Black Hole Accretion and Feedback

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black holes

escape velocity from surface of a star is $v = (2GM/R)^{1/2}$

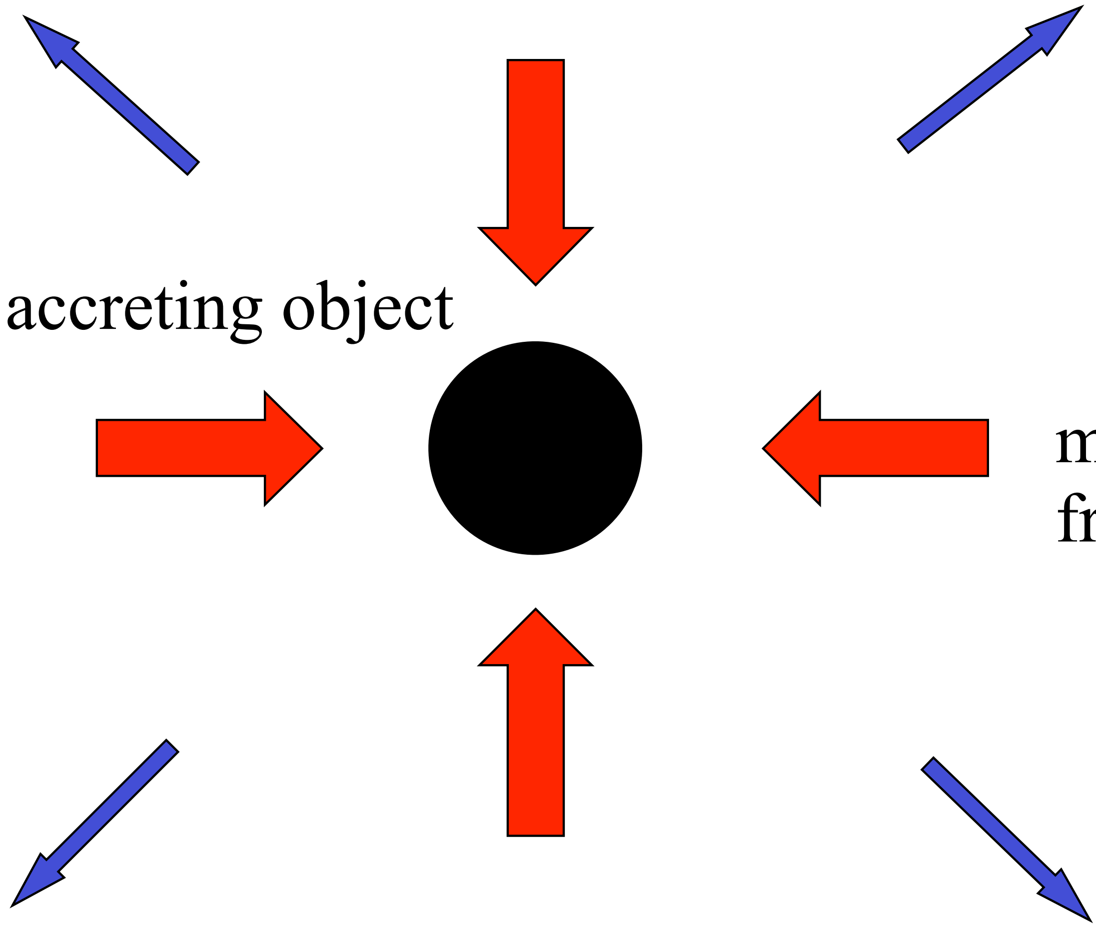
this reaches c for

$$R = \frac{2GM}{c^2} = 3\frac{M}{M_\odot}\ \mathrm{km}$$

Schwarzschild radius

black holes

accretion = release of gravitational energy from infalling matter



accreting object

matter falls in
from distance

energy released as electromagnetic
(or other) radiation

accretion energy release

for accretor of mass M, radius R, gravitational energy release per unit mass is

$$\Delta E_{\rm acc} = \frac{GM}{R}$$

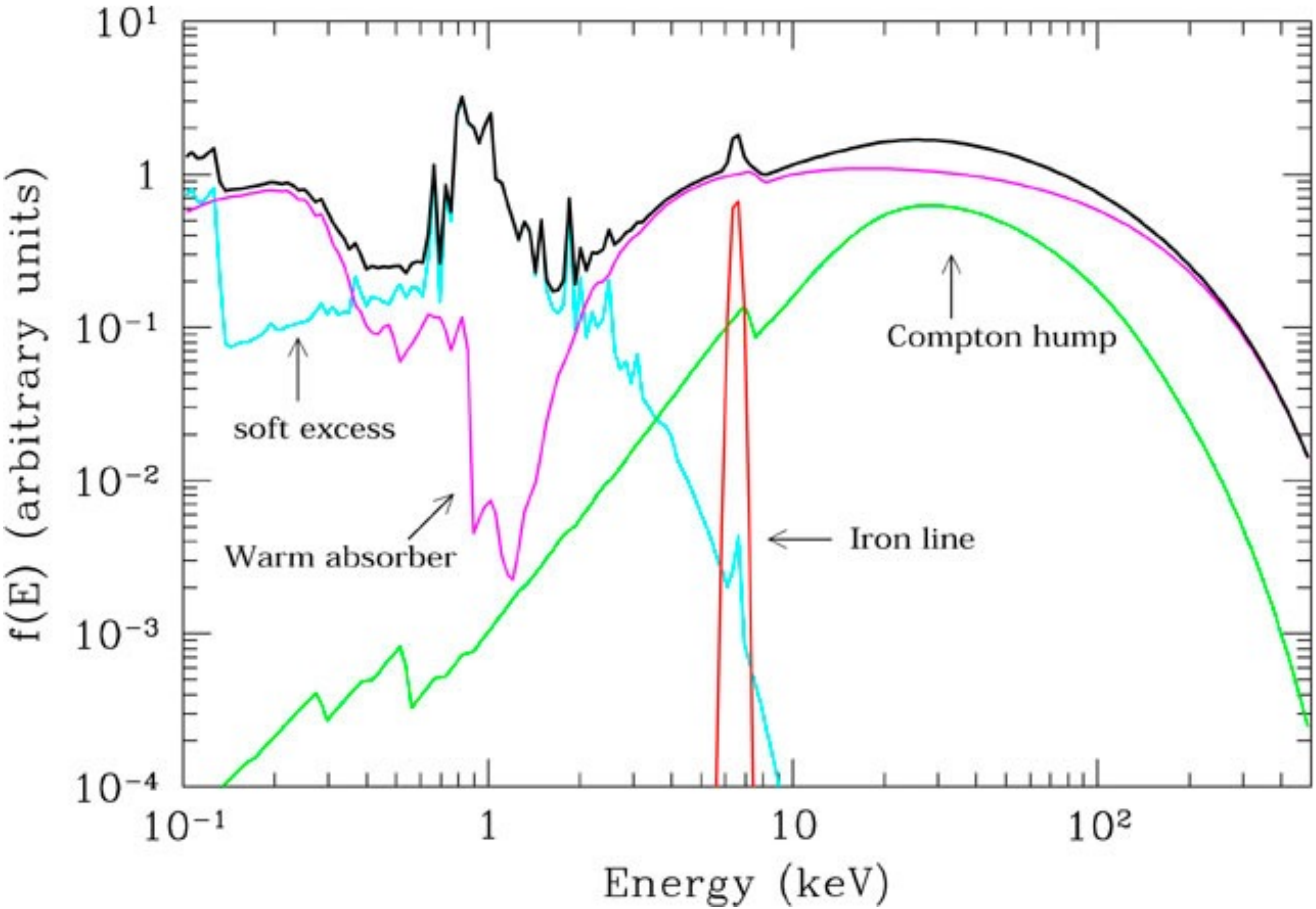
black hole: $R = 2GM/c^2$, so $\Delta E_{\rm acc} = c^2/2$

