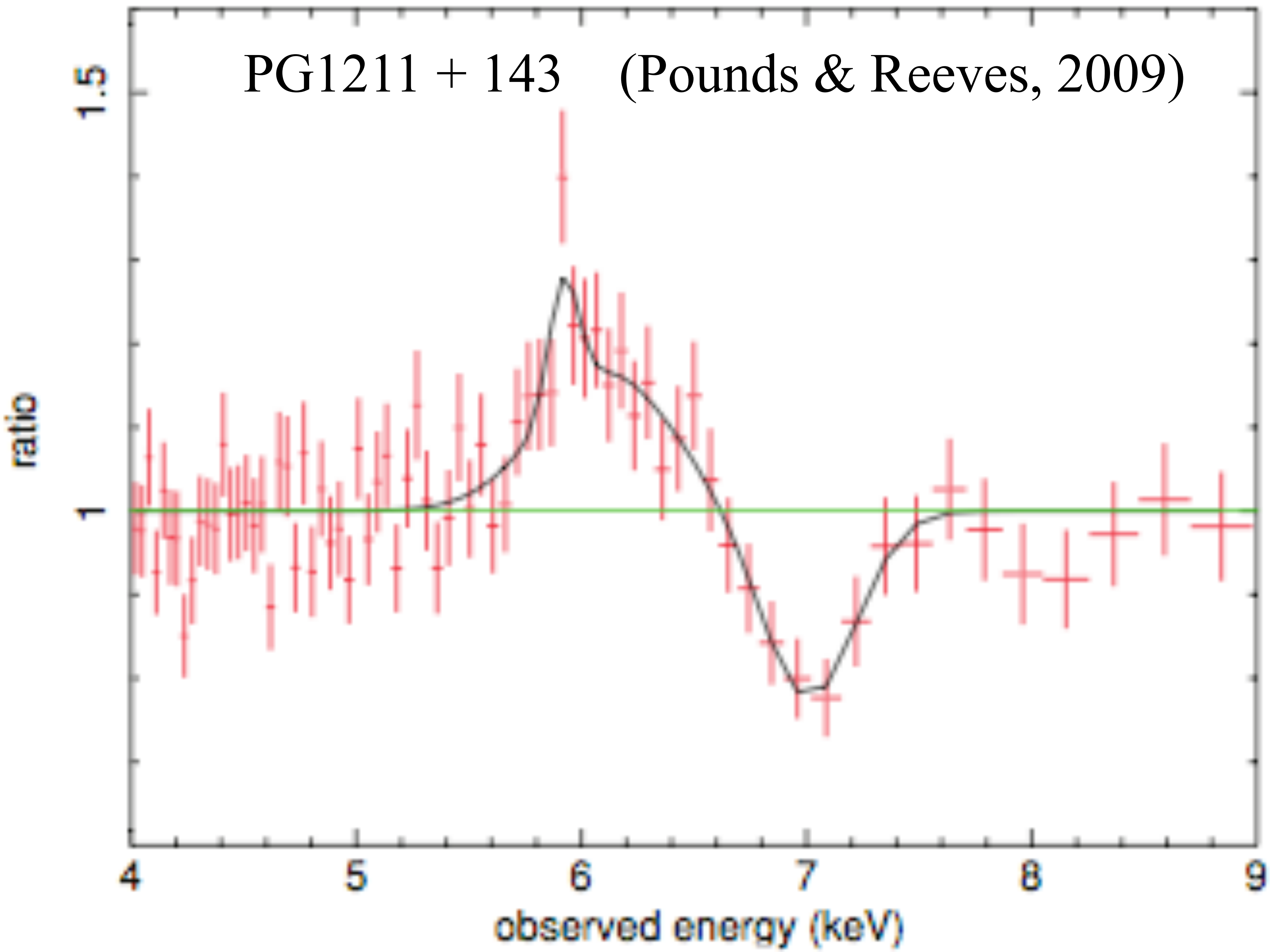
$$\dot{M} v = \frac{L_{\rm Edd}}{c}$$

outflows have effectively spherical geometry since

(a) basic outflow pattern is roughly spherical



(b) disc axis moves randomly as accretion orientation changes



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

`ultrafast outflow' -- `UFO'

mass outflow rate

- measure velocity v directly from blueshift of absorption line

- ionization state of wind gas determined by the quantity $\xi = L_i/NR^2$, where L_i is the luminosity able to produce a given ion, N is the number density of the gas, and R the distance from the ionizing source (i.e. the quasar)

- measure L_i directly from quasar spectrum

- combining these gives mass outflow rate

$$\dot{M}_{\rm out} = 4\pi b m_p N R^2 v \sim 1{\rm M_\odot\,yr^{-1}} \sim \dot{M}_{\rm Edd}$$

where the wind has solid angle $4\pi b$: $b \sim 1$ since most local AGN show UFO--type outflows

outflow affects galaxy bulge

outflow energy $\sim 0.1 M_{BH} c^2$ is $\sim 10^{61}$ erg
for $10^8 M_\odot$ black hole
binding energy of bulge of mass $10^{11} M_\odot$
and $\sigma = 200$ km s^{-1} is 10^{58} erg

more than enough energy to unbind bulge – only a fraction used

galaxy must notice presence of hole

Eddington outflows: summary

momentum outflow rate

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

speed

$$v = \frac{L_{\rm Edd}}{\dot{M}_{\rm out} c} = \frac{\eta c}{\dot{m}} \sim 0.1c$$

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

energy outflow rate

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

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

outflow shock

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

either

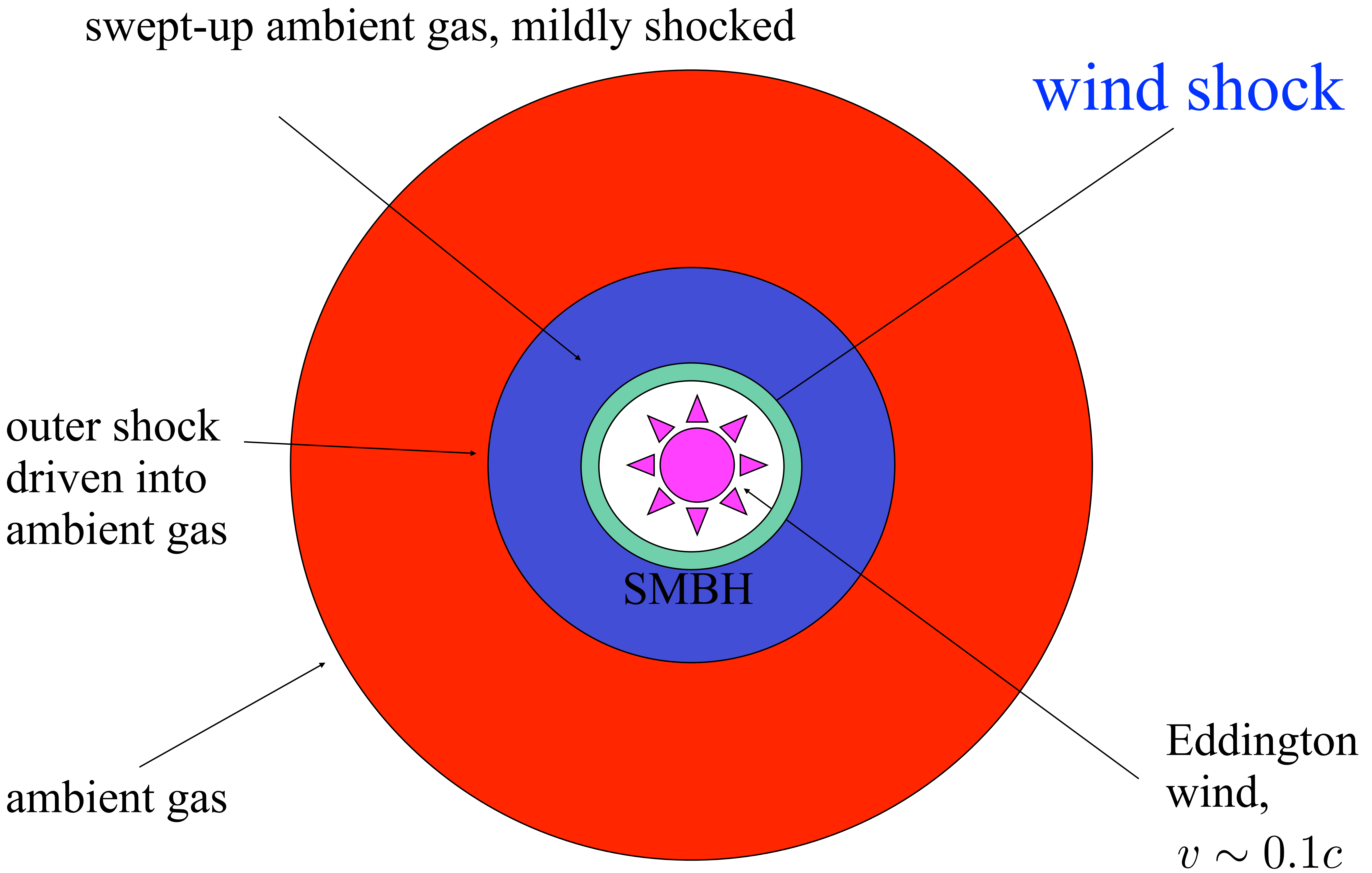
(b) shocked gas cools: `momentum–driven flow'
negligible thermal pressure

