Accretion

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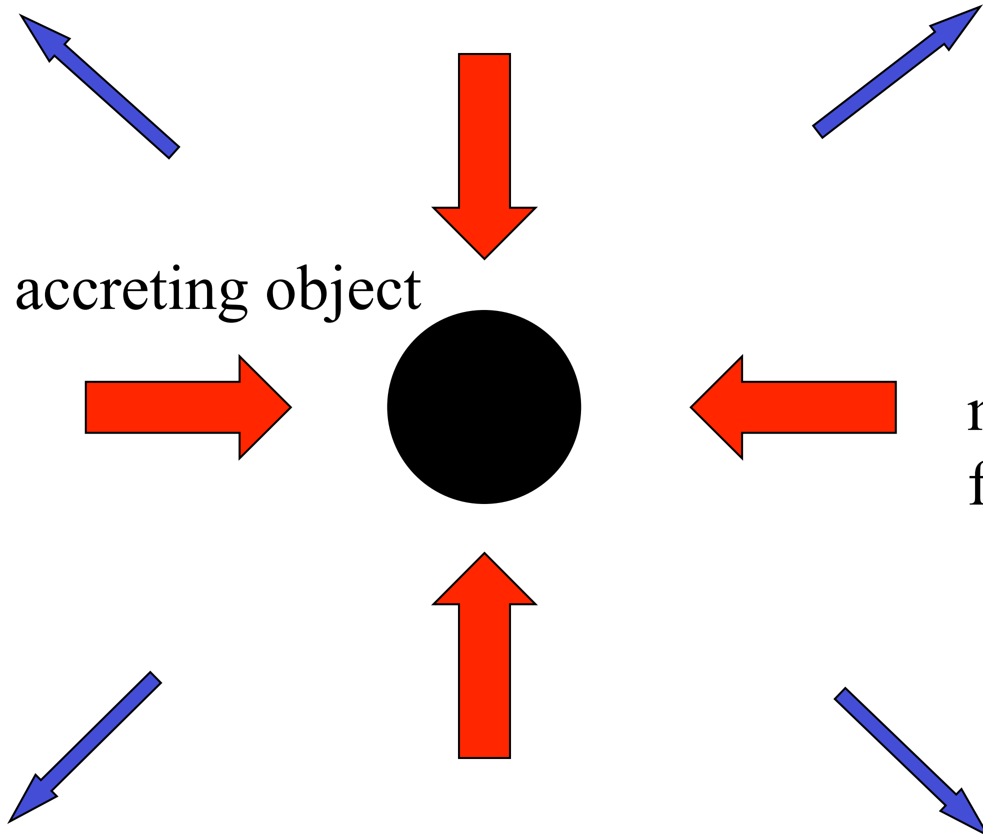
accretion = release of gravitational energy from infalling matter



but accreting matter always has (specific) angular momentum

$$j \sim (GMR_0)^{1/2}$$

where M is gravitating mass at radius R_0 from accretor

so even if destabilized it hangs up centrifugally at some radius

$$R_{\rm circ} \sim \left(\frac{j^2}{GM_{\rm accretor}}\right)^{1/2} \sim fR_0 >> R_{\rm accretor}$$

e.g in a close binary, $R_{\rm circ} \sim$ binary separation
feeding AGN: infalling matter has $R_{\rm circ} >> R_s$(SMBH)

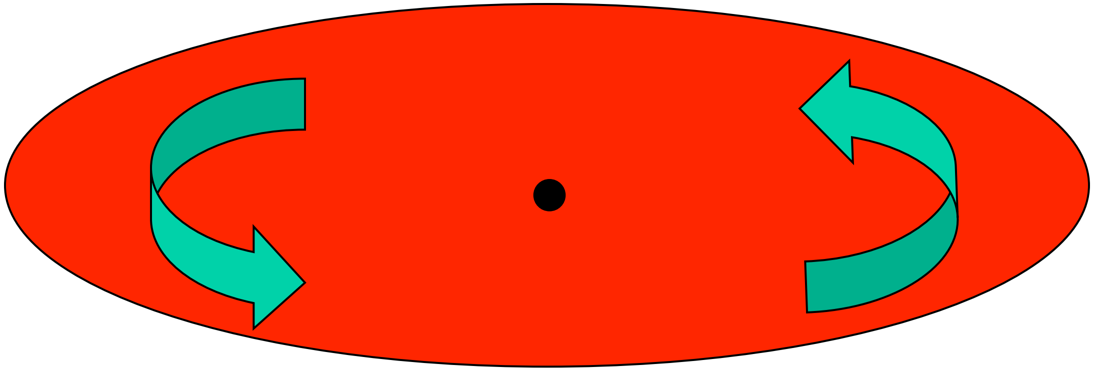
must lose angular momentum in order to accrete so

1. spherical (Bondi) accretion is never a good approximation

2. accretion is *always* from a disc:

energy losses via dissipation are always faster than a.m. losses, and orbit of lowest energy for fixed angular momentum is a circle matter spirals in through a sequence of circular orbits.

this is an *accretion disc* – thickness H is smaller than radius R



accretion discs are universal

condition for a thin disc (H<<R)

disc is almost hydrostatic in z-direction, so

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$$\frac{1}{\rho}\frac{\partial P}{\partial z} = \frac{\partial}{\partial z}\left(\frac{GM}{(R^2+z^2)^{1/2}}\right)$$

but if the disc is thin, $z << R$, so this is

$$\frac{1}{\rho}\frac{\partial P}{\partial z} = -\frac{GMz}{R^3}$$

with $\partial P/\partial z \sim P/H,\ z \sim H$ and $P \sim \rho c_s^2,$ where c_s is sound speed, we find

$$H \sim c_s \left(\frac{R}{GM}\right)^{1/2} \sim \frac{c_s}{v_K} R$$

hence *thin disc requires Kepler velocity to be highly supersonic*

since $c_s \propto T^{1/2}$, *this requires that the disc can* ***cool.***

if this holds we can also show that

the azimuthal velocity is close to Kepler so for discs,

thin $\Longleftrightarrow$ Keplerian $\Longleftrightarrow$ efficiently cooled

*either **all three** of these properties hold, or **none** do!*

need some means of removing angular momentum: *viscosity*

early parametrization $\nu \sim \lambda u$ with typical length and velocity scales λ, u . Now argue that

$$\lambda < H, u < c_s$$

first relation obvious, second because supersonic random motions would shock. Thus set

$$\nu = \alpha c_s H$$

and argue that $\alpha < 1$, *but* no reason to suppose $\alpha = const$

`alpha—prescription' useful because disc structure only depends on low powers of α - but *no predictive power* surface density of disc changes diffusively on viscous timescale

$$t_{\rm visc} = \frac{R^2}{\nu} = \left(\frac{R}{H}\right)^2 \frac{1}{\alpha\Omega}$$

AGN disc: $H/R \sim 10^{-3}, \Omega(R) = (GM/R^3)^{1/2}$, so

$$t_{\rm visc} \sim 5 \times 10^{10} R_{\rm pc}^{3/2} M_8^{-1/2} \ {\rm yr!}$$

$(R_{\rm pc} = R/({\rm pc}),\ M_8 = M/10^8 M_\odot)$

-- gas feeding AGN must have tiny a.m. *before* forming a disc *physical* angular momentum transport

a disc has

$$\frac{\partial}{\partial R}(R^2\Omega) > 0, \quad \text{but} \quad \frac{\partial \Omega}{\partial R} < 0$$

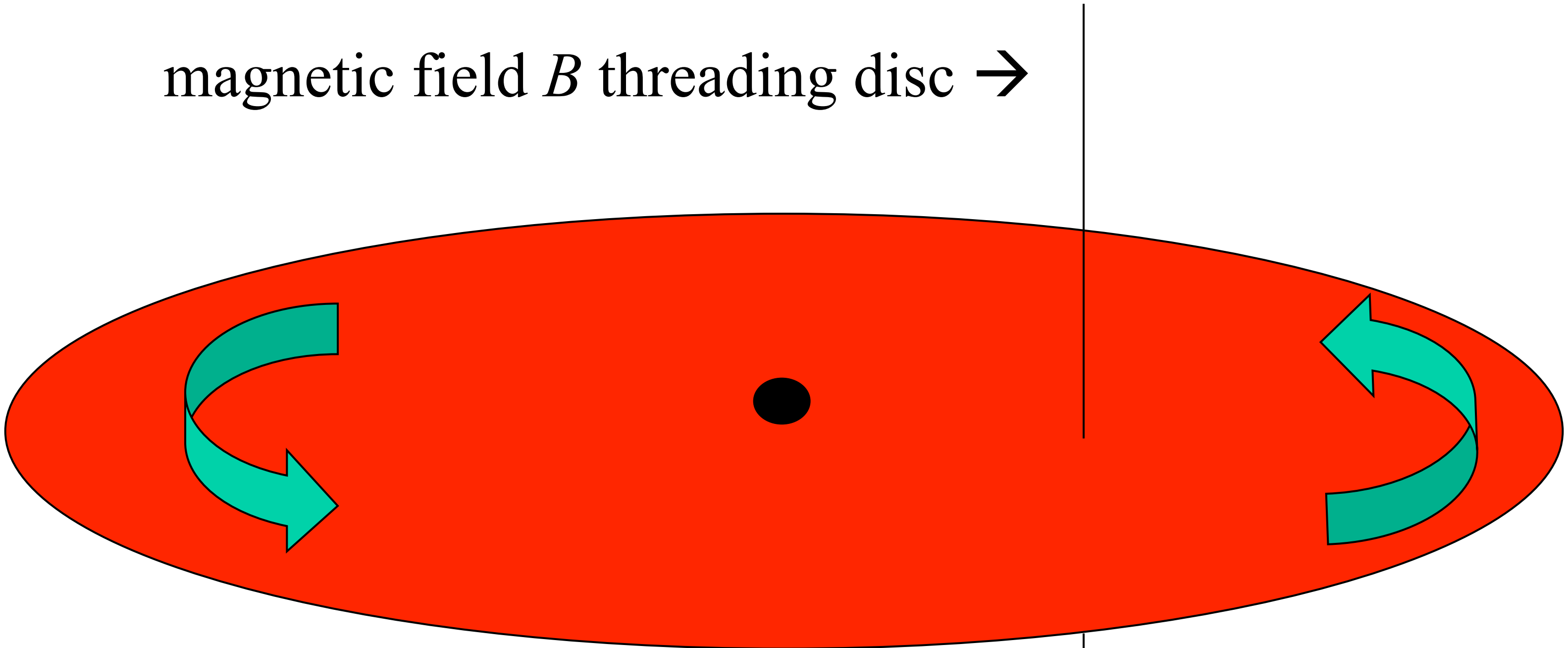
accretion requires a mechanism to transport a.m. outwards, but first relation → *stability* against axisymmetric perturbations (Rayleigh criterion).