compare with nuclear yield (hydrogen burning): $\Delta E_{\rm nuc} = 0.007c^2$

accretion on to a black hole is the most efficient way of getting energy from normal matter: GR => accretion efficiency η is ~ 0.1

it must power the most luminous objects in the Universe

e.g. quasars, active galactic nuclei (AGN)



quasars/AGN broadband spectrum

Soltan argument

- integrated quasar luminosities give $L = \eta c^2 \dot{M}$

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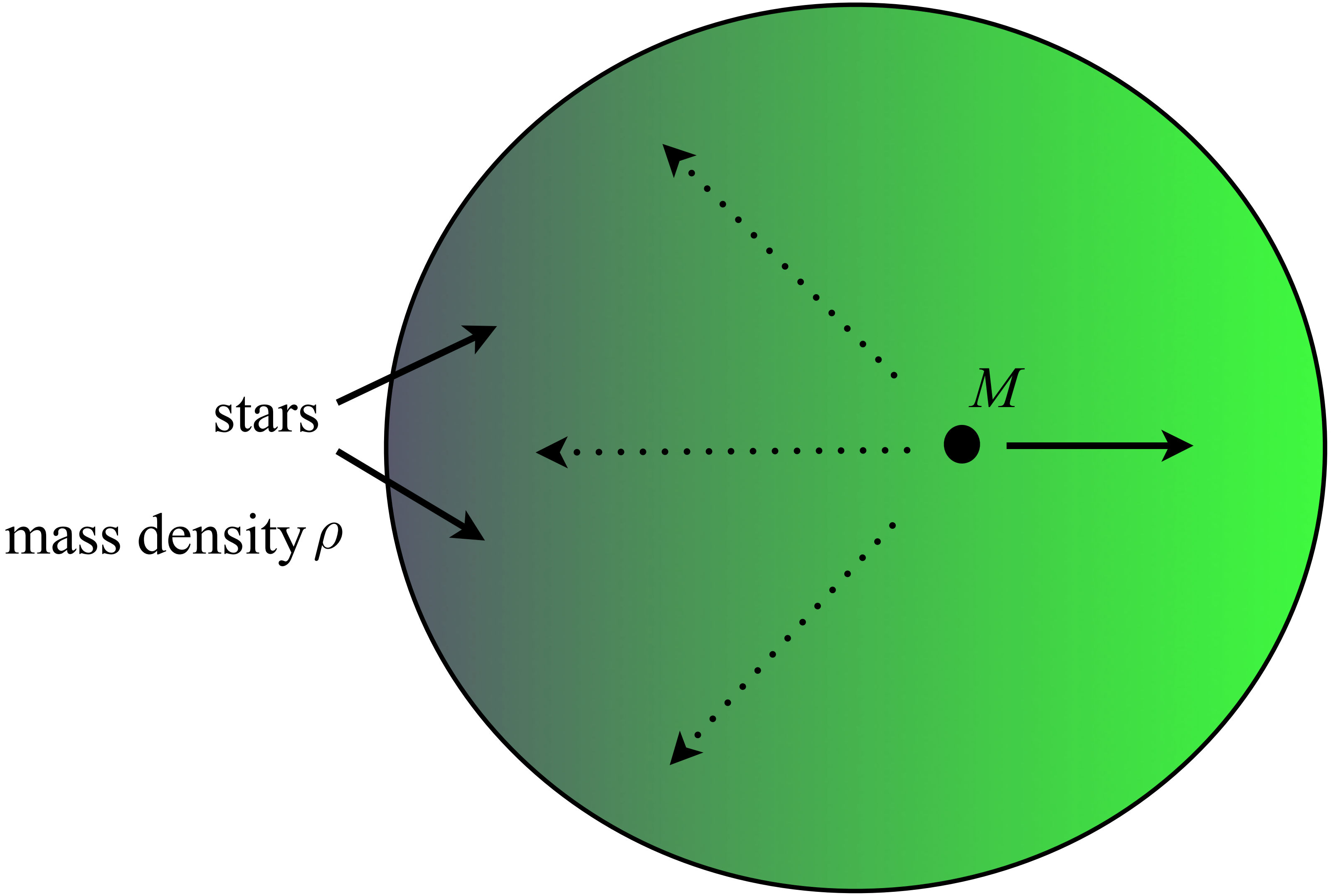
almost every galaxy hosts an SMBH

where are the holes? dynamical friction



moving mass M slowed by raising gravitational `wake' in star motions

dynamical friction

drag force gives equation of motion of moving mass M as

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{4\pi C G^2 M \rho}{v^2}$$

(e.g. Sparke & Gallagher, pp 224 - 5)