or

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

Compton cooling by quasar radiation field very effective out to large bulge radii (cf Ciotti & Ostriker, 1997, 2001)

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


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

wind shock

electrons (and ions) reach energies $E \simeq 9m_p v^2/16$ in the wind shock

hotter $(T \sim 10^{11}\ \mathrm{K})$ than the quasar radiation field $(T \sim 10^7\ \mathrm{K})$

Compton cooling time is

$$t_C = \frac{3m_e c}{8\pi\sigma_{\rm T} U_{\rm rad}} \frac{m_e c^2}{E}$$

where

$$U_{\rm rad} = \frac{L_{\rm Edd}}{4\pi R^2 cb}$$

is the radiation intensity of the quasar thus $\quad t_C = \frac{2}{3}\frac{cR^2}{GM}\left(\frac{m_e}{m_p}\right)^2\left(\frac{c}{v}\right)^2 b \simeq 10^5 R_{\rm kpc}^2\left(\frac{c}{v}\right)^2 b M_8^{-1}\ {\rm yr}:$

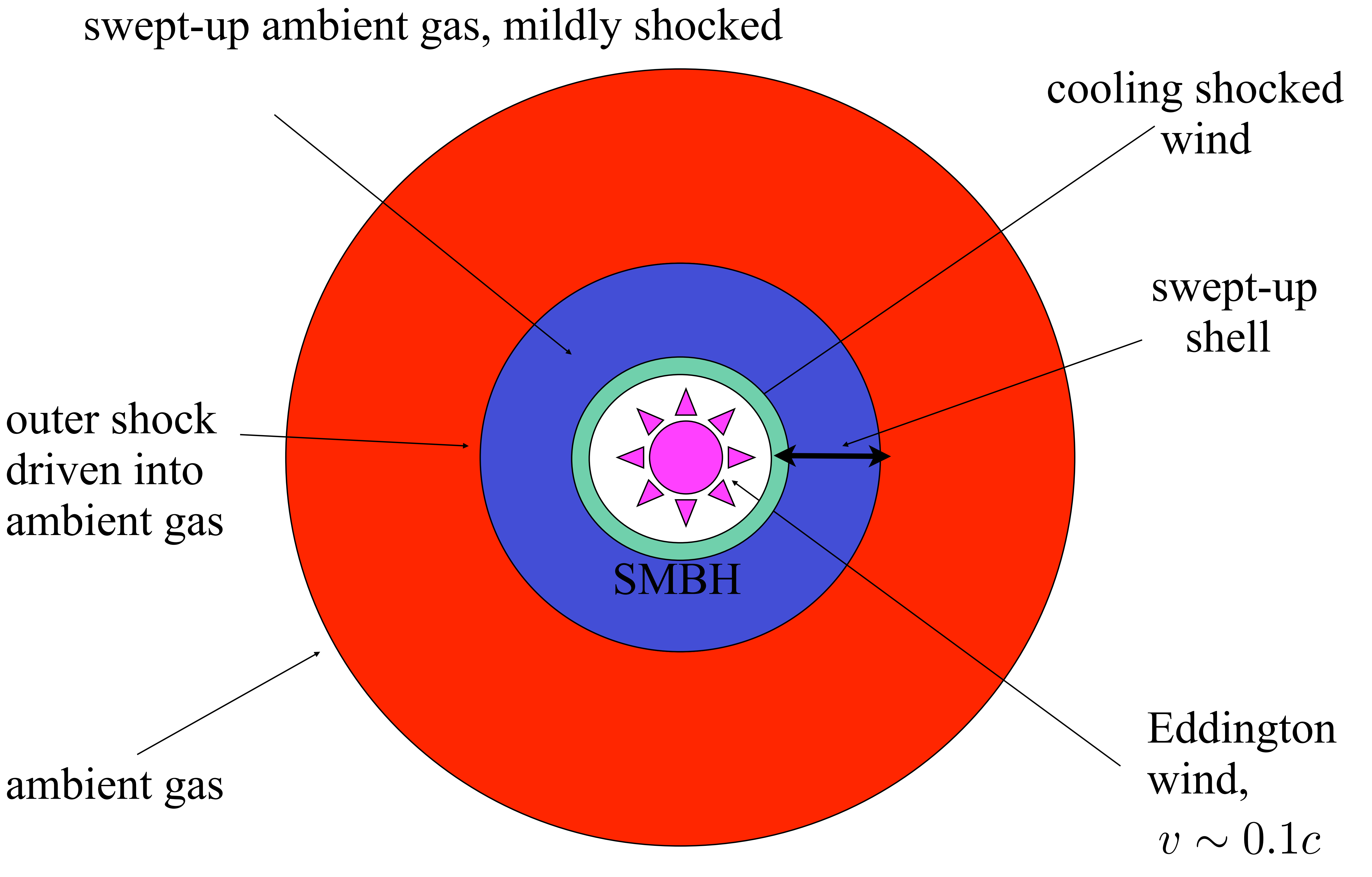
this is shorter than the shock travel time $t_{\rm shock} \sim R/\dot{R}_s \sim R/\sigma$ for shock radii

$$R < R_C \sim 0.5\frac{M_8}{\sigma_{200}}\ {\rm kpc}$$

two-fluid effects (electrons cooler than ions) can decrease R_C to as little as 20 pc - but still larger than SMBH influence radius $R_{\rm inf}$

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

strong cooling makes shocked region very narrow (`isothermal')


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

bulge mass distribution

- typical bulge (formed by mergers) has

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

$\sigma = \mathrm{constant}$ is velocity dispersion: `isothermal distribution'

- cumulative mass inside radius R is

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

- most of this mass is stars: with *gas fraction* $f_g(\sim 0.1)$ the gas has

$$\rho_g(r) = \frac{f_g \sigma^2}{2\pi G r^2} \qquad \text{and} \qquad M_g(R) = \frac{2 f_g \sigma^2 R}{G}$$