most potential mechanisms sensitive to a.m. gradient, so transport a.m. *inwards*!

need a mechanism sensitive to Ω or v_K

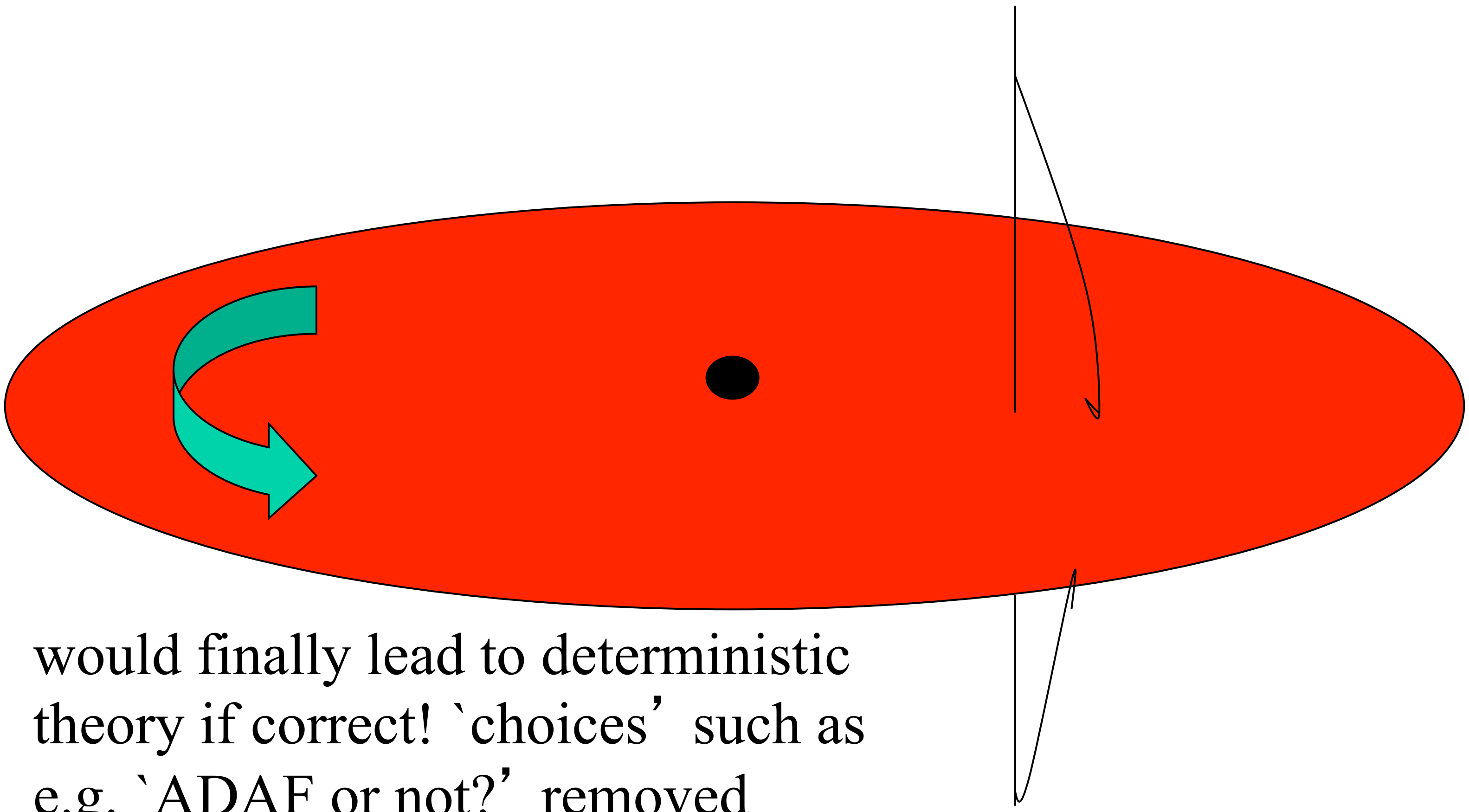
Balbus—Hawley (magnetorotational, MRI) instability

magnetic field B threading disc →



magnetic tension tries to *straighten* line
imbalance between gravity and rotation *bends* line

vertical fieldline perturbed outwards, rotates faster than surroundings, so centrifugal force > gravity → *kink increases.* line connects fast-moving (inner) matter with slower (outer) matter, and speeds latter up: ***outward a.m. transport***

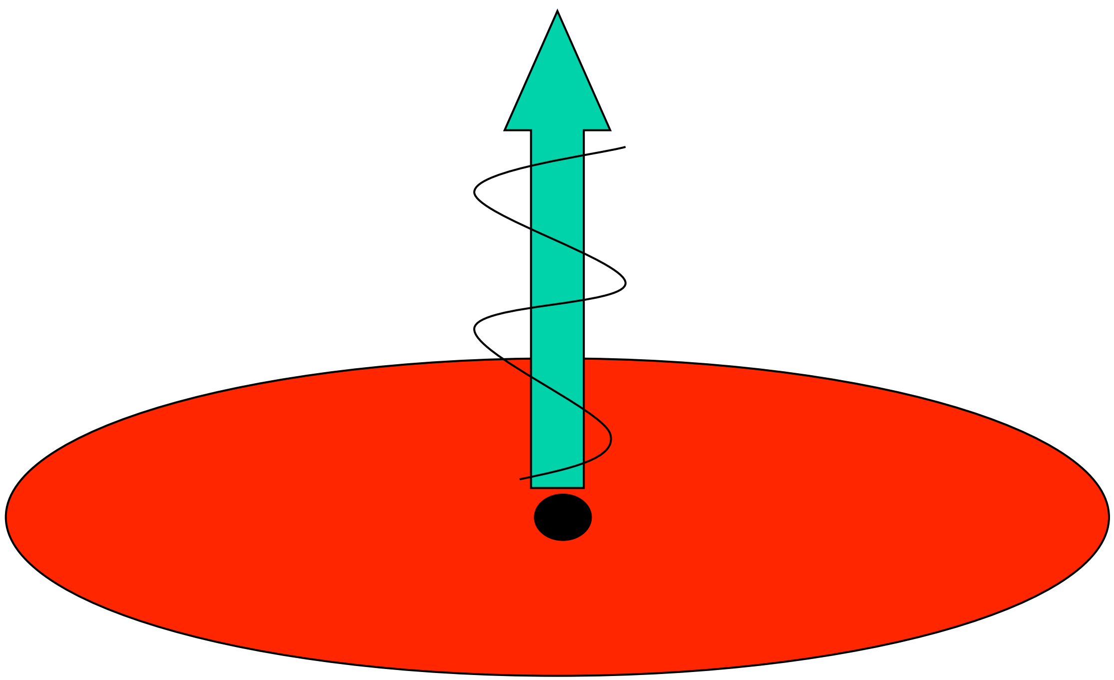


would finally lead to deterministic theory if correct! `choices' such as e.g. `ADAF or not?' removed

Jets

one observed form of outflow: jets with ~ escape velocity from point of ejection, ~ c for black holes