with $C \simeq 10$, giving

$$v^3 = v_0^3 \left(1 - \frac{t}{t_{\rm fric}}\right)$$

mass halts (spirals in to centre of mass of stellar distribution) after a time

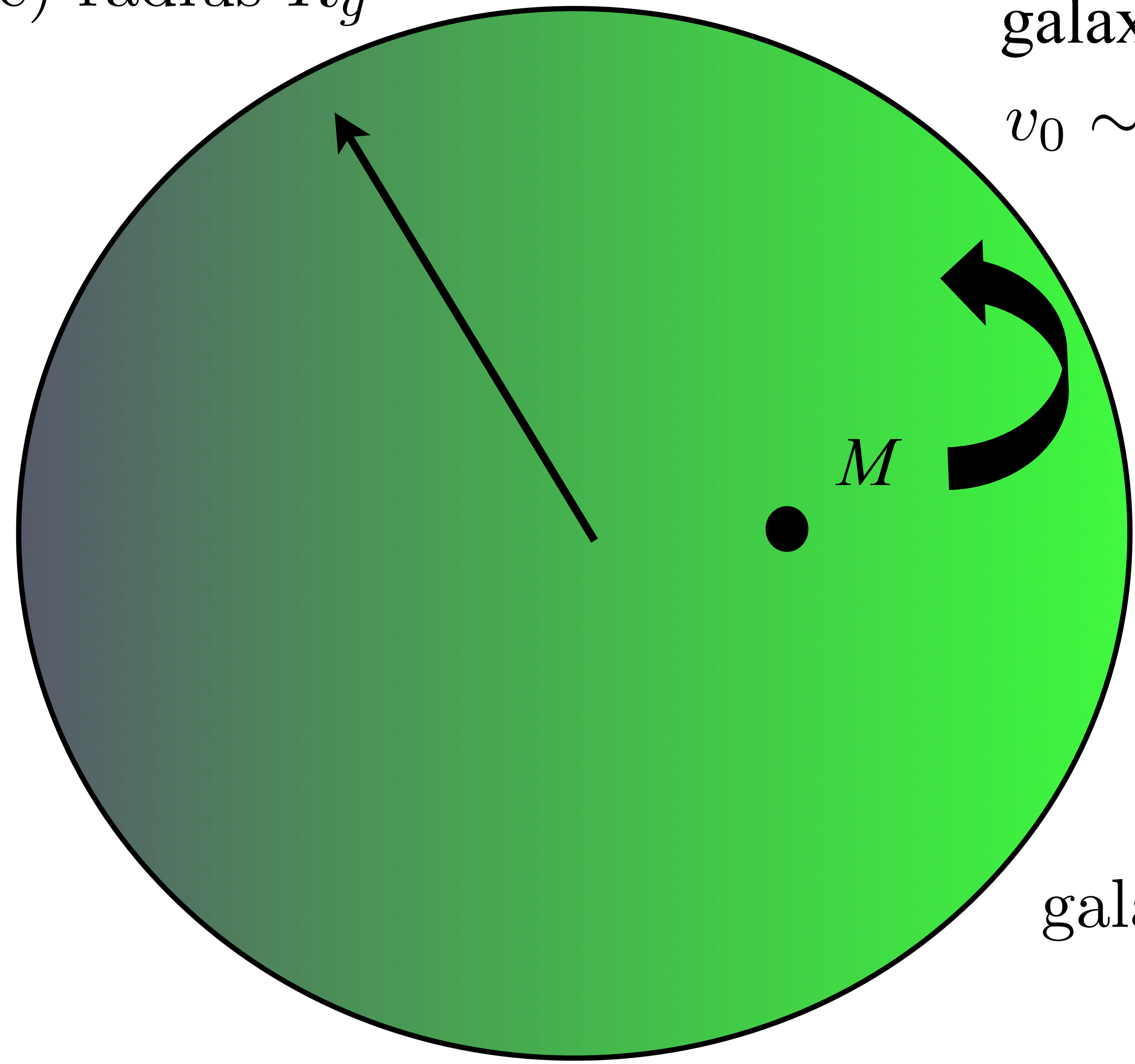
$$t_{\rm fric} = \frac{v_0^3}{12\pi C G^2 M \rho}$$

dynamical friction

galaxy (bulge) radius R_g

SMBH orbiting in galaxy:

$v_0 \sim (GM_g/R_g)^{1/2}$



galaxy mass M_g

dynamical friction

with $\rho = 3M_g/4\pi R_g^3$ we find

$$t_{\rm fric} = \frac{1}{9C}\frac{M_g}{M}\left(\frac{R_g^3}{GM_g}\right)^{1/2}$$

and with $M = 10^8 M_\odot$, $M_g = 10^{11} M_\odot$, $R_g = 10$ kpc we get

$$t_{\rm fric} \sim 10^8 \text{ yr}$$

short compared with age of galaxy - SMBH at centre of host

Books

- Introduction to Active Galaxies, Peterson

  good introduction to observed AGN properties, measurements etc

- Galaxies in the Universe, Sparke and Gallagher

  introduction to galaxy properties and evolution

- Accretion Power in Astrophysics, 3rd Ed., Frank, King & Raine (APIA)

  standard reference for basic accretion theory
  (SMBH part now rather dated)