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

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

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

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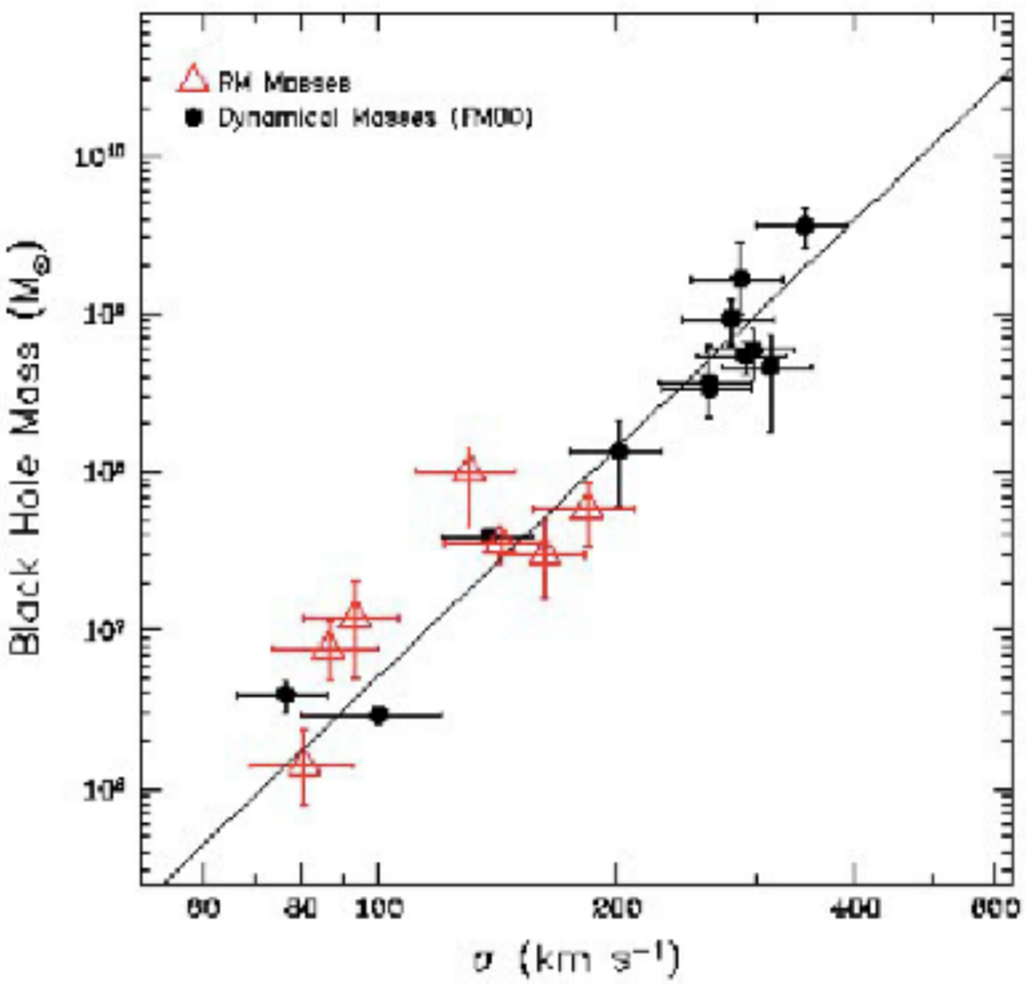
if $M < M_\sigma$, no solution at large R (rhs < 0)

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

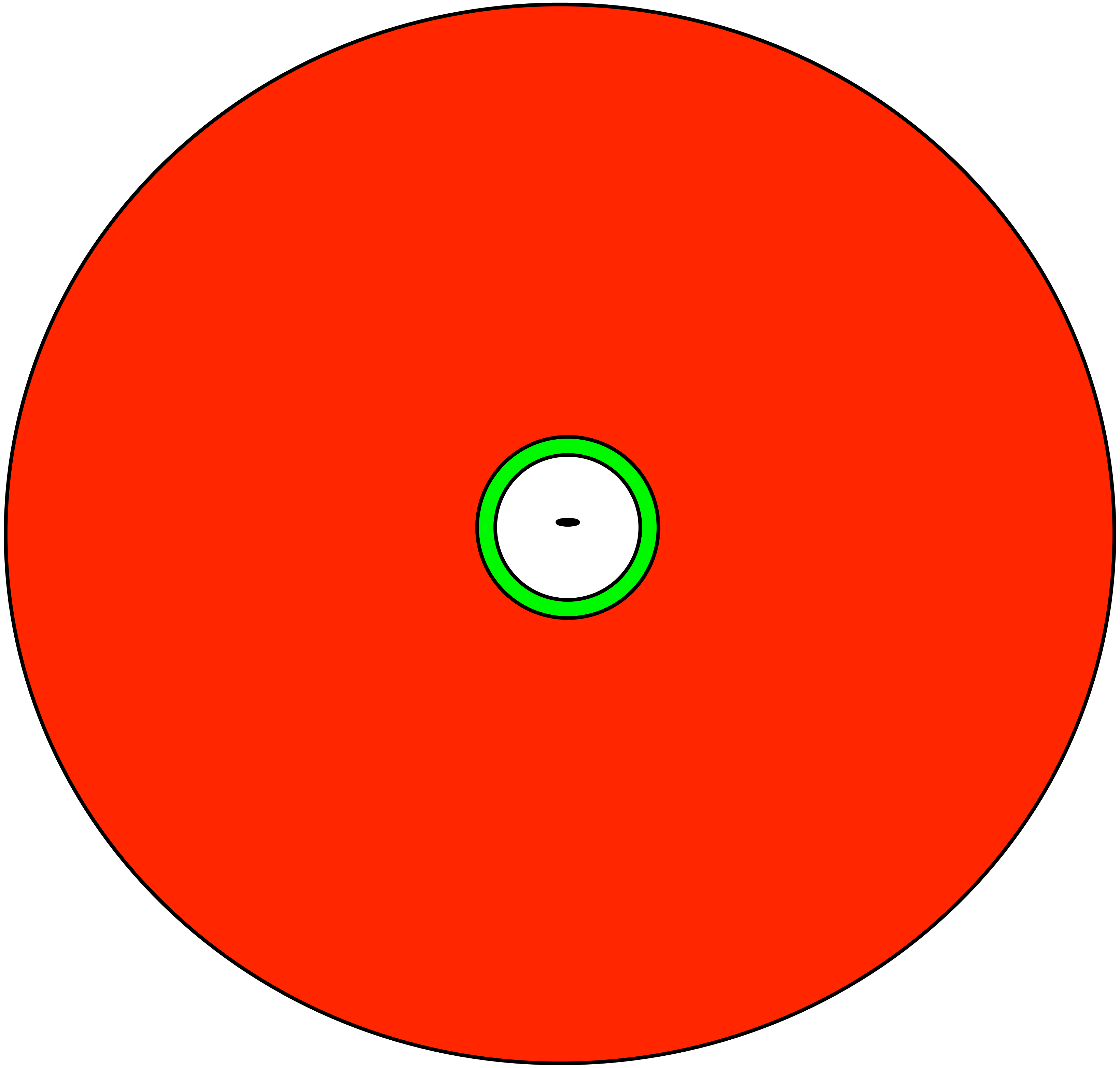
$$M_\sigma = \frac{f_g \kappa}{\pi G^2}\sigma^4 \simeq 2 \times 10^8 M_\odot \sigma_{200}^4$$