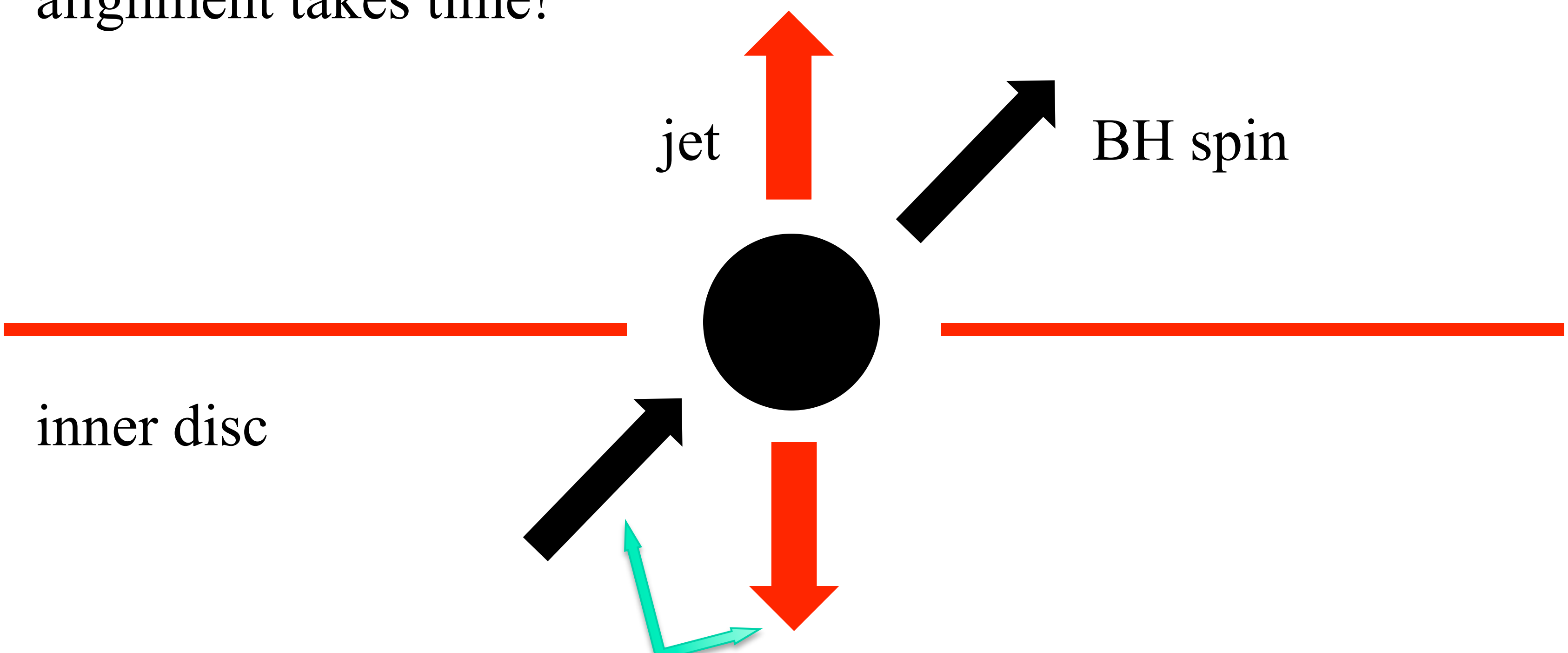
launching and collimation not understood – but Lorentz factors $\gamma >> 1$ probably require toroidal magnetic field, since



disc must choose choose to put a lot of energy into little matter jets generally come from deepest part of potential – near accretor,

so jet direction is orthogonal to plane of inner disc

this does not need to be the same as the BH spin direction:
alignment takes time!

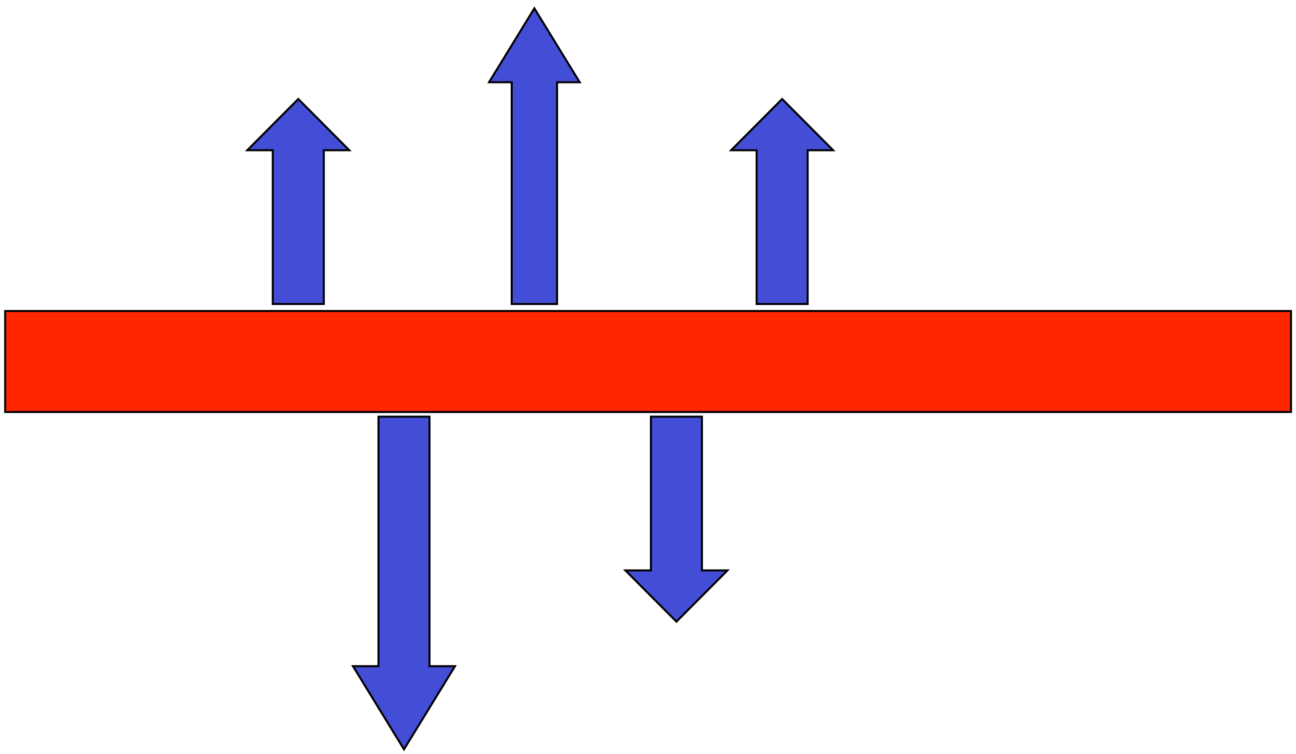


disc – spin alignment via Lense—Thirring effect + dissipation disc may have *two* states:

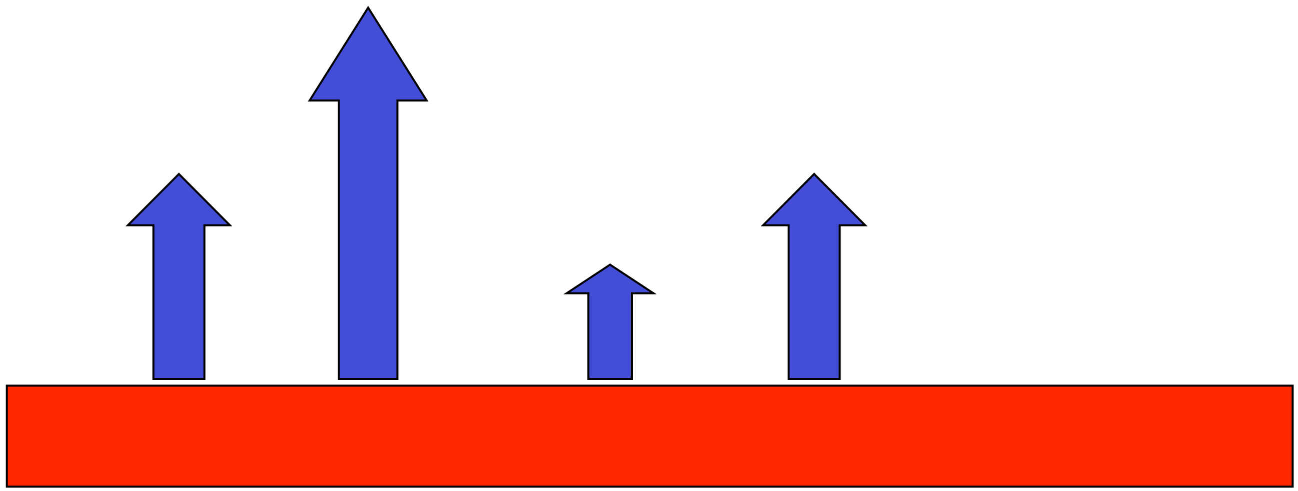
1. infall energy goes into radiation (standard)

2. infall energy goes into winding up internal disc field – thus

disc



generally vertical field directions uncorrelated in neighboring disc annuli (dynamo random); BUT



occasionally all fields line up → matter swept inwards, strengthens field → energy all goes into field → jet ???