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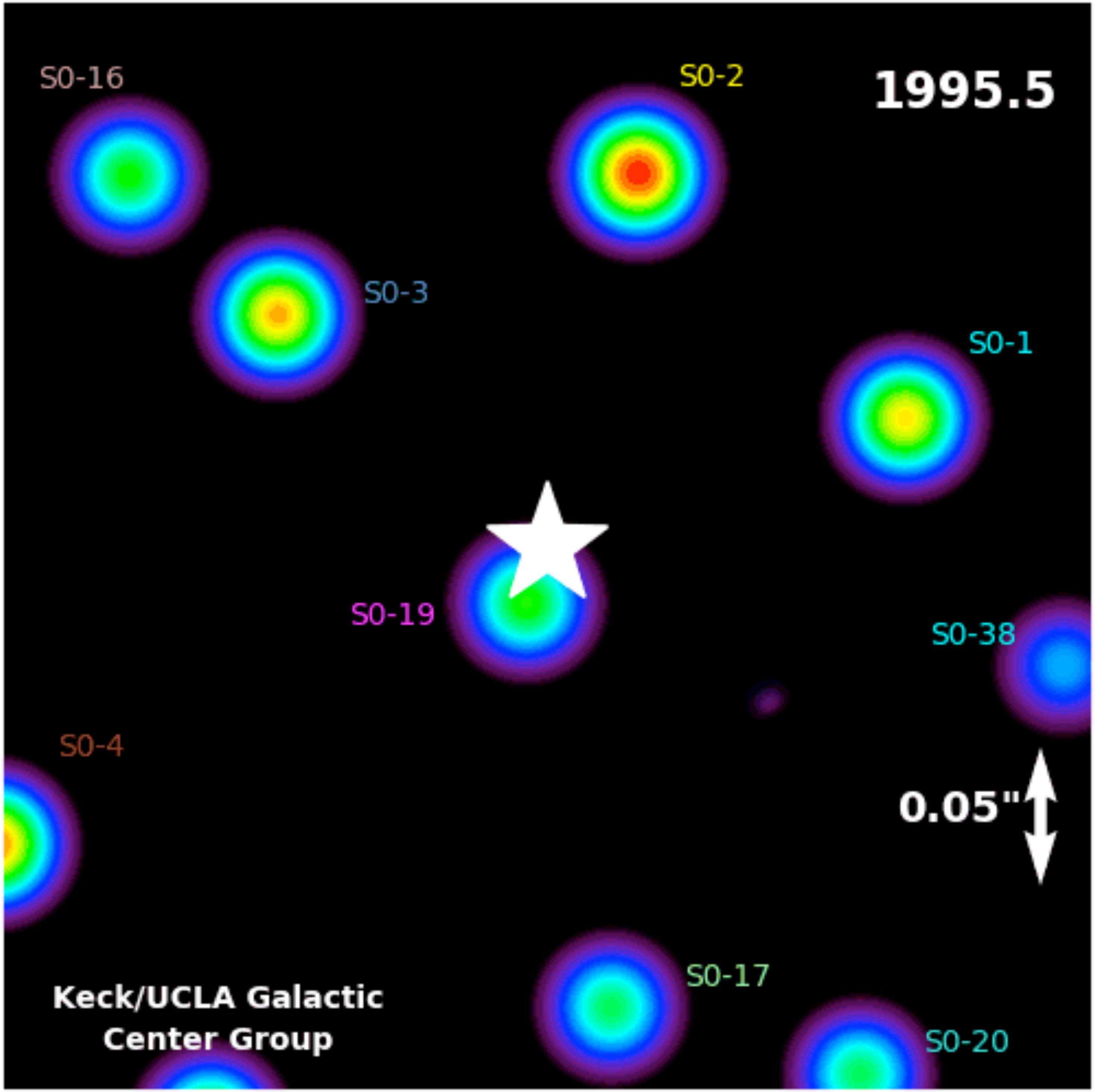
centre of Milky Way

infrared source Sgr A* in Galactic Centre shows clear dynamical evidence of SMBH

$$M \simeq 4 \times 10^6 M_\odot$$

from motions of surrounding stars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Keck/UCLA Galactic
Center Group
S0-20

motion near a point mass

(e.g. APIA pp 234 - 236)

energy equation for Newtonian point mass is

$$\frac{v^2}{2} - \frac{GM}{r} = E$$

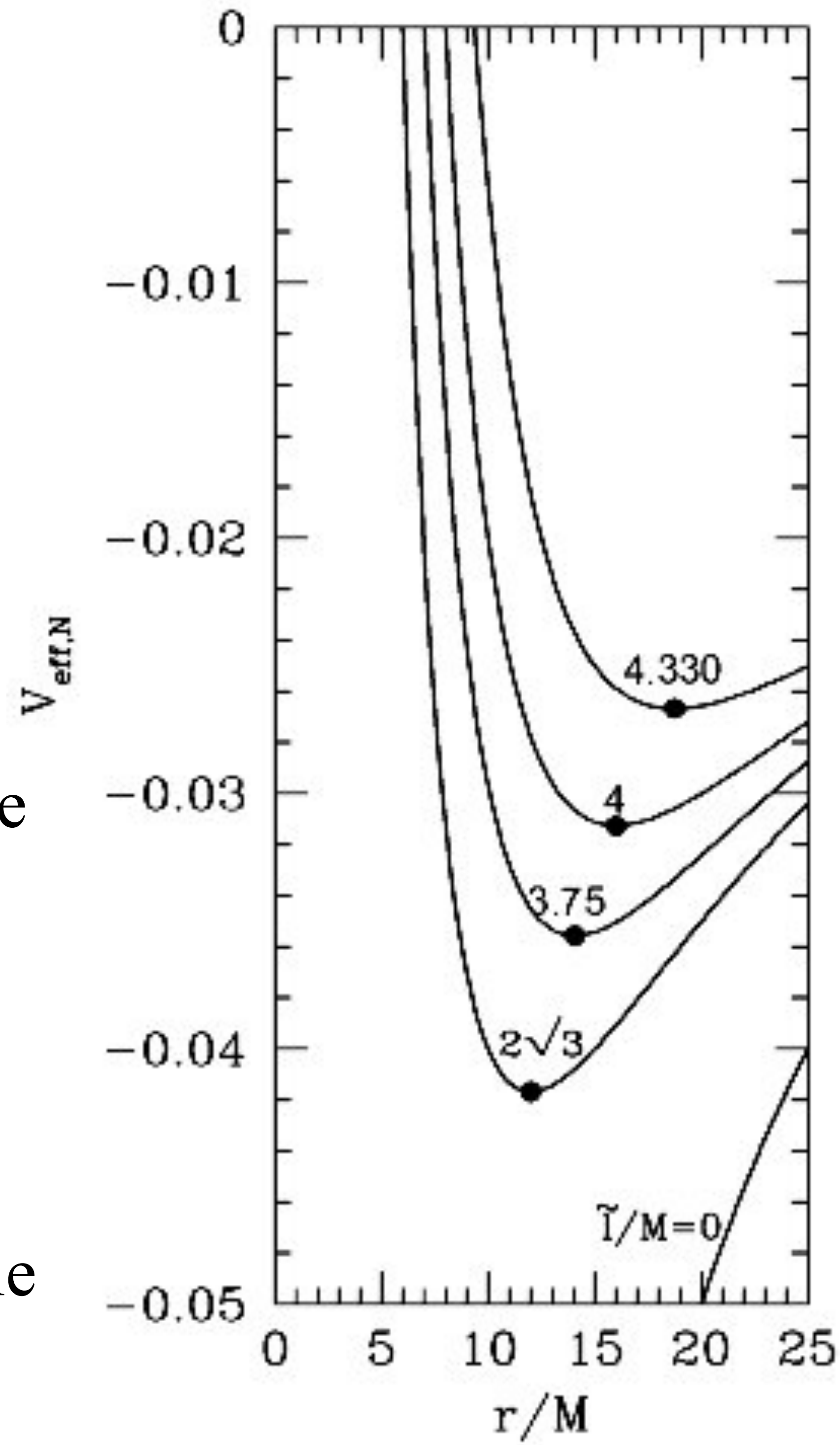
now with $v^2 = \dot{r}^2 + r^2\dot{\theta}^2$
and $r^2\dot{\theta} = J$ (specific a.m.) we have