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 $M = M_\sigma$



transition to energy-driven flow once M_σ reached

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

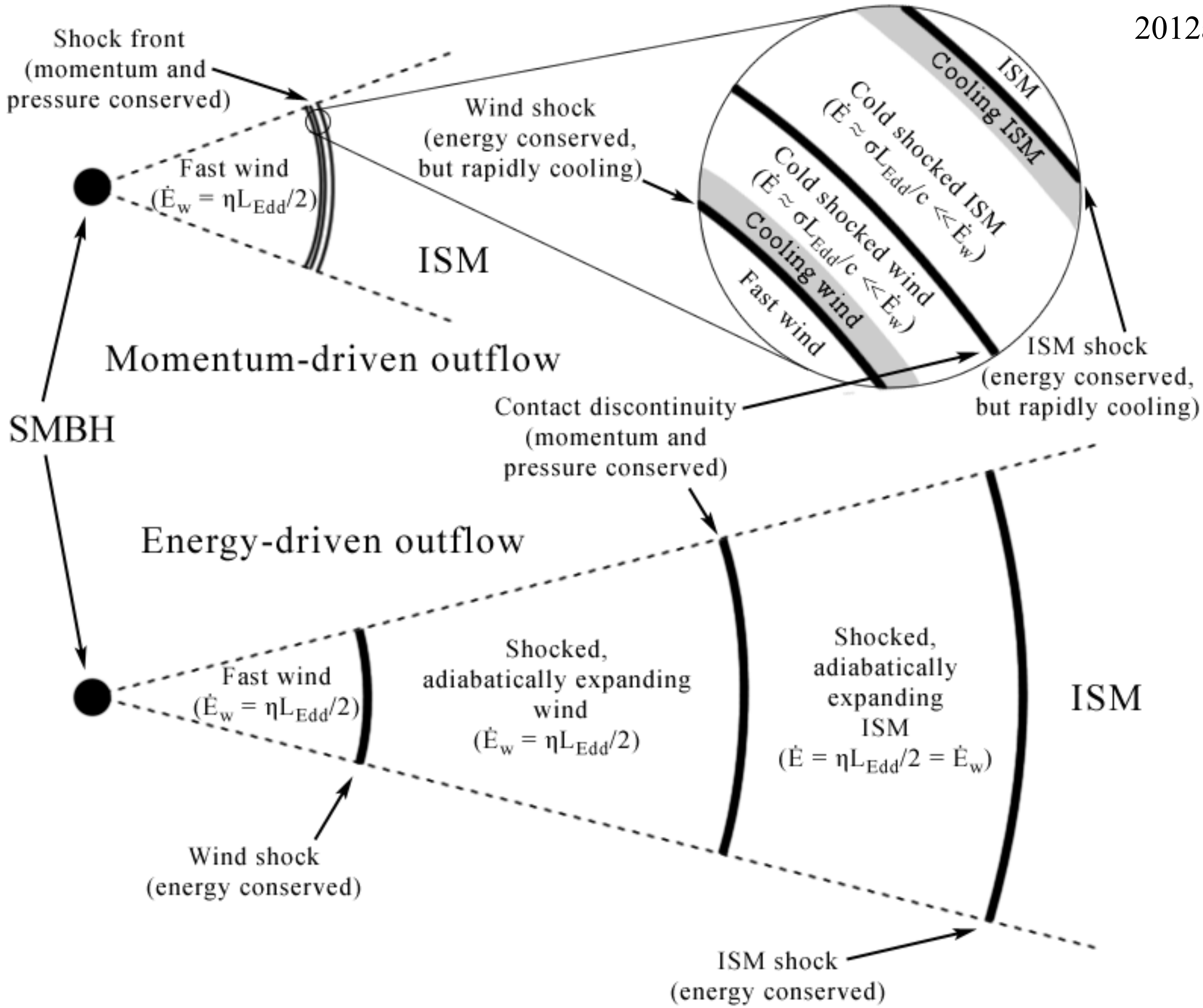
but once $M > M_\sigma$, R can exceed R_C: wind shock no longer cools

wind shock is adiabatic: hot postshock gas does $P\mathrm{d}V$ work on surroundings

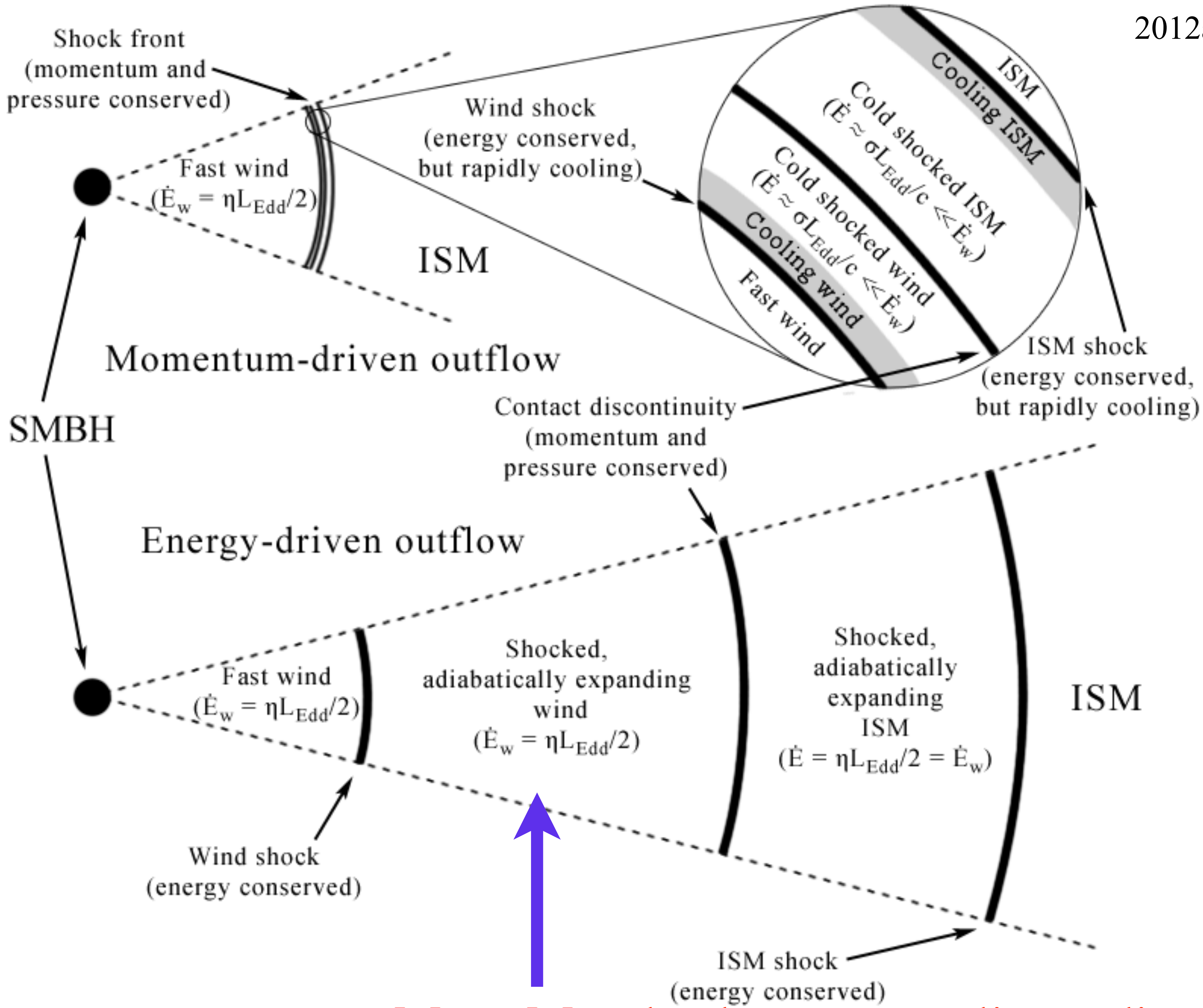
eqn of motion now contains *total* postshock pressure P (gas plus ram)

wind shock always stays near cooling radius: high sound speed ensures near-constant pressure in extended region from here to contact discontinuity (radius R) with swept-up host gas

Zubovas & King, 2012a



Zubovas & King, 2012a



once BH grows to $M > M_\sigma$, shock passes cooling radius

=> large-scale energy-driven flow

equation of motion of swept-up shell (contact discontinuity) is

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[M(R)\dot{R}\right] + \frac{GM(R)[M + M_{\mathrm{tot}}(R)]}{R^2} = 4\pi R^2 P$$

energy equation is

$$\frac{\mathrm{d}}{\mathrm{d}t}[VU] = \frac{1}{2}\dot{M}_{\mathrm{out}}v^2 - P\frac{\mathrm{d}V}{\mathrm{d}t} - \frac{GM(R)M_{\mathrm{tot}}(R)}{R^2}\dot{R}$$

where

$$V = \frac{4\pi}{3}R^3, \quad U = \frac{3}{2}P, \quad \dot{M}_{\mathrm{out}}v = \frac{L_{\mathrm{Edd}}}{c},$$

$$M(R) = \frac{2f_g\sigma^2 R}{G}, \quad M_{\mathrm{tot}}(R) = \frac{2\sigma^2 R}{G}, \quad v = \eta c$$

using equation of motion to eliminate P from energy equation finally determines motion of shell at R