(e.g. King, Pringle, West, Livio, 2004)

jets seen (at times) in almost all accreting systems: AGN, LMXBs etc accretion produces radiation: radiation makes pressure – can this inhibit further accretion?

radiation pressure acts on electrons; but electrons and ions (protons) cannot separate because of Coulomb force: radiation pressure force on an electron is

$$F_{\rm rad} = \frac{L\sigma_T}{4\pi c r^2}$$

(in spherical symmetry).
gravitational force on electron—proton pair is

$$F_{\rm grav} = \frac{GMm_p}{r^2} \qquad (m_e << m_p)$$

thus accretion is inhibited once $F_{\rm rad} > F_{\rm grav}$, i.e. once

$$L > L_{\rm Edd} = \frac{4\pi GMc}{\kappa} = 1.3 \times 10^{38}\frac{M}{M_\odot}\ {\rm erg\,s^{-1}}$$

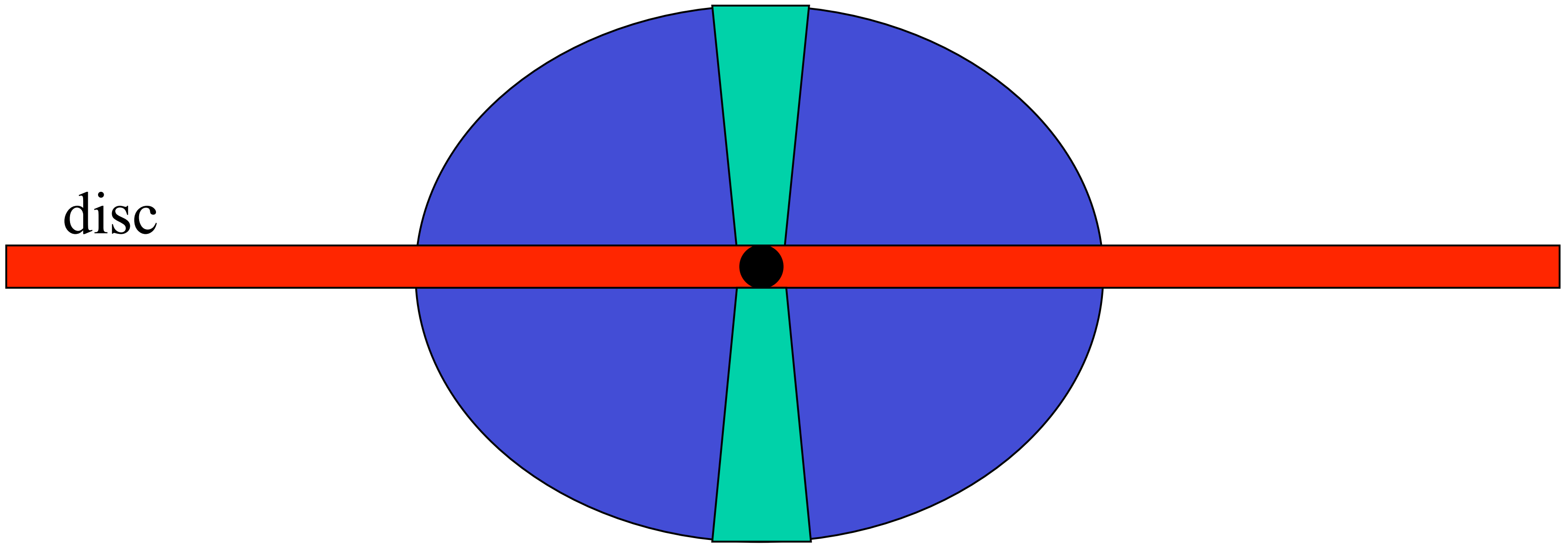
$$(\kappa \simeq \sigma_T/m_p = \ \text{opacity} \ \gtrsim \ \text{electron scattering})$$

so what happens if accretor is fed at rates

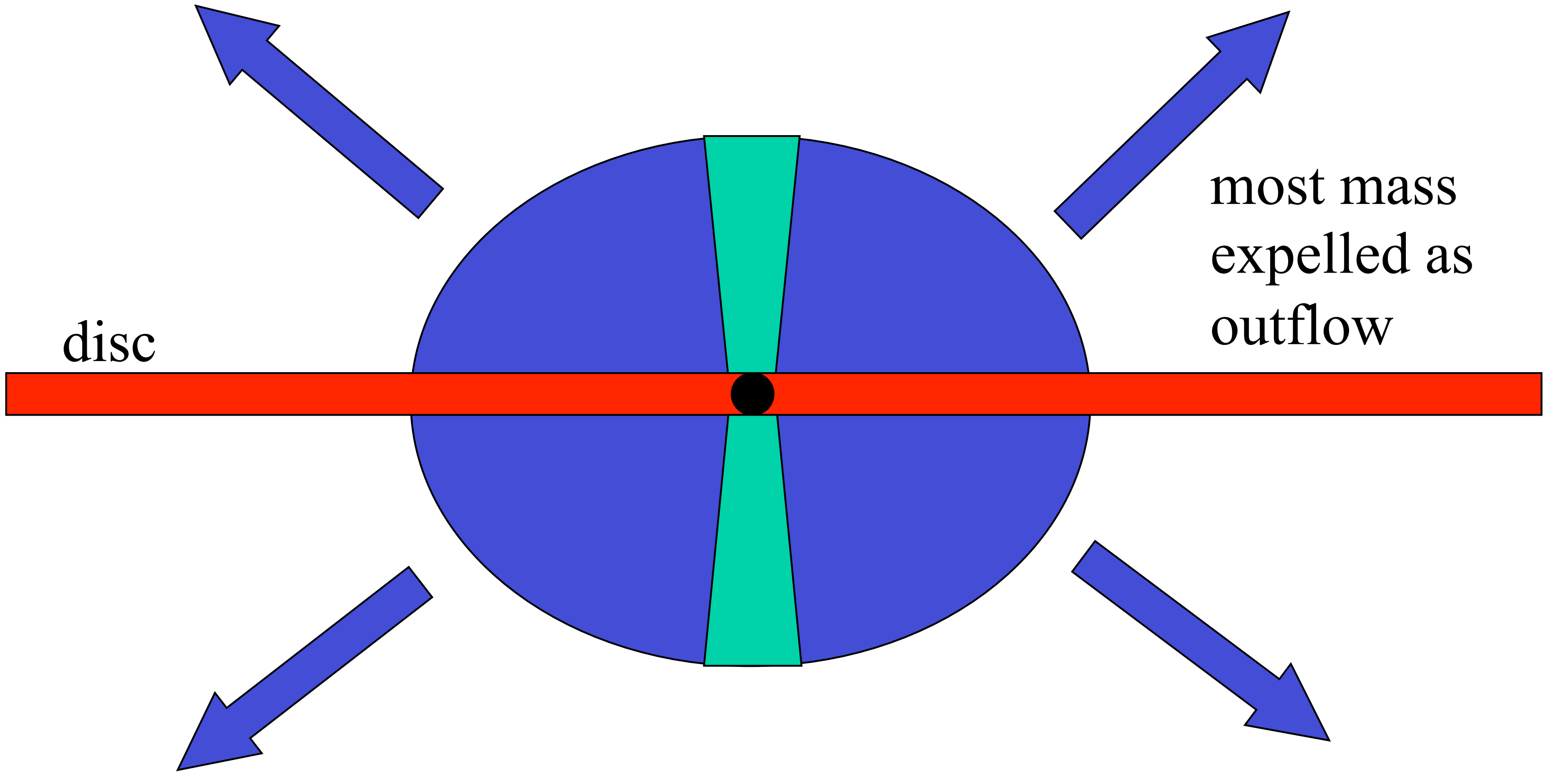
$$\dot M > \dot M_{\rm Edd} = L_{\rm Edd}/\eta c^2 \ ?$$

Super-Eddington Accretion

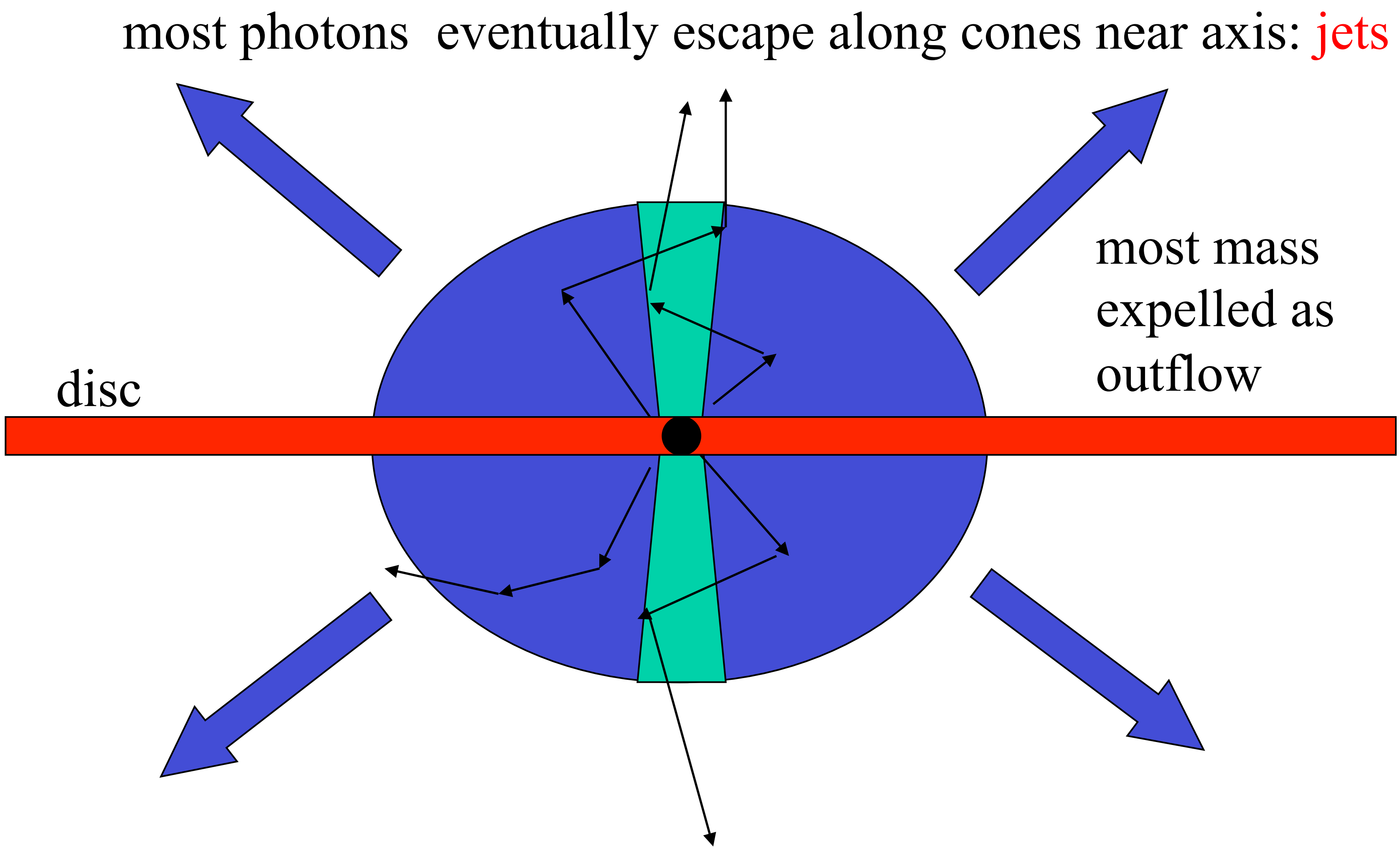
(Shakura & Sunyaev, 1973)



