Accretion and Outflows in AGN

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- SMBH growth means accretion

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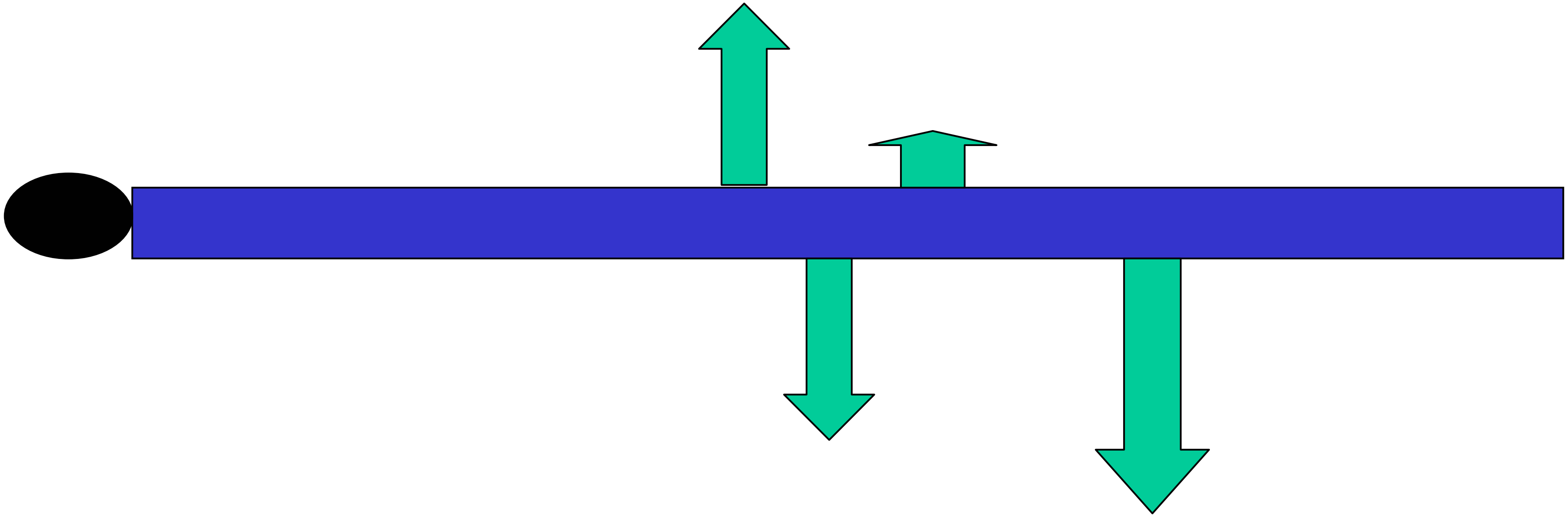
- then a miracle occurs – matter sinks to vicinity of SMBH
- ultimately this matter must accrete as a disc

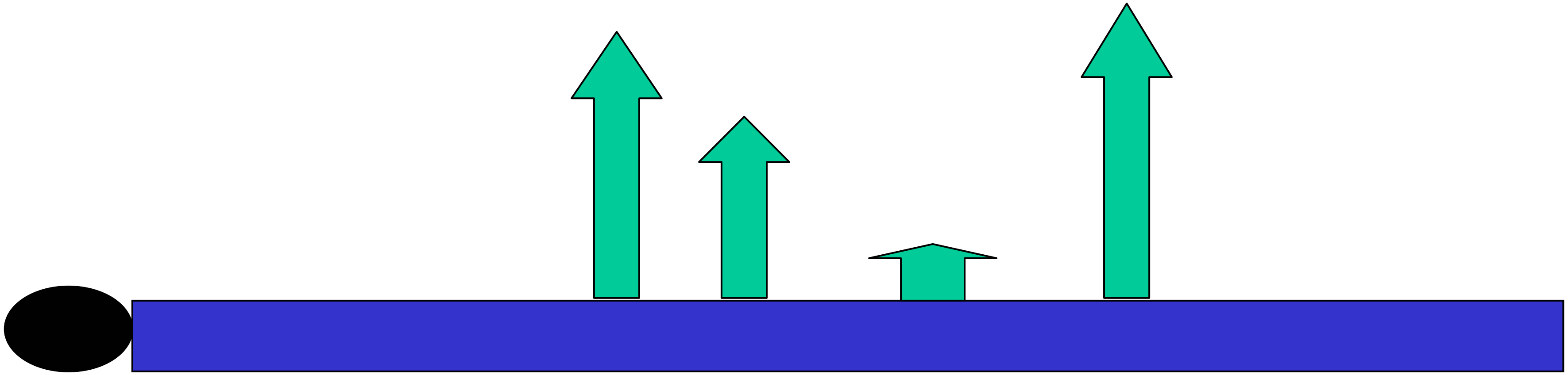
- disc accretion probably driven by magneto-rotational instability (MRI)