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

coasting solution $\dot{R} = v_e = {\rm constant}$ has

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

(where SMBH mass M appearing in $L_{\rm Edd}$ is set to M_σ)

(King, 2005)

once quasar driving switches off (i.e. $L_{\mathrm{Edd}} = 0$) at $R = R_0$ the velocity decays as

$$\dot{R}^2 = 3\left(v_e^2 + \frac{10}{3}\sigma^2\right)\left(\frac{1}{r^2} - \frac{2}{3r^3}\right) - \frac{10}{3}\sigma^2$$

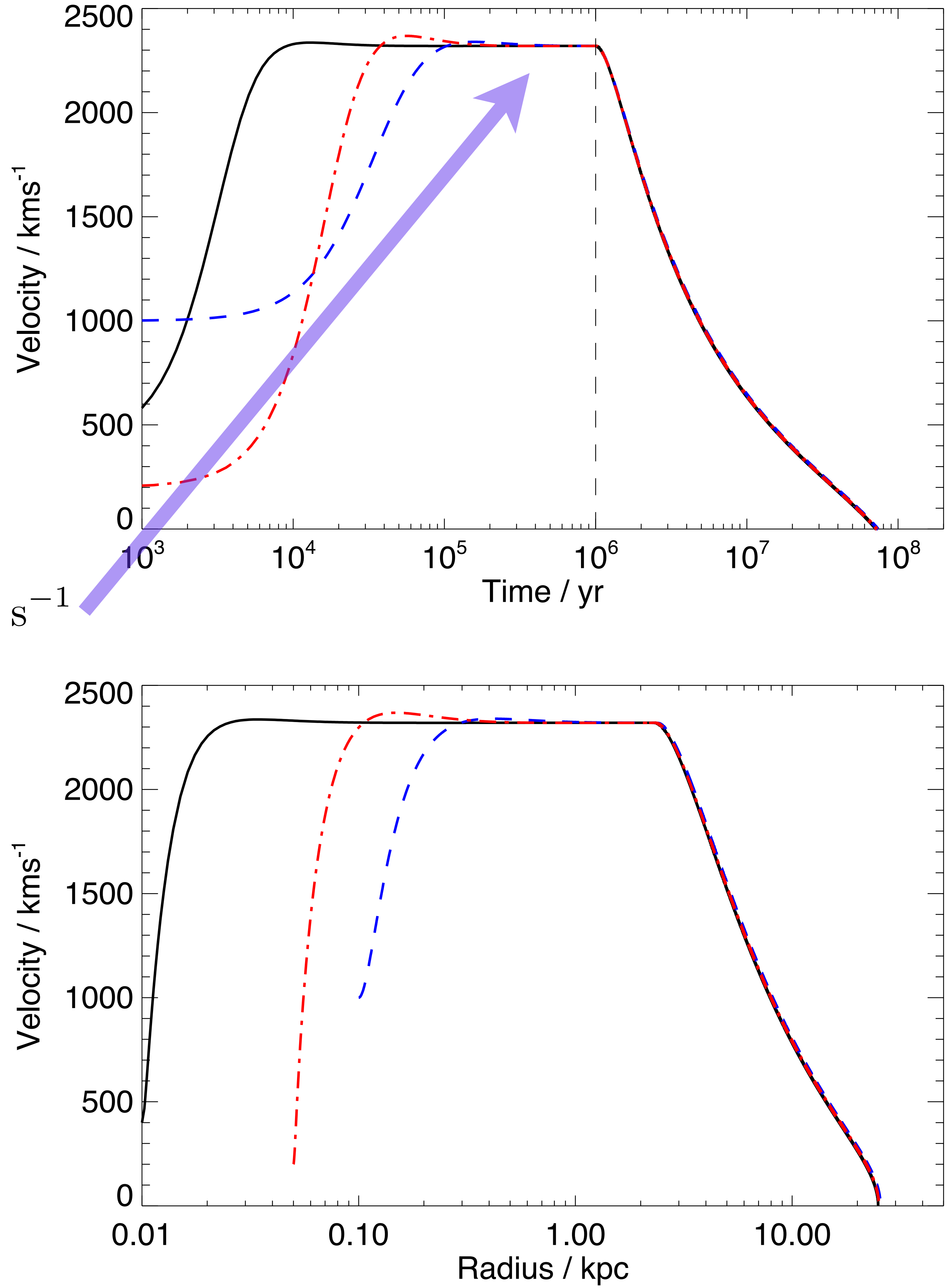
where $r = R/R_0 \geq 1$

numerical solutions show that coasting + decay are attractors -- all outflows do this

(King, Zubovas & Power, 2011)

energy--driven outflows rapidly converge to

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



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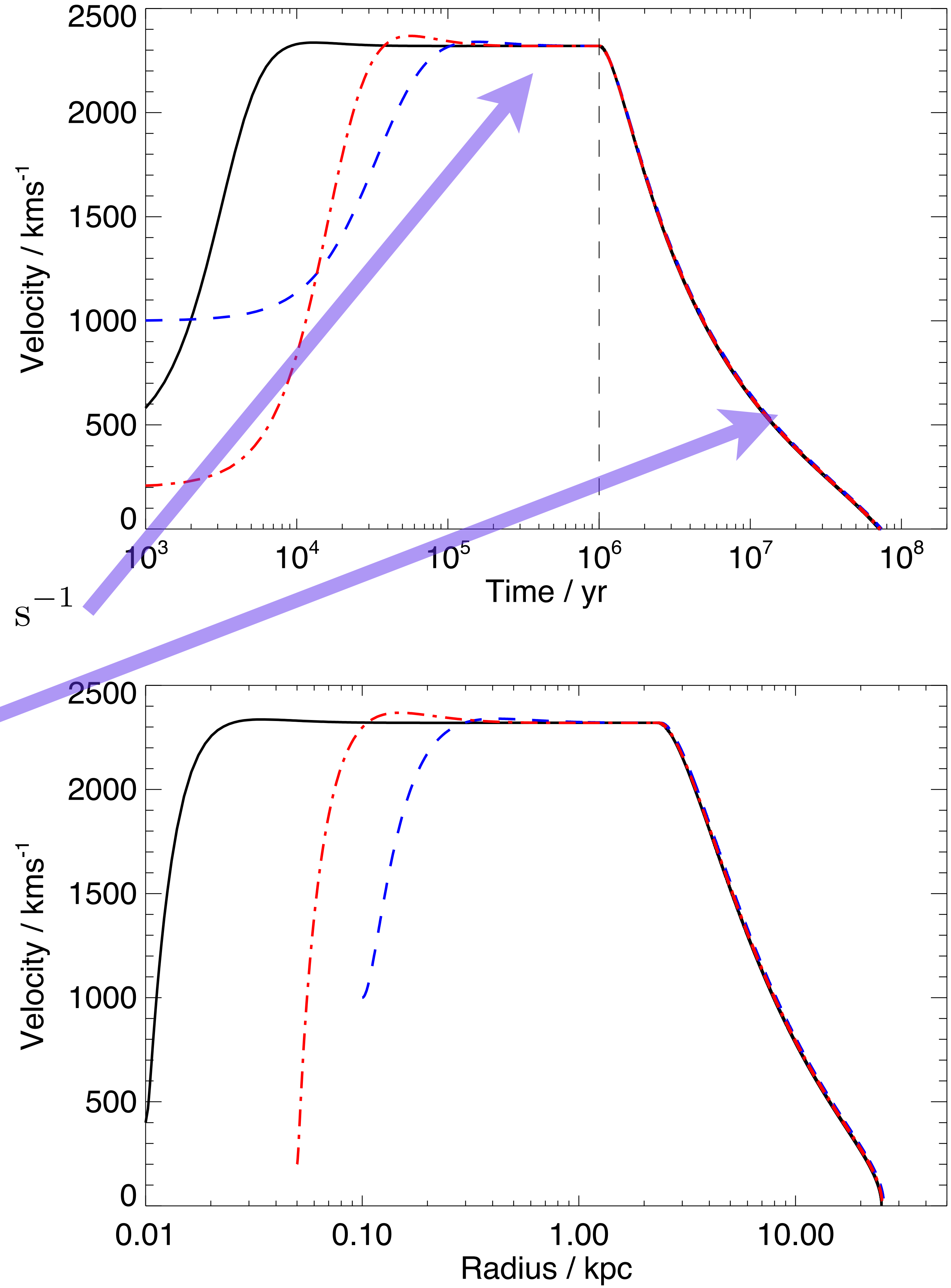
and persist even after central quasar turns off