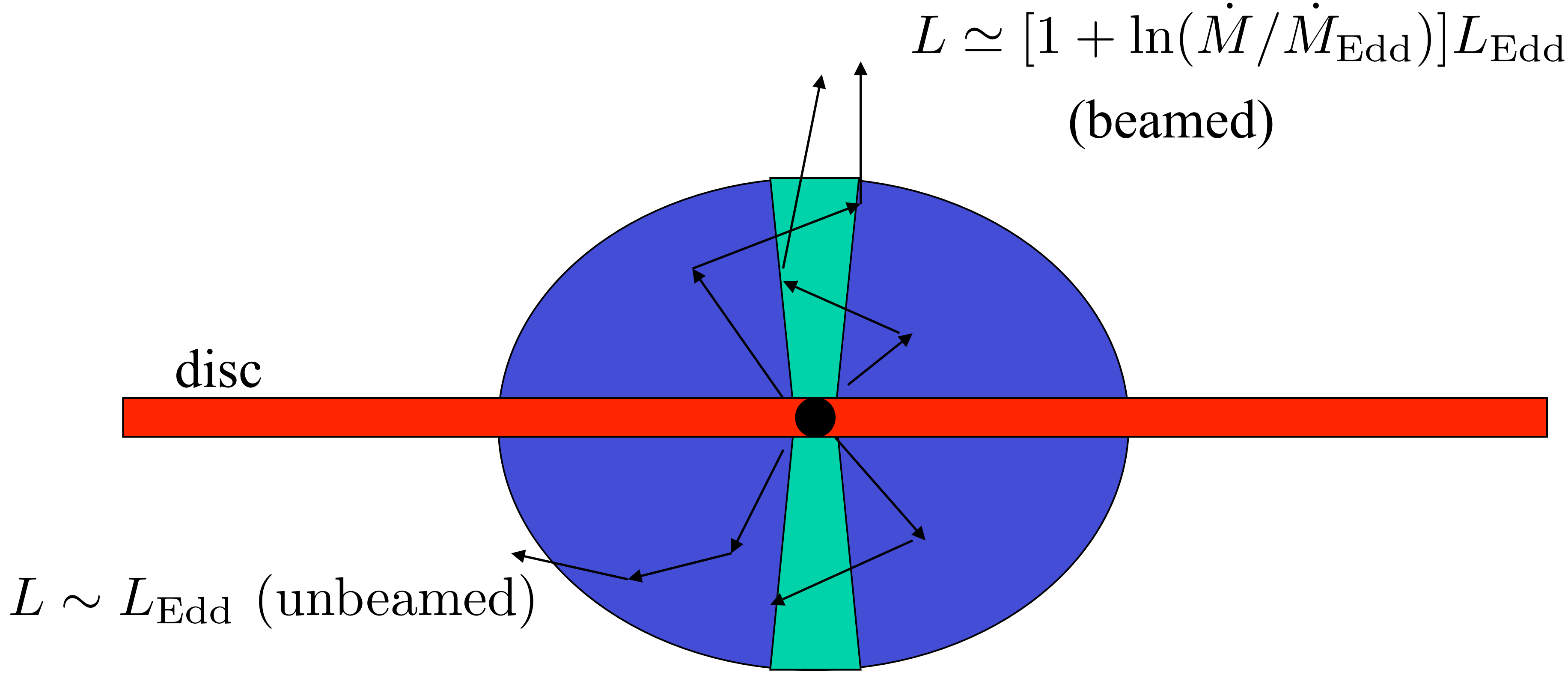
Super-Eddington Accretion



Super-Eddington Accretion

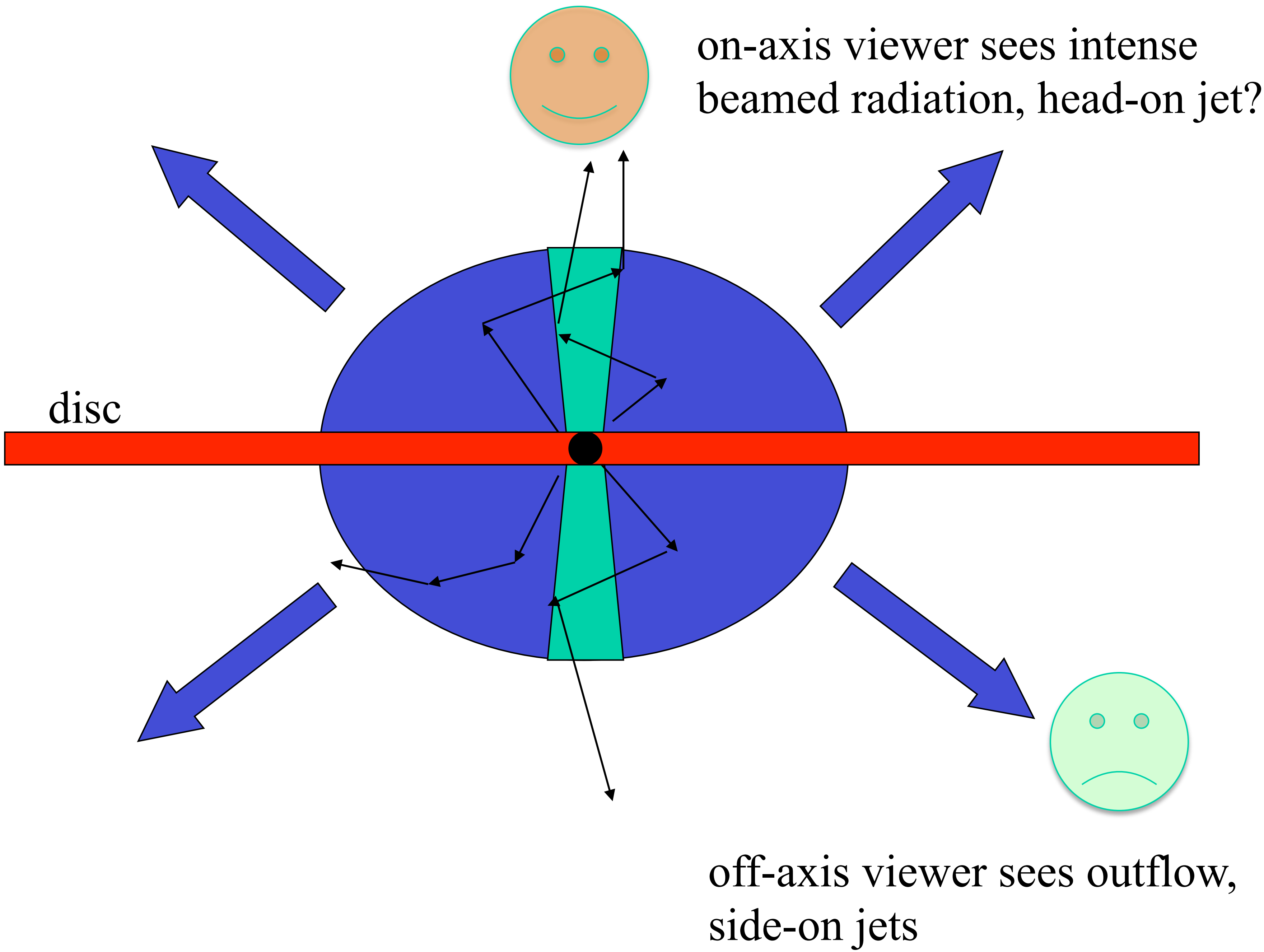


Super-Eddington Accretion



local Eddington limit requires $\dot{M}(R) = \dot{M}_{\rm Edd}\dfrac{R}{R_{\rm sph}}$, where