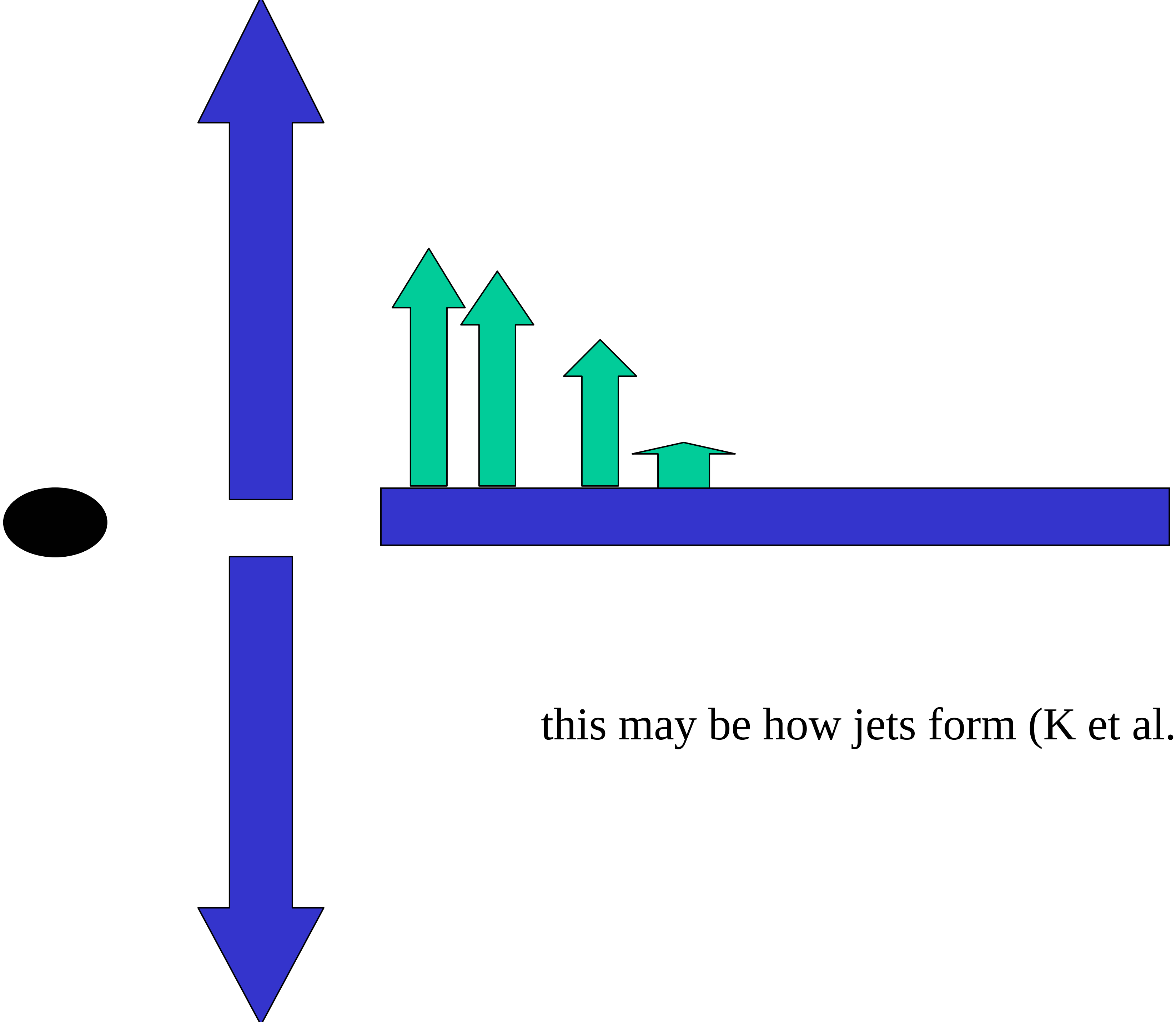
tangled magnetic fields transport angular momentum out, matter in

accretion

- but occasionally the fields all line up



- fields transport more a.m. out, more mass in -- amplifies field
- diffusion equation for mass becomes a wave equation



this may be how jets form (K et al., 2004)

- what about accretion rates?
- no reason for mergers to know about Eddington limit so Mdot may exceed Eddington rate
- observational selection favours AGN near L_{Edd}, especially at high z
- need high Mdot to grow SMBH in time
- do we see evidence of super-Eddington accretion in AGN?