$$\frac{1}{2}\dot{r}^2 + V(r) = E$$

where

$$V(r) = \frac{J^2}{2r^2} - \frac{GM}{r}$$

is the *effective potential* for a particle of fixed angular momentum J



motion near a point mass

- $J = 0$: particle falls in to origin

- nonzero J : particle *escapes* i.e. $r \to \infty$, if $E > 0$, but is *bound* (r stays finite) if $E < 0$

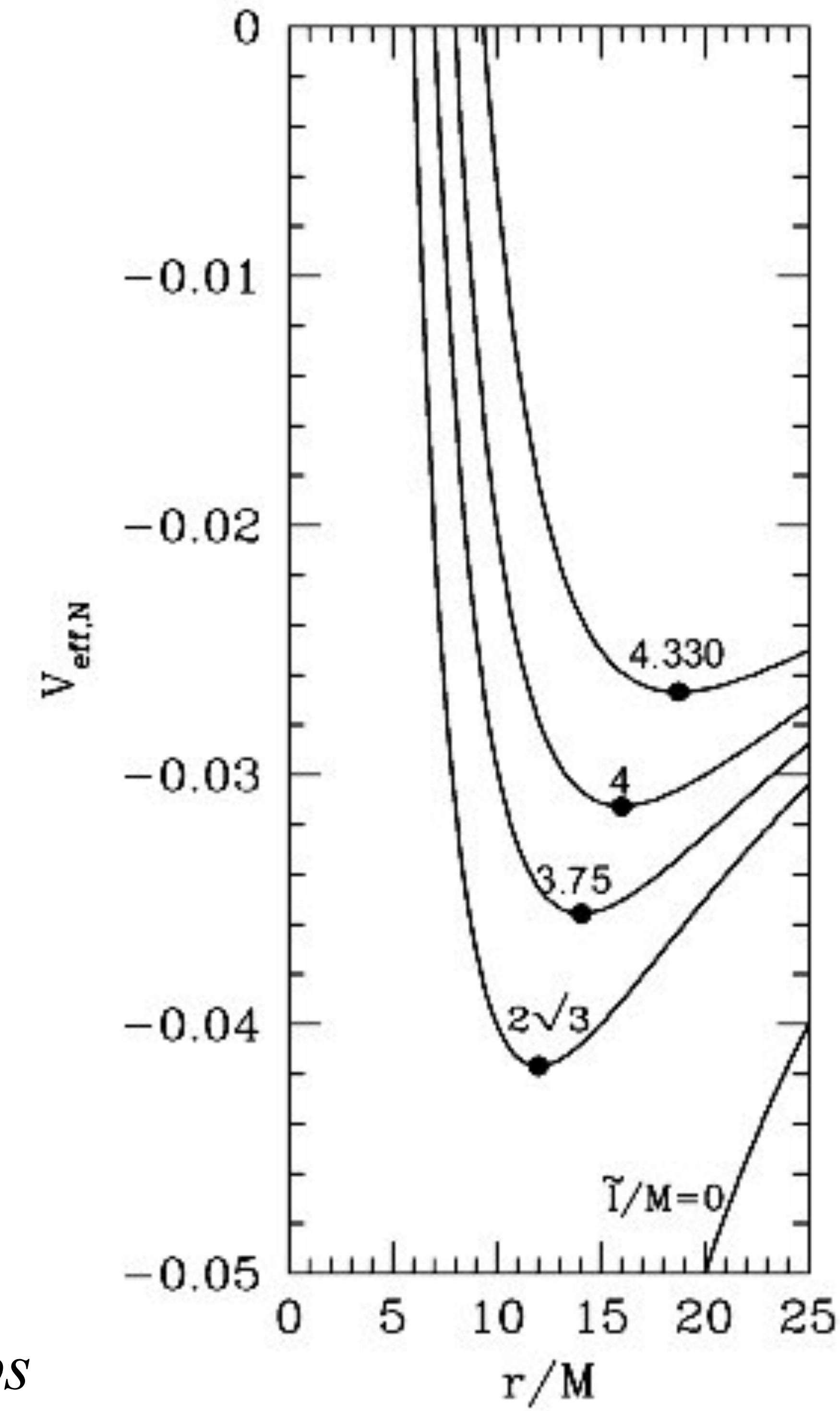
- circular orbit requires $\dot{r} = 0$, so