$R_{\rm sph} \sim (\dot{M}/\dot{M}_{\rm Edd})R_s$, $R_s =$ Schwarzschild radius – most matter expelled here


on-axis viewer sees intense beamed radiation, head-on jet?
disc
off-axis viewer sees outflow, side-on jets

off-axis viewer sees outflow, side-on jets: SS433

(cf Begelman, King & Pringle, 2006)

on-axis viewer sees intense beamed radiation

ultraluminous X—ray source = ULX

don't need exotic objects (e.g. intermediate-mass black holes) to make *most* ULXs, but just $\dot{M} >> \dot{M}_{\rm Edd}$

this happens naturally in various stages of binary evolution

e.g. ~ every high-mass XRB probably becomes a ULX (like SS433)
similarly, most ultracompact binaries start as ULXs

ULXs don't have to be black holes, just super-Eddington!

correlation $L_{\rm obs} \propto T^{-4}$ is observed for blackbody component of many ULXs (Kajava & Poutanen, 2009)

suggests beaming goes as

$$b \propto r^{-2} \propto \dot{M}^{-2}$$

(recall that $R_{\rm sph} \propto \dot{M} R_s$)

ULX luminosity is

$$L_{\rm obs} = \frac{L_E}{b}[1 + \ln(\dot{M}/\dot{M}_E)]$$

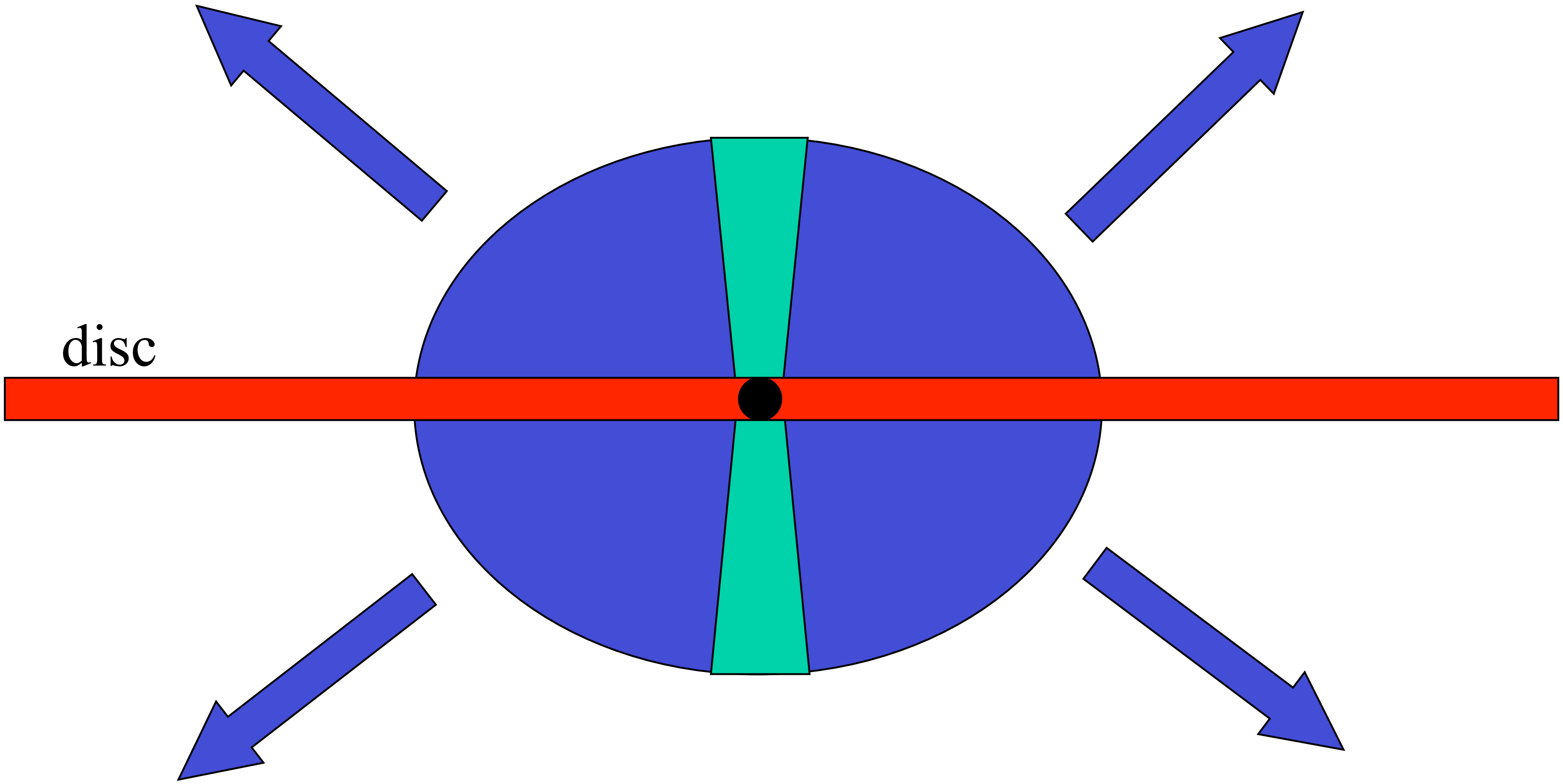
where b is beaming factor, set by inflow geometry.

consider intrinsic blackbody emission from source near BH,

luminosity $L_{bb} = lL_E$, size $R = rR_s \propto rM$

find $$L_{bb} \propto R^2T^4 \propto r^2M^2T^4 \propto L_{bb}^2T^4\frac{r^2}{l^2}$$

so $$\boxed{L_{\rm obs} = \frac{1}{b}L_{bb} \propto T^{-4}\frac{l^2}{r^2b}}$$



physically reasonable, as central structure is always Eddington but physical scale of funnel area goes as $r^2 \propto \dot{M}^2$, cf `Polish doughnuts'

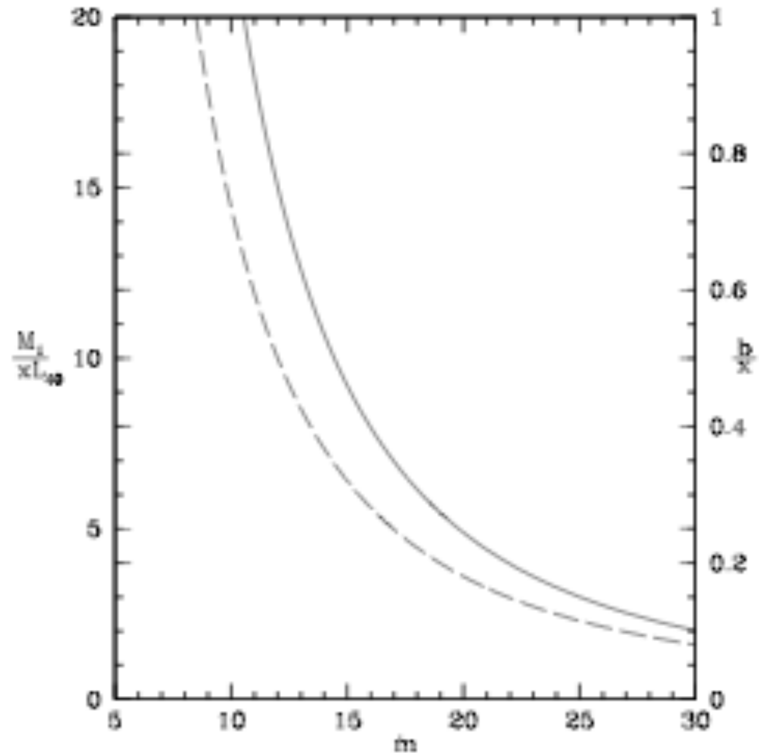
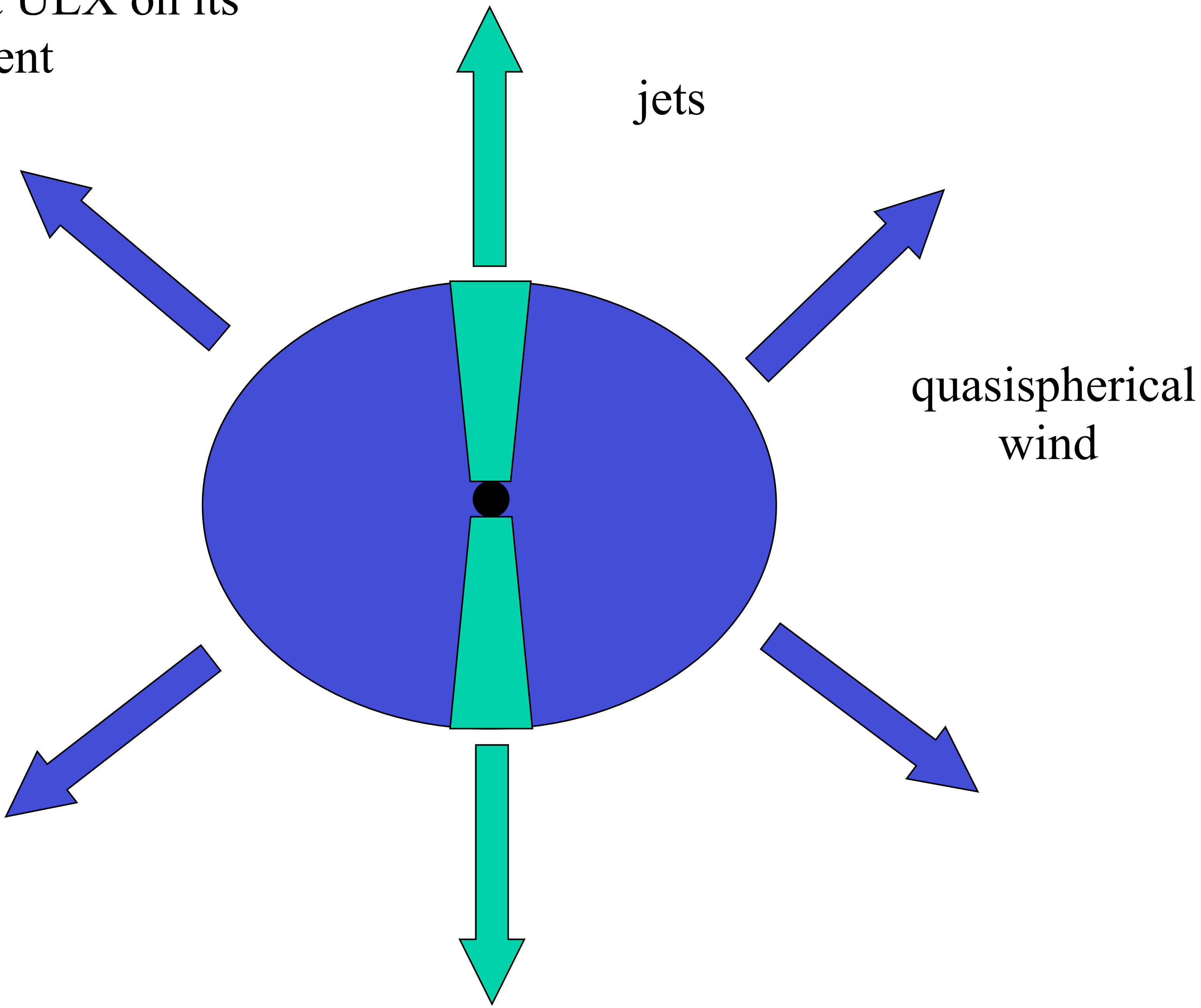