- X-ray observations of some narrow-line quasars with $L \sim L_{Edd}$ show blueshifted absorption lines, suggesting *outflows*

e.g. PG1211+143 (Pounds et al., 2003a):

$v \simeq 0.08c$

(from H and He-like Fe, S, Mg,…)

- observed ionization parameter $\xi = L/NR^2$ and ionizing luminosity L give

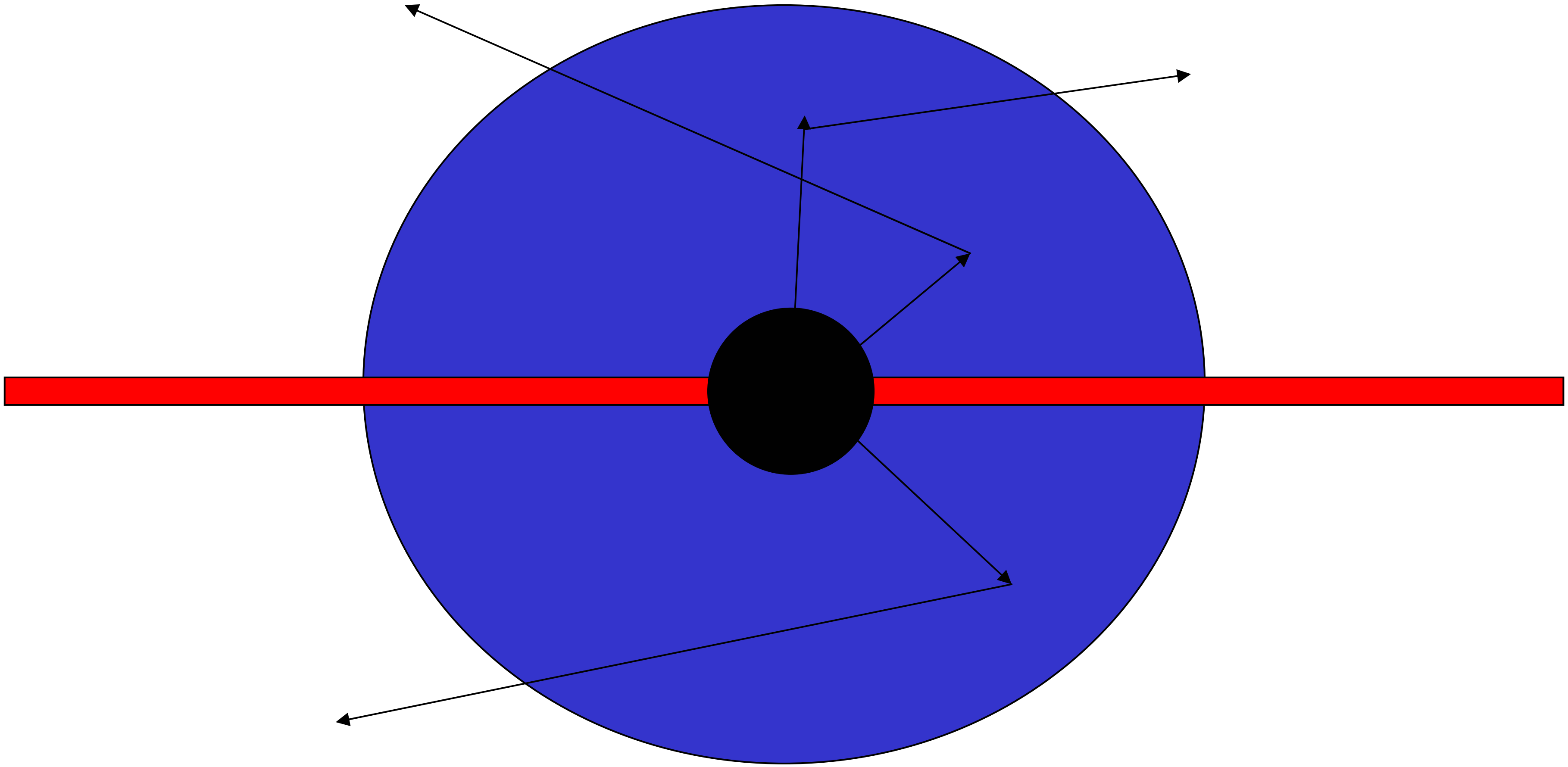
$$\dot{M}_{out} = 4\pi b R^2 N v m_H$$

- *then*

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

- other systems similar, e.g. PG844+349 (Pounds et al., 2003b) PDS 465 (Reeves et al., 2003)