$$V(r) = E = \text{constant}$$

and

$$\frac{\mathrm{d}V}{\mathrm{d}r} = 0$$

circular orbits are possible at minima of effective potential



circular speeds grow as radius drops

motion near a *black hole*

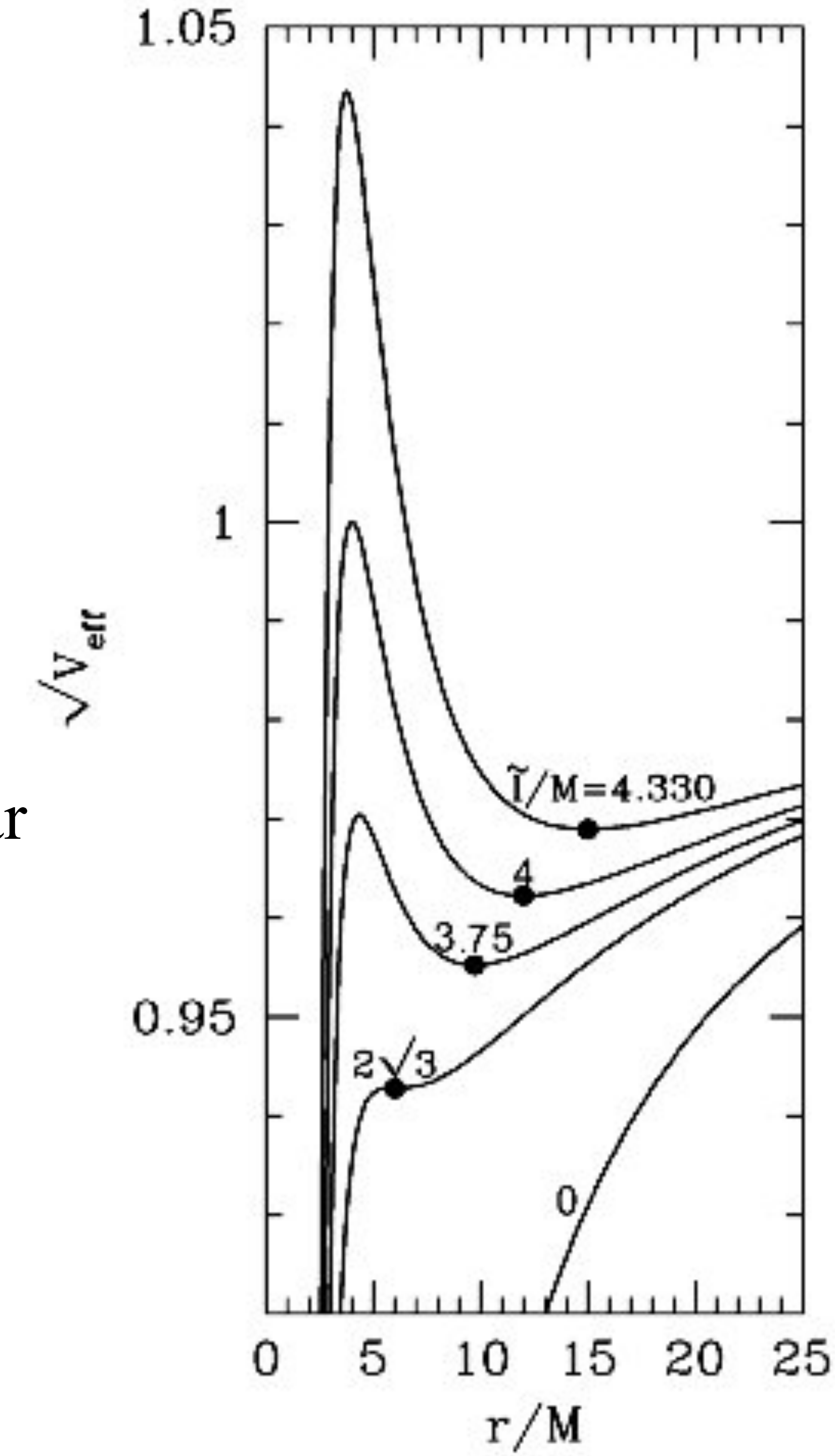
circular speed cannot exceed *c,* so effective potential *does not have minima* inside a certain radius:

innermost stable circular orbit:
`ISCO'

ISCO radius depends on spin angular momentum J_h of hole

$$J_h = \frac{GM^2}{c} a$$

a is (dimensionless) Kerr parameter



spinning (Kerr) black hole

- characterized *completely* by mass M and spin parameter a

- black holes with same M, a are *identical* \`a black hole has no hair'

- spin a.m. is limited (\`breakup') by $-1 < a < 1$

- negative a implies spin in opposite sense to a.m. of test particle orbit, i.e. orbit is retrograde

- circular orbits have unique importance because matter has angular momentum and accretes on to black hole through a disc

- Kerr a specifies ISCO radius: specific binding energy of this specifies accretion energy yield per unit mass η

ISCOs and accretion yields

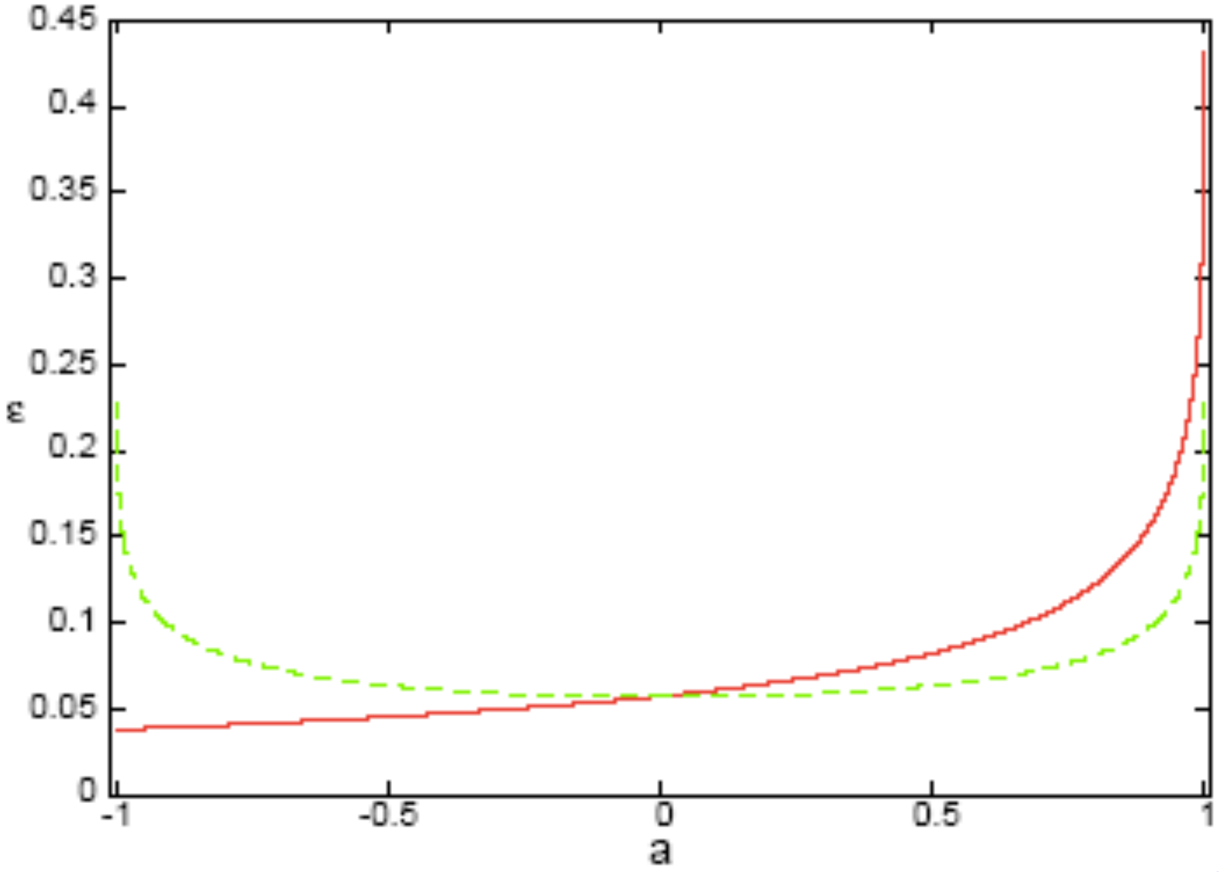
$$R_{\mathrm{ISCO}} = z\frac{GM}{c^2} \qquad \eta = 1 - \left[1 - \frac{2}{3z}\right]^{1/2}$$