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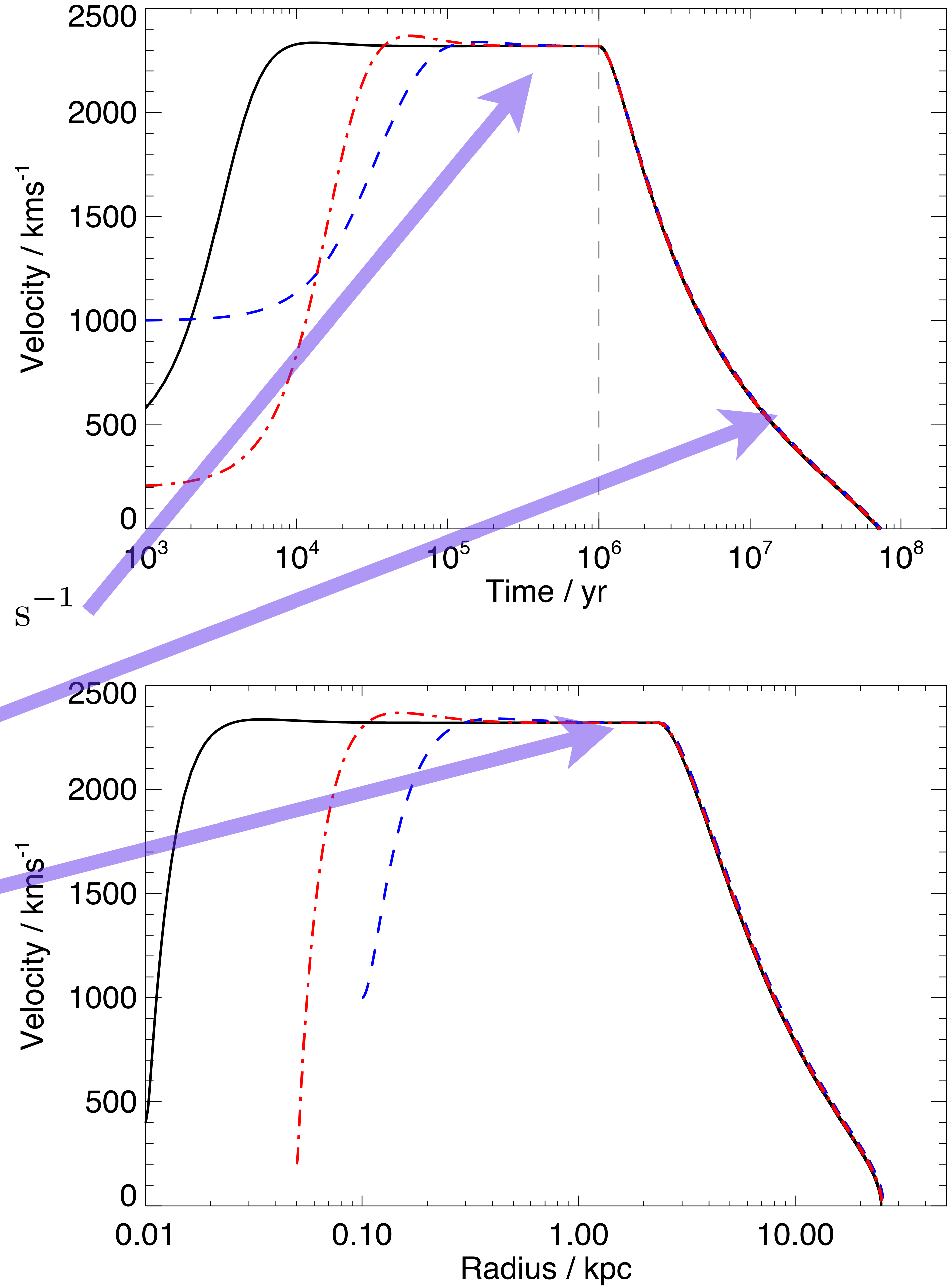
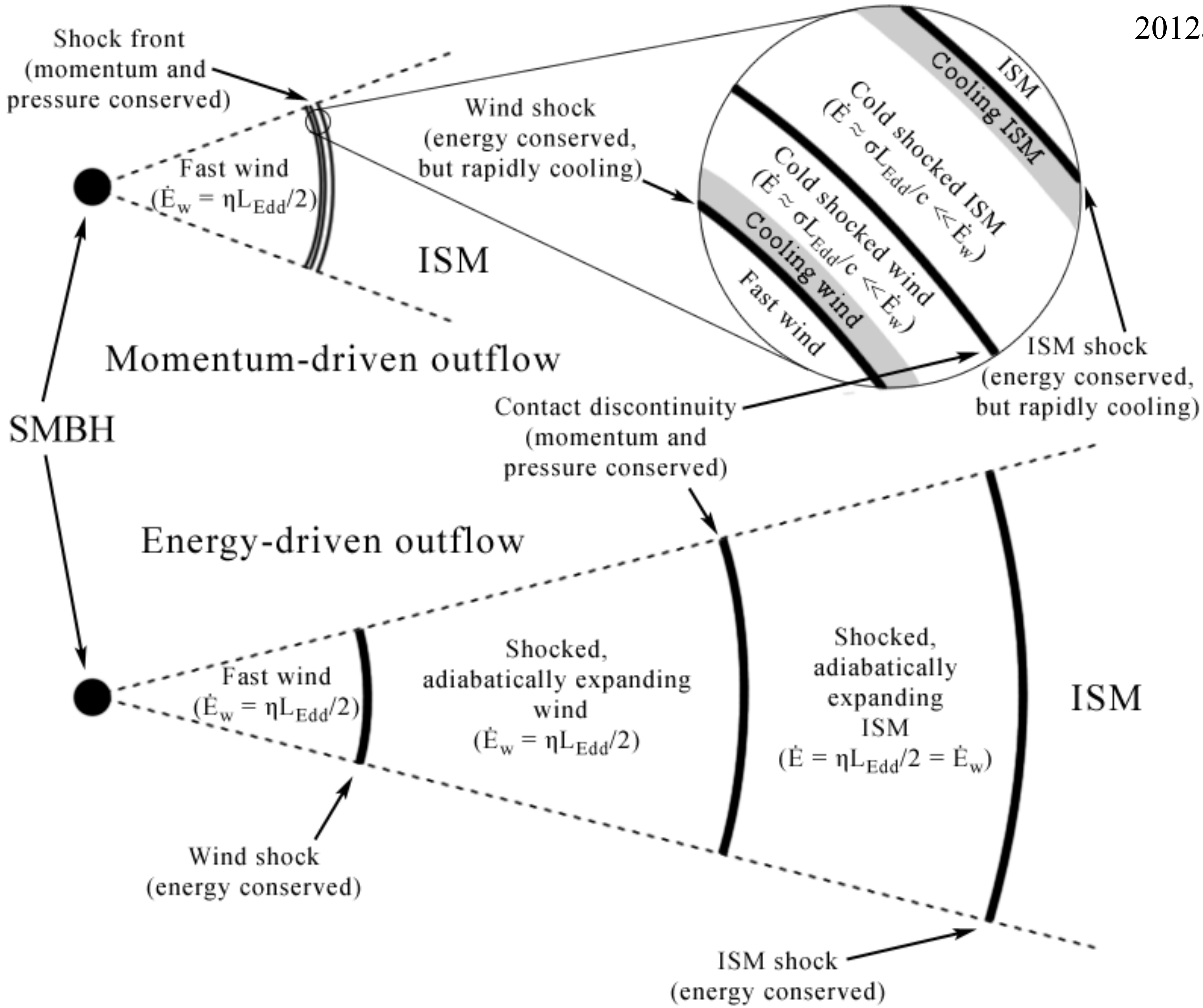
and persist even after central quasar turns off

high velocity outflow at large radius



Zubovas & King, 2012a



forward shock speed

$\dot{R} = v_e$ $\quad$ $v_{\rm out}$

galaxy frame

shocked ISM $\quad$ ambient ISM, at rest

shock

$\dot{R} - v_{\rm out}$ $\quad$ $v_{\rm out}$

shocked ISM $\quad$ ambient ISM

shock

shock frame

$$\frac{v_{\rm out}}{\dot{R} - v_{\rm out}} = \frac{\gamma + 1}{\gamma - 1} => v_{\rm out} = \frac{\gamma + 1}{2} \dot{R}$$