- suggests radiation field $L \sim L_{Edd}$ transfers $\sim$ *all* its momentum to the outflow, i.e. $\tau_{scattering} \sim 1$



- $\tau \sim 1$ is plausible since $N_H \sim 10^{24}$ cm^{-2}
- also $L \approx L_{Edd}, \dot{M}_{out} > \dot{M}_{Edd}$
- suggests response to super-Eddington accretion is to expel excess accretion as an outflow with thrust given purely by L_{Edd}, i.e.

$$\boxed{\dot{M}_{out} v \approx \frac{L_{Edd}}{c}}$$

- NB mechanical energy flux $\frac{1}{2}\dot{M}_{out} v^2 \approx \frac{L_{Edd} v}{c}$ requires knowledge of v or $\dot{M}_{out}$

relevance to growth of nuclear black holes:

most of mass assembled by luminous accretion
(Soltan, 1982, Yu & Tremaine, 2002)

- probably need to grow on Salpeter timescale – i.e. $L \sim L_{\mathrm{Edd}}$
- suggests $\dot{M}_{acc} > \dot{M}_{Edd}$
- outflows with thrust L_{Edd}/c must have been common as nuclear black holes grew

- effect on host galaxy must be large: it must absorb most of outflow momentum and energy – galaxies are not `optically thin' to matter – unlike radiation

- e.g. PG1211+143 could have accreted at $\sim 1 M_\odot \text{ yr}^{-1}$ for $\sim 5\times 10^7$ yr

- mechanical energy deposited in this time $\sim 10^{60}$ erg

- cf binding energy $\sim 10^{59}$ erg of galactic bulge with $M \sim 10^{11} M_\odot$ and velocity dispersion $\sigma \sim 300 \text{ km s}^{-1}$

- re-examine effect of super-Eddington accretion on growing nuclear black holes (Silk & Rees, 1998; Haehnelt 1998; Blandford, 1999; Fabian, 1999)

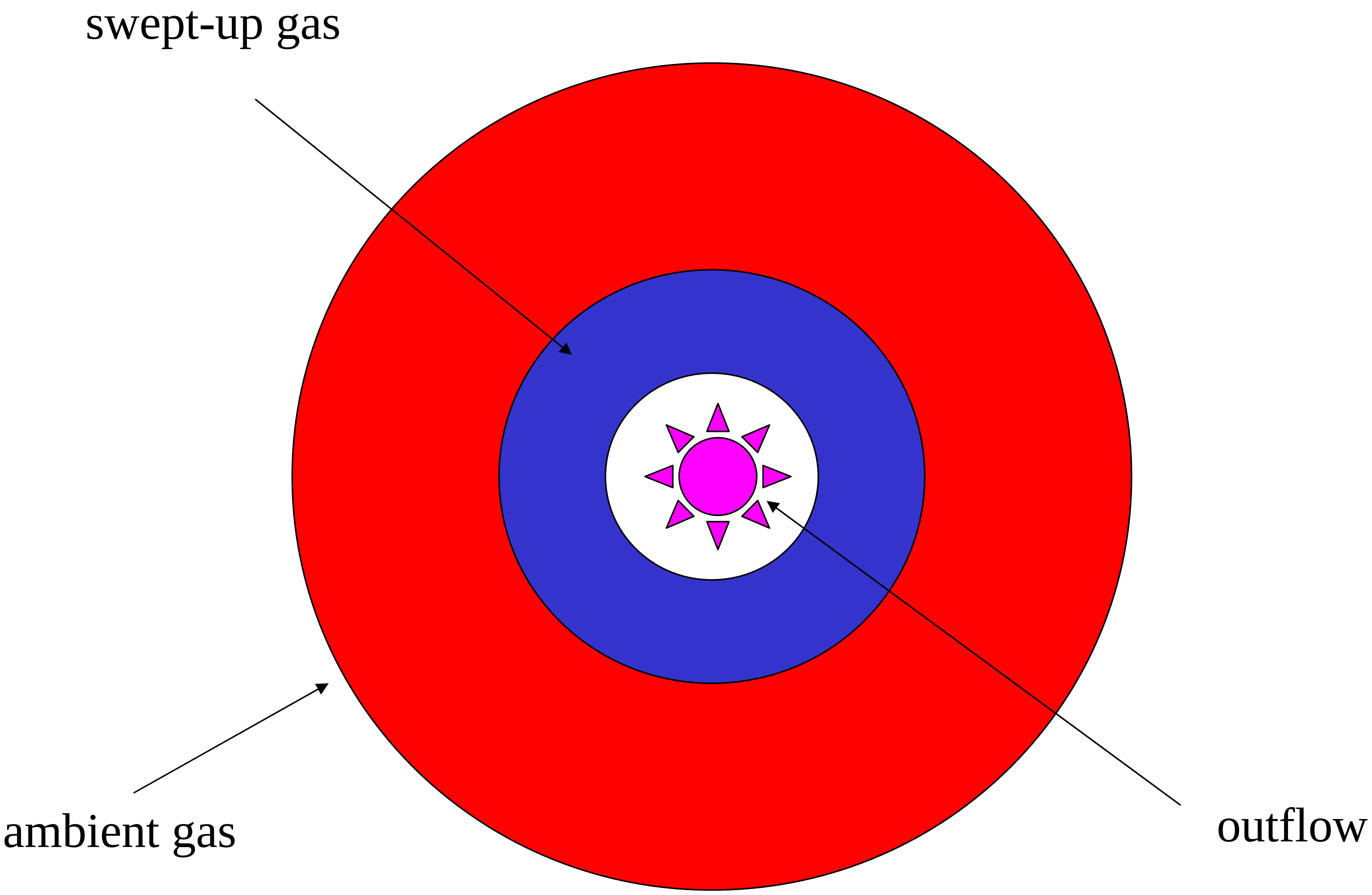
- model protogalaxy as an isothermal sphere of dark matter: gas density is