	a	z	η
maximal retrograde	-1	9	0.038
Schwarzschild	0	6	0.057
maximal prograde	1	1	0.422

BH spin parameter a determines efficiency η

η

(red curve)



a

accretion yields

- efficiency $\eta = 0.1$ is reasonable
- => accretion luminosity $L = \eta c^2 \dot{M} = 10^8 L_\odot$ for accretion rate $\dot{M} = 1 M_\odot \, \mathrm{yr}^{-1}$
- accretion on to SMBH explains quasar luminosities

accretion on to SMBH power AGN and quasars

what is their significance for the Universe – where do they fit?

AGN are the growth phases of the SMBH in ALL galaxies

peak of quasar activity = peak of SMBH growth at $z \sim 2$

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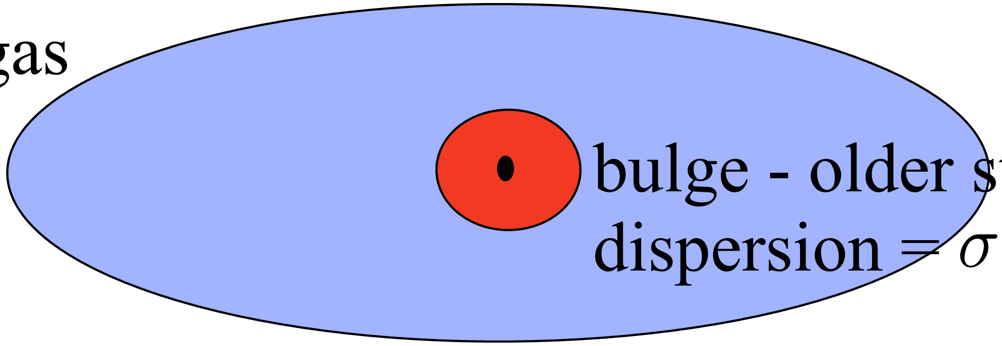
galaxies