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

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

and radius as

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

outflow rate of shocked interstellar gas is

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

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

approximate equality

$$\frac{1}{2}\dot{M}_{\rm w}v_{\rm w}^2 \simeq \frac{1}{2}\dot{M}_{\rm out}v_{\rm out}^2$$

means swept-up gas must have momentum rate $> L_{\rm Edd}/c$, since can rewrite it as

$$\frac{\dot{P}_{\rm w}^2}{2\dot{M}_{\rm w}} \simeq \frac{\dot{P}_{\rm out}^2}{2\dot{M}_{\rm out}}$$

$$\dot{P}_{\rm out} = \dot{P}_{\rm w}\left(\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm w}}\right)^{1/2} \sim 20\sigma_{200}^{-1/3}l^{1/6}\frac{L_{\rm Edd}}{c}$$

all molecular outflows have super-Eddington thrust!

(Zubovas & King, 2012a)

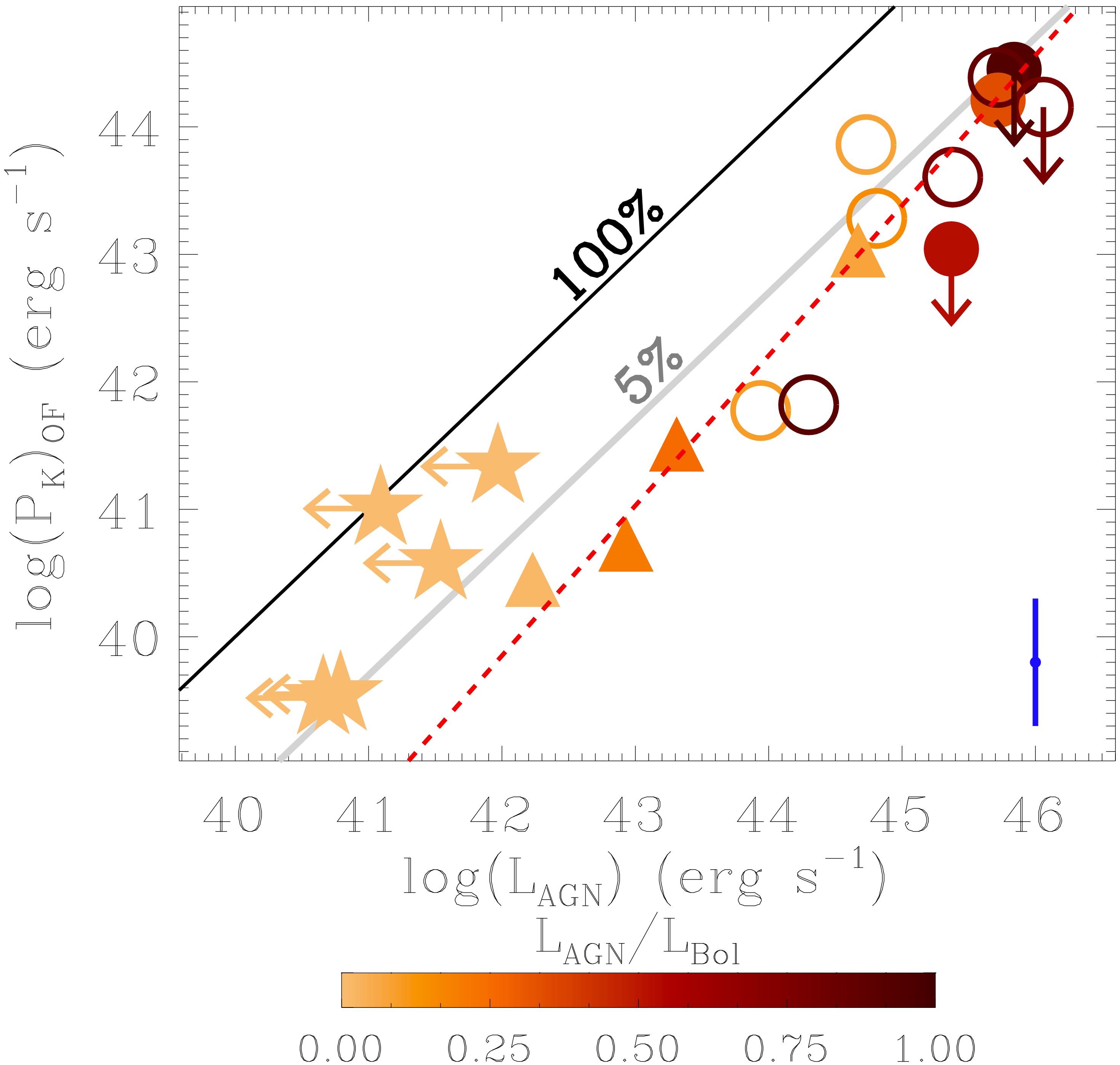


Fig. 12. Correlation between the kinetic power of the outflow and the AGN bolometric luminosity. Symbols and colour-coding as in Fig. 8. The grey line represents the theoretical expectation of models of AGN feedback, for which $P_{\rm K,OF} = 5\% L_{\rm AGN}$. The red dashed line represents the linear 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.