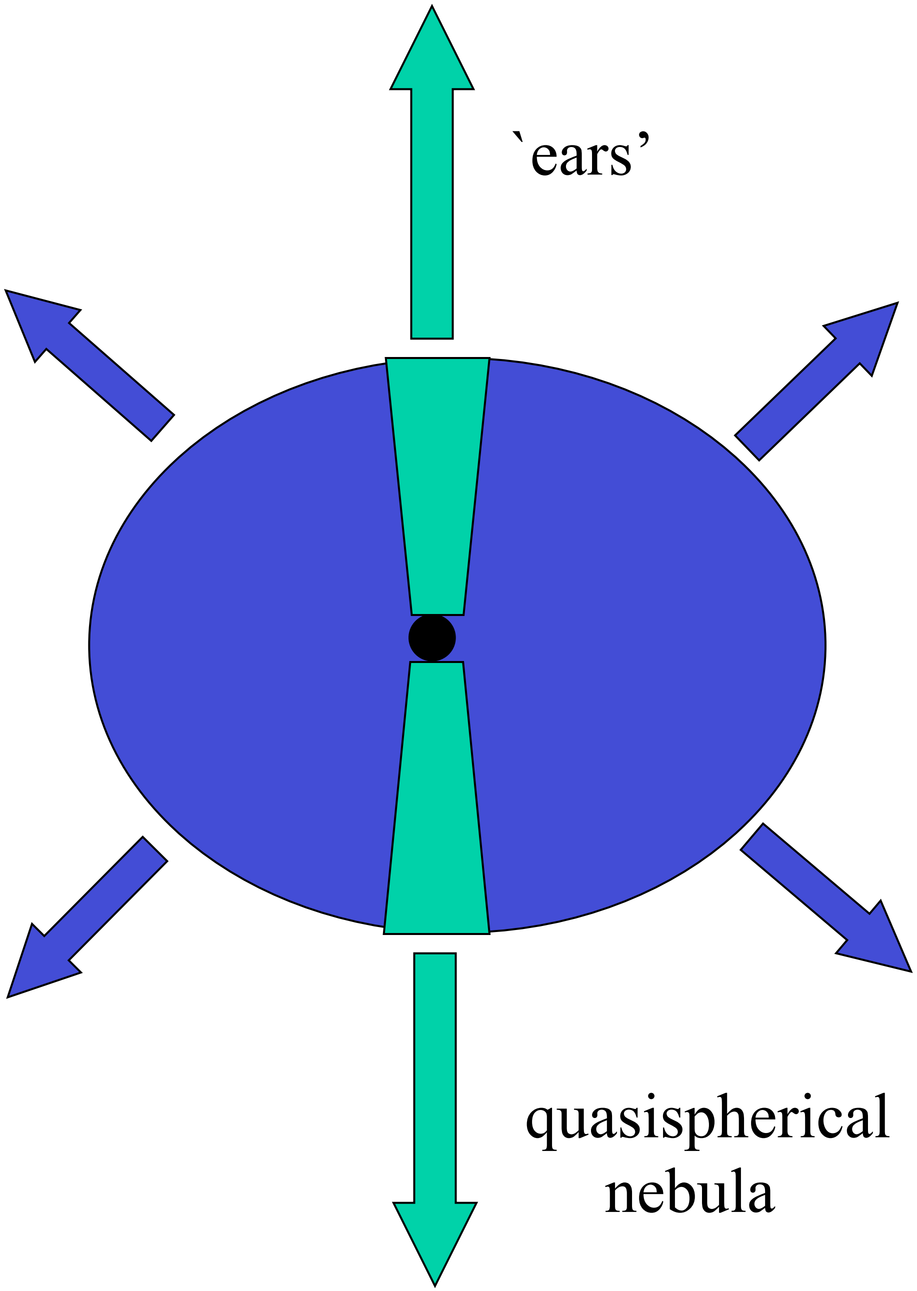
Figure 1. Beaming factor b (dashed curve) and accretor mass M_1 (solid curve, in $M_\odot$) as functions of the Eddington ratio $\dot{m}$ for ULXs. Here L_{40} is the inferred isotropic bolometric luminosity in units of 10^{40} erg s^{-1} and $x \sim 1$ a dimensionless quantity given by equation (7)

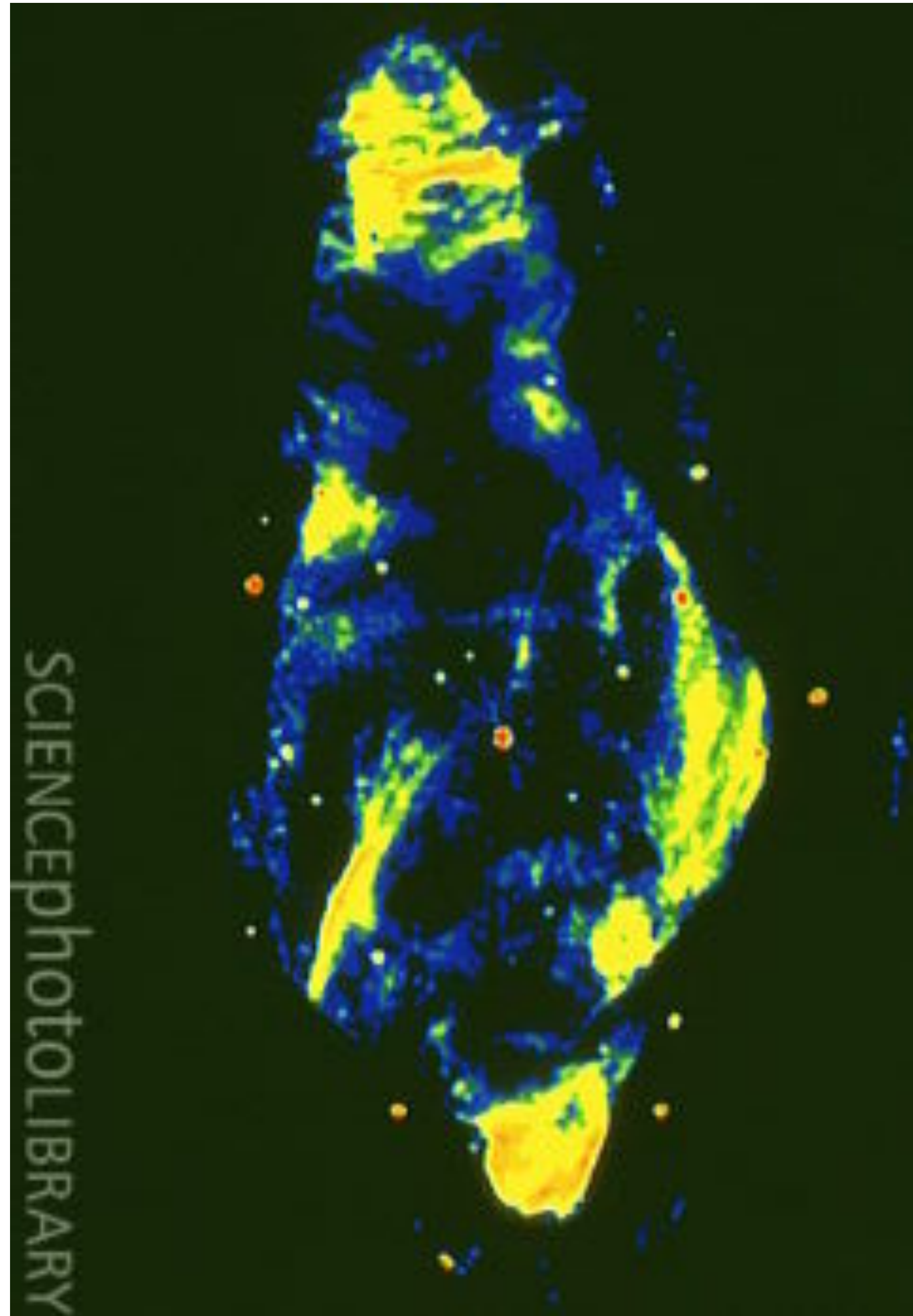
(King, 2009)

effect of a ULX on its environment



SS433 and W50





are there supermassive analogues of ULXs?