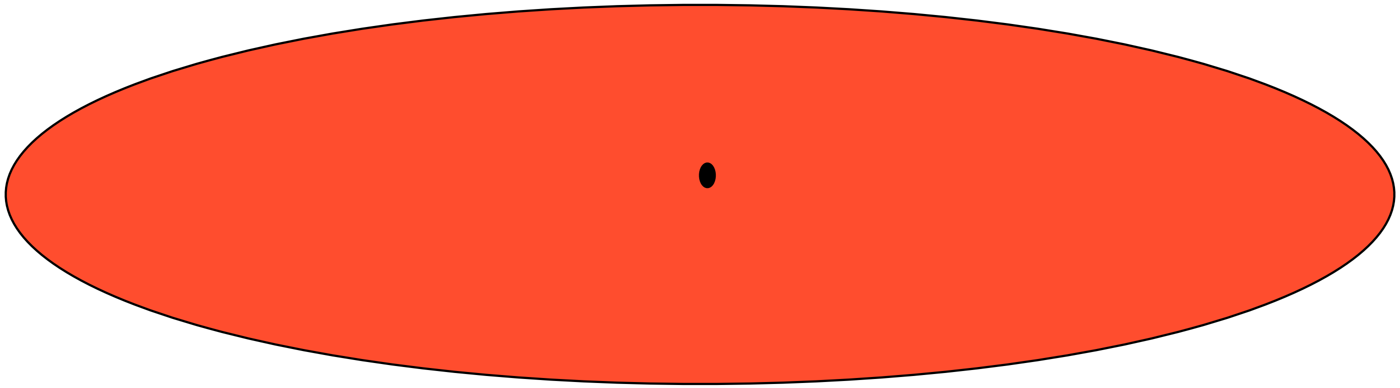
spiral galaxy

disc - young stars
forming from gas



bulge - older stars: velocity
dispersion = σ

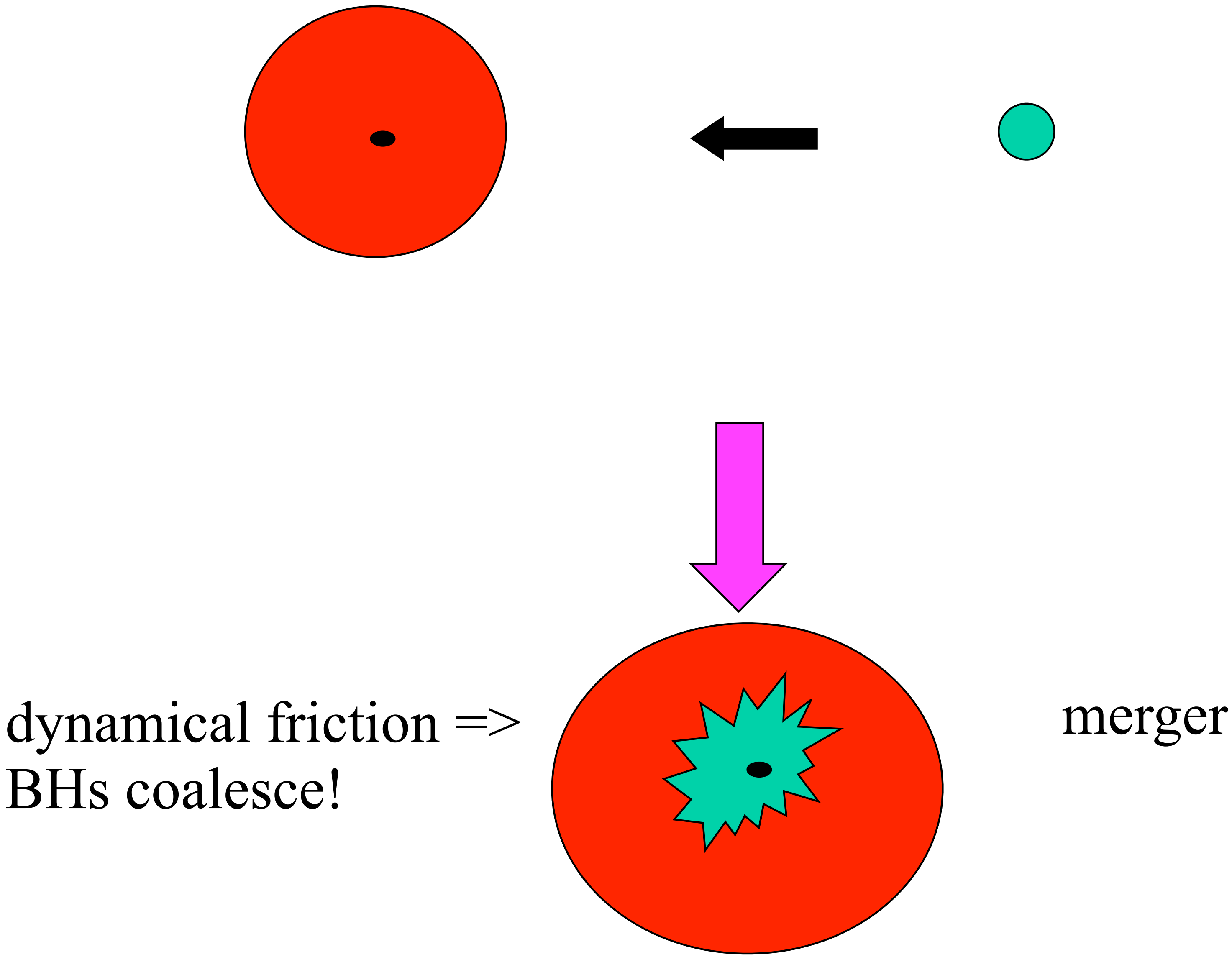
elliptical galaxy - merger of spirals?



little gas left - old stars only
`red and dead'

galaxies merge

cosmological picture of growth: big galaxy swallows small



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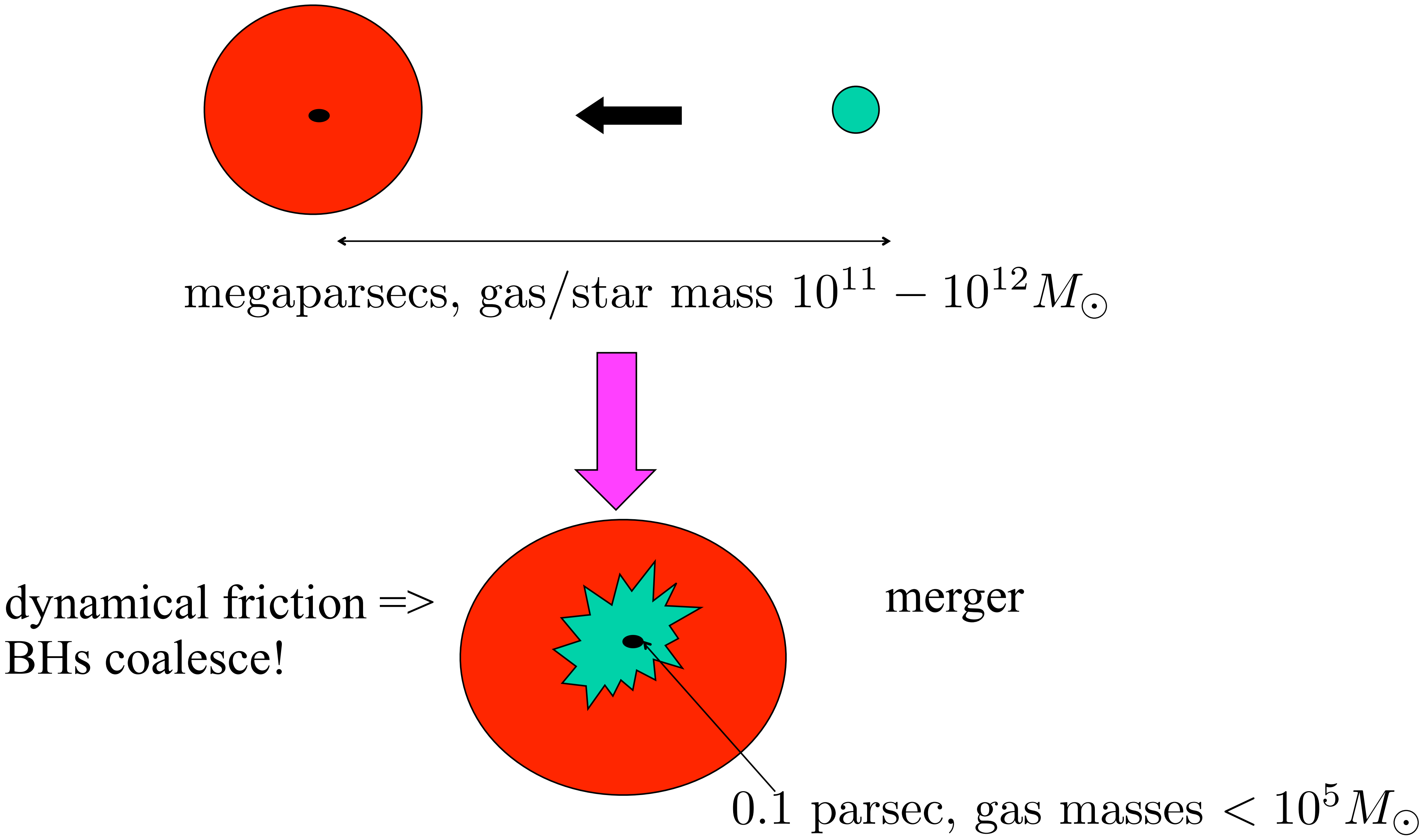