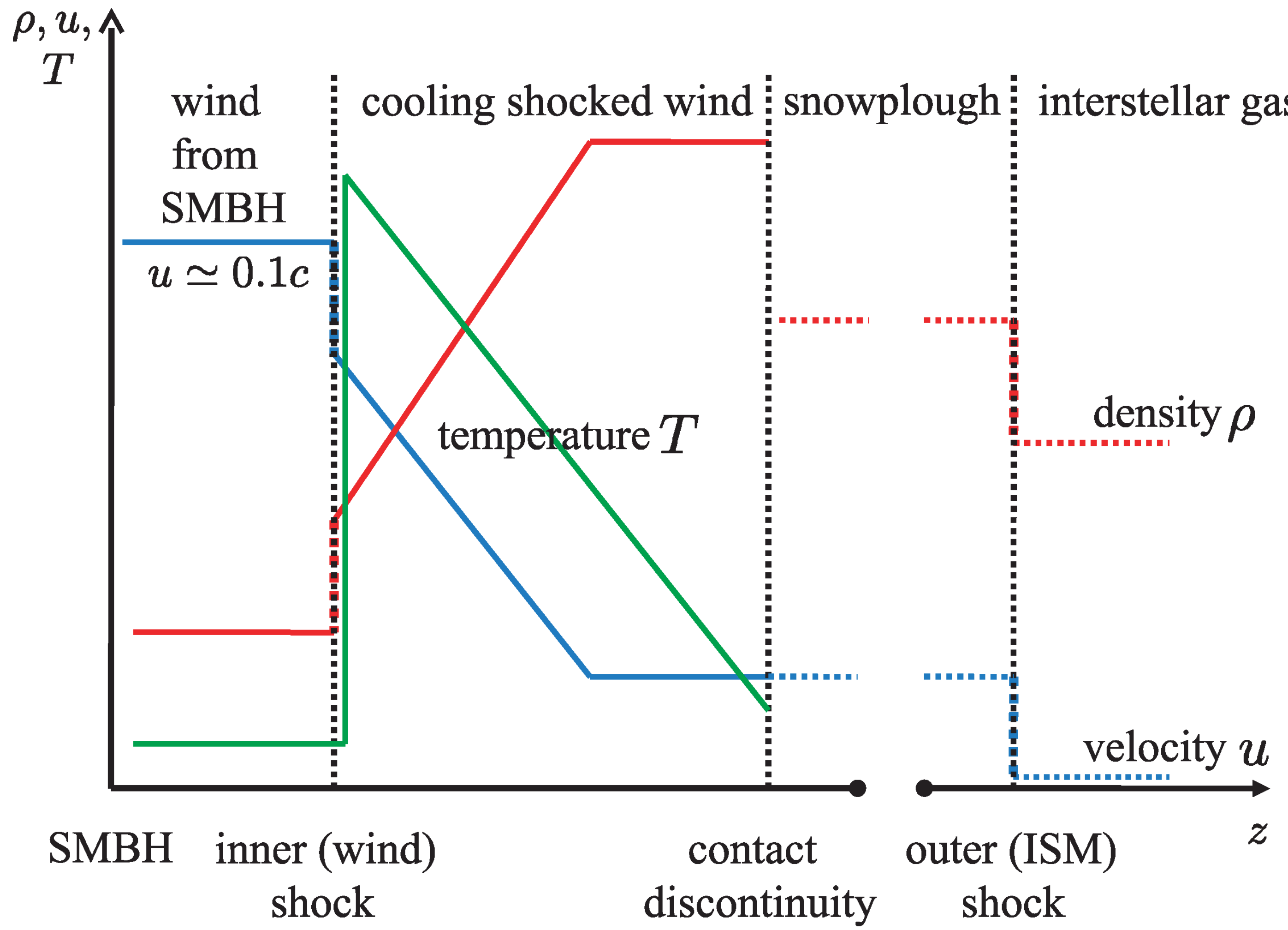


Figure 2. Impact of a wind from an SMBH accreting at a super-Eddington rate on the interstellar gas of the host galaxy: schematic view of the radial dependence of the gas density ρ, velocity u and temperature T. At the inner shock, the gas temperature rises strongly while the wind density and velocity, respectively, increase (decrease) by factors of $\sim$4. Immediately outside this (adiabatic) shock, the strong Compton cooling effect of the quasar radiation severely reduces the temperature, and slows and compresses the wind gas still further. This cooling region is very narrow compared with the shock radius (see Fig. 1), and may be observable through the inverse Compton continuum and lower excitation emission lines. The shocked wind sweeps up the host ISM as a 'snowplough'. This is more extended than the cooling region (cf. Fig. 1), and itself drives an outer shock into the ambient ISM of the host. Linestyles: red, solid: wind gas density ρ; red, dotted: ISM gas density ρ; blue, solid: wind gas velocity u; blue, dotted: ISM gas velocity u; green, solid: wind gas temperature T. The vertical dashed lines denote the three discontinuities, inner shock, contact discontinuity and outer shock.

UFO winds are episodic

X-ray absorption through wind measures column density

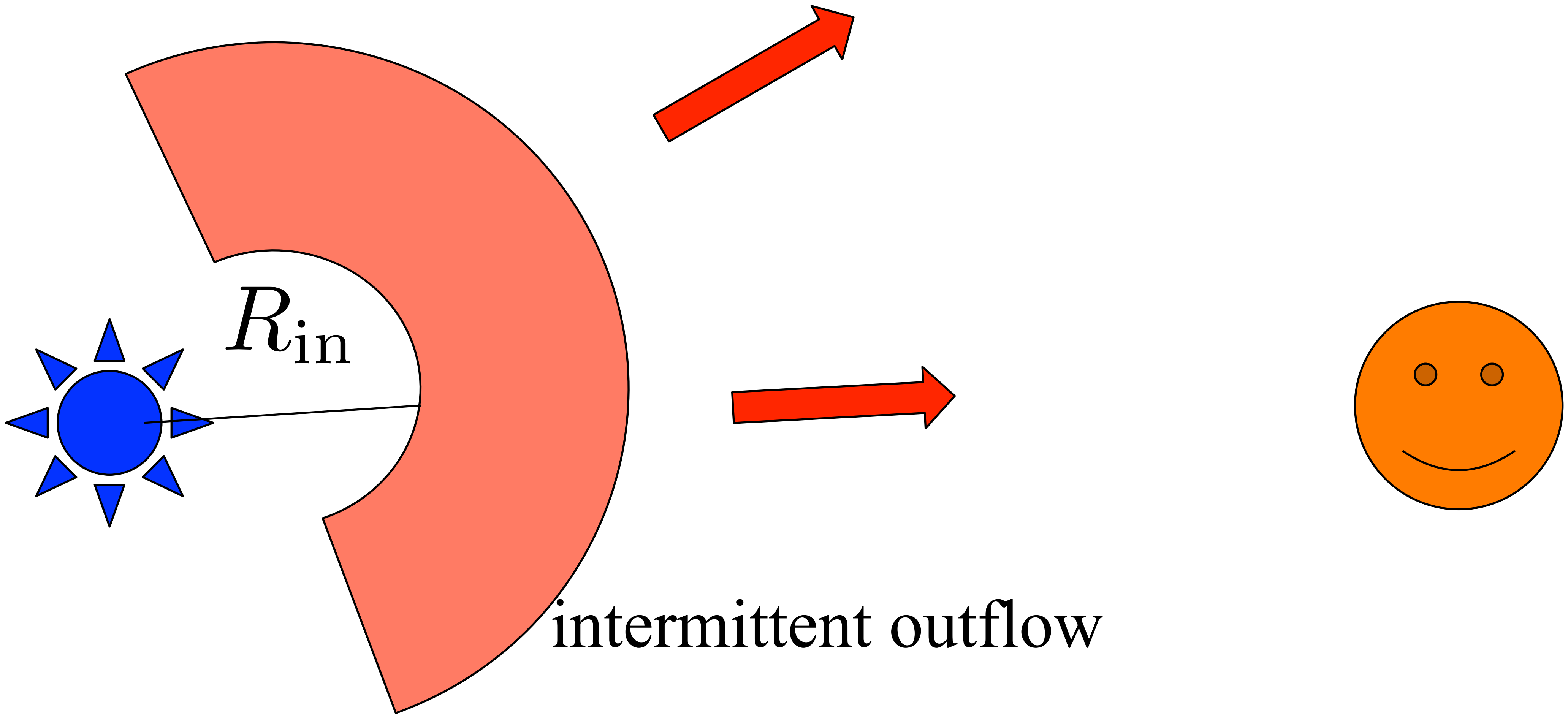
$$N_H = \int \frac{\rho}{m_p} \mathrm{d}r = \int_{R_{\rm in}}^{\infty} \frac{\dot{M}_{\rm out}}{4\pi m_p r^2 v} \mathrm{d}r$$

so $$N_H = \frac{\dot{M}_{\rm out}}{4\pi m_p R_{\rm in} v}$$

but $R_{\rm in} = vt$, where t is time since wind switched off

a full Eddington wind from vicinity of SMBH has Thomson optical depth of order 1, so that $N_H \simeq 10^{24}\,\mathrm{cm}^{-2}$

a smaller column => inner edge of wind is further from SMBH:



observed X—ray column fixed by inner boundary of flow $R_{\rm in}$

$$N_H = \frac{GM}{bv^2 R_{\rm in}\sigma_T}, \text{ using } \dot M_{\rm out} v = L_{\rm Edd}/c$$

so if outflow stopped a time $t_{\rm off} = R_{\rm in}/v$ ago, we have

$$t_{\rm off} = \frac{GM}{bv^3 N_H \sigma_T} \simeq 0.25 \frac{M_8}{v_{0.1}^3 N_{23} b}\ {\rm yr}$$

recent!