how super—Eddington can an AGN BH be?

in virial equilibrium, mass inside radius R obeys $GM/R \propto \sigma^2$

with $\sigma =$ velocity dispersion of host galaxy

hence a gas mass $M \sim f_g \sigma^2 R/G$ can fall in, on a timescale

$t \sim R/\sigma$, so maximum accretion rate is

$$\dot{M}_{\rm dyn} \sim \frac{f_g \sigma^3}{G}$$

compare with Eddington accretion rate $\dot{M}_{\rm Edd} \sim \dfrac{4\pi GM}{\kappa\eta c}$

➔ Eddington ratio

$$r_{\rm Edd} = \frac{\dot{M}_{\rm dyn}}{\dot{M}_{\rm Edd}} = \frac{f_g \sigma^3 \kappa \eta c}{4\pi G^2 M} = \frac{\eta c}{4\sigma} \simeq 50 \frac{\eta_{0.1}}{M_8^{1/4}},$$

using M—sigma relation $M \simeq \frac{f_g \kappa}{\pi G^2} \sigma^4$

hence *AGN have only modest Eddington ratios:*

leads to M – sigma relation (King 2003, 2005)

as quasispherical outflow shuts off accretion on to SMBH *can AGN ever be more super—Eddington than this?*

for a star, the $\dot{M} \sim \frac{\sigma^3}{G}$ argument produces

$$\dot{M} \sim \frac{M_2}{P}$$

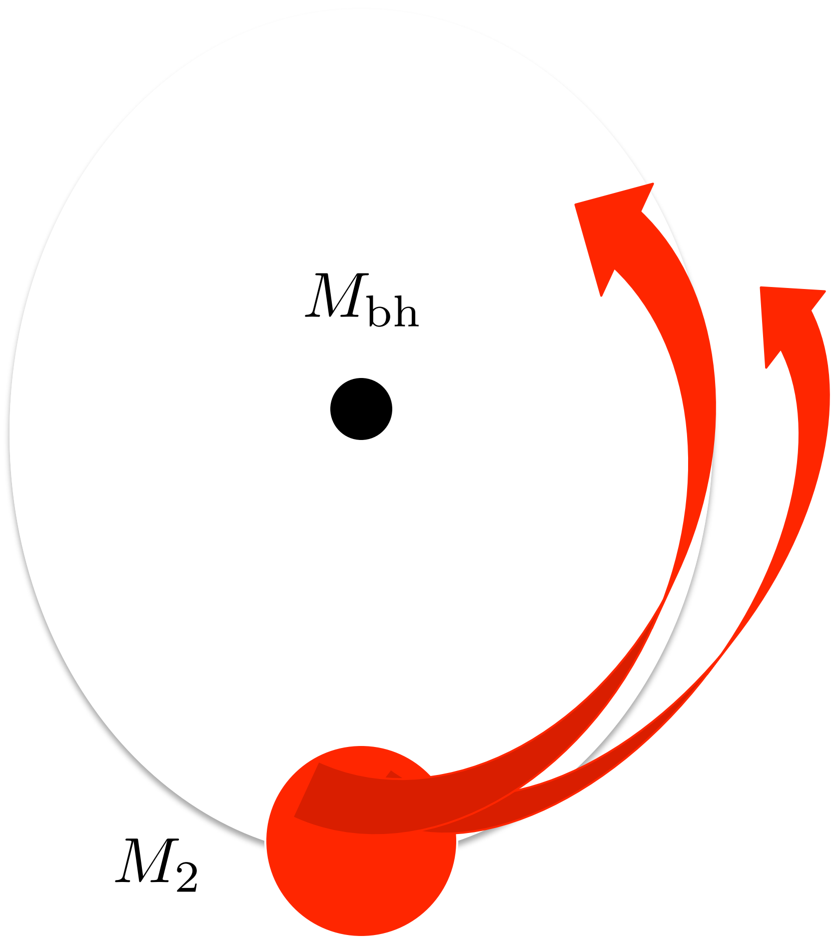
where P is the period of the circular orbit when star fills Roche lobe

this obeys $M = 0.11 P_{\rm hr} M_{\odot}$, with $P_{\rm hr} =$ period in hours

this suggests $\dot{M} \sim 10^4 M_{\odot}\ {\rm yr}^{-1}$

but this is deceptive!

in practice stars do not have circular orbits near a supermassive black hole, but are scattered in on near—parabolic orbits and disrupted at pericentre $R = a$



half of star unbound from SMBH – bound half has a range of return times

$$T \sim \frac{2\pi G M_{\rm bh}}{E^{3/2}}$$

where E is - orbital energy: this has a spread

$$E \sim \frac{G M_{\rm bh}}{a^2} R_2$$

but tidal lobe filling at pericentre requires

$$\frac{R_2}{a} \sim \left(\frac{M_2}{M_{\rm bh}}\right)^{1/3}$$

so spread in T is $\sim P \left(\frac{M_{\rm bh}}{M_2}\right)^{1/2} \sim 10^4 P$

hence in practice we get only $\dot{M} \sim 1 M_\odot \ {\rm yr}^{-1}$

which is just Eddington for $M_{\rm bh} = 10^8 M_\odot$

tidal disruption requires $M \lesssim {\rm few} \times 10^6 M_\odot$ since otherwise star does not fill Roche lobe before accreting to SMBH

narrow parameter space for super—Eddington tidal disruption: is Sw 1644+57 (Bloom et al., 2011) this kind of event? distance >> previous events: suggests *beaming* of HE emission – like ULX?

Summary

- accretion is always via a disc – Bondi is never a good approximation
- thin ⇐⇒ Keplerian ⇐⇒ disc cools: theory incomplete (viscosity!)
- AGN disc: $t_{\rm visc} > t_{\rm H}$ unless $R < 1$ pc
- jets orthogonal to inner disc plane, not necessarily parallel to BH spin
- ULX beaming goes as $b \propto r^{-2}$
- most ULXs are super-Eddington phase of close stellar—mass binaries
- ULX quasispherical winds ⇒ nebulae
- AGN analogues of ULXs rare: tidal disruptions like Sw 1644+57

this leads to determinate equation for observed luminosity

$$L_{\rm obs} = 2.2 \times 10^{36} m_1 \dot{m}^2 (1 + \ln \dot{m})\ {\rm erg\,s^{-1}}$$

with

$$m_1 = M_1/M_\odot, \dot{m} = \dot{M}/\dot{M}_E$$

so accretor mass required to explain observed luminosity $L_{\rm obs} = 10^{40} L_{40}\ {\rm erg\,s^{-1}}$

is

$$\frac{m_1}{L_{40}} = \frac{4500}{\dot{m}^2(1 + \ln \dot{m})}$$

so can explain most ULXs with stellar-mass binaries and modest Eddington factors (hence beaming)

not all ULXs must be black holes!

since $$\dot{M} = \dot{m}\dot{M}_E \propto L_E \dot{m} \propto (M_1/\eta c^2)\dot{m}$$

where η is the efficiency (about 0.1 for both neutron stars and black holes, larger Eddington factor $\dot{m}$ can compensate for smaller accretor mass, even with lower absolute accretion rate

thus a $10M_\odot$ black hole with $\dot{m} = 15$ produces same apparent luminosity as a $1.4M_\odot$ neutron star with $\dot{m} = 30$

neutron star has lower accretion rate (stronger beaming)
white dwarf ULXs also possible (supersoft)

beaming – luminosity correlation now predicts luminosity function

nearest ULXs are at ~ 0.7 Mpc, with luminosities ~ few times

$$10^{39} - 10^{40}\ \mathrm{erg\,s^{-1}}$$

agrees with observed LF (Mainieri et al., 2010)

NB ULXs in ellipticals *must be transient* (GRS 1915+105-like)
since all HMXBs have disappeared since star formation

in spirals both types of ULXs can coexist

pseudoblazars?

a ULX with the same Eddington factor as SS433 $(\dot{m} \sim 3000 - 10^4)$

would appear extremely bright — nearest would be at > 660 Mpc, with apparent luminosity

$$L > 10^{45}\ \mathrm{erg\,s^{-1}}$$

-- right distance and luminosity for an AGN, but

not centred on host galaxy – e.g. PKS 1413 + 135?

Summary

- stellar—mass binary can survive super—Eddington mass transfer by ejecting excess
- viewed off—axis these systems are like SS433, or X—ray transients
- viewed on—axis these are ULXs (`SS433-like, GRS1915+105-like')
- no need for exotic explanations (e.g. IMBH) – neutron star or even white—dwarf ULXs are possible
- beaming probably goes as $b \propto \dot{m}^{-2}$ (Eddington factor) – LF agrees
- pseudoblazars possible
- no bright AGN analogues of ULXs