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

with $f_g = \Omega_{\mathrm{baryon}}/\Omega_{\mathrm{matter}} \simeq 0.16$

- so gas mass inside radius R is

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


swept-up gas
ambient gas
outflow

- dynamics depend on whether gas cools (`momentum-driven’) or not (`energy-driven’)

- Compton cooling is efficient out to radius R_c such that

$$M(R_c) \sim 2\times 10^{11}\sigma^3_{200}M_8^{1/2}M_\odot$$

where $\sigma_{200} = \sigma/200\ \mathrm{km\ s^{-1}}$, $M_8 = M/10^8 M_\odot$

- flow is momentum-driven (i.e. gas pressure is unimportant) out to $R = R_c$

- ram pressure of outflow drives expansion of swept-up shell:

$$\frac{d}{dt}[M(R)\dot{R}] = 4\pi R^2 \rho v^2 = \dot{M}_{out} v = \frac{L_{Edd}}{c}$$

so

$$M(R)\dot{R} = \frac{L_{Edd} t}{c}$$

Since $M(R) = 2f_g\sigma^2 R/G$ we get

$$R^2 = \frac{GL_{Edd} t^2}{2 f_g \sigma^2 c}$$

(integration constants negligible for large t)

Thus shell moves with constant speed $v_m = R/t$, with

$$v_m{}^2 = \frac{GL_{Edd}}{2 f_g \sigma^2 c}$$

- v_m increases with L_{Edd}, i.e. with BH mass M

- shell expands at speed v_m provided $R <$ cooling radius R_c

- outside R_c shell expands at higher (energy-driven) speed v_e

- v_e also increases with M

- now consider growth of M by accretion

- initially M small, $\dot{M}_{acc} > \dot{M}_{Edd}$ and $v_m < v_e <$ escape velocity ~ σ: hole accretes at rate $\dot{M}_{Edd}$

- eventually M large enough that $v_m < \sigma < v_e$: M cannot grow beyond the point where $v_m = \sigma$

- thus given an adequate gas supply, e.g. through mergers, hole grows until $v_m^2 = GL_{Edd}/2f_g\sigma^2 c = \sigma^2$, i.e.

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

or $M \simeq 1.5\times 10^8 \sigma_{200}^4 M_\odot$

(King, 2003)

- this is very close to the observed relation (Ferrarese & Merritt, 2000; Gebhardt et al., 2000; Tremaine et al, 2002)

- if instead $L_{BH} = \Gamma L_{Edd}$, derived M goes as Γ^{-1} –
  cf Murray, Quataert & Thompson (astro-ph/0406070)
  for absorption of UV from accretion

- if swept-up mass ends as bulge stars, get $M^{5/4} \sim M_{bulge}$
  or

$$M \sim 7\times 10^{-4} M_8^{-1/4} M_{bulge}$$

- this derivation requires largely spherical geometry (small a.m. to define disc plane only)

- would not halt inflow if most mass lies in a plane – requires most mass growth before this point

- derivation requires most mass growth in super-Eddington phases

- few observed AGN in such phases, so either obscured, or high z

- observed super-Eddington quasars are late in gaining mass – low M rather than high $\dot{M}_{acc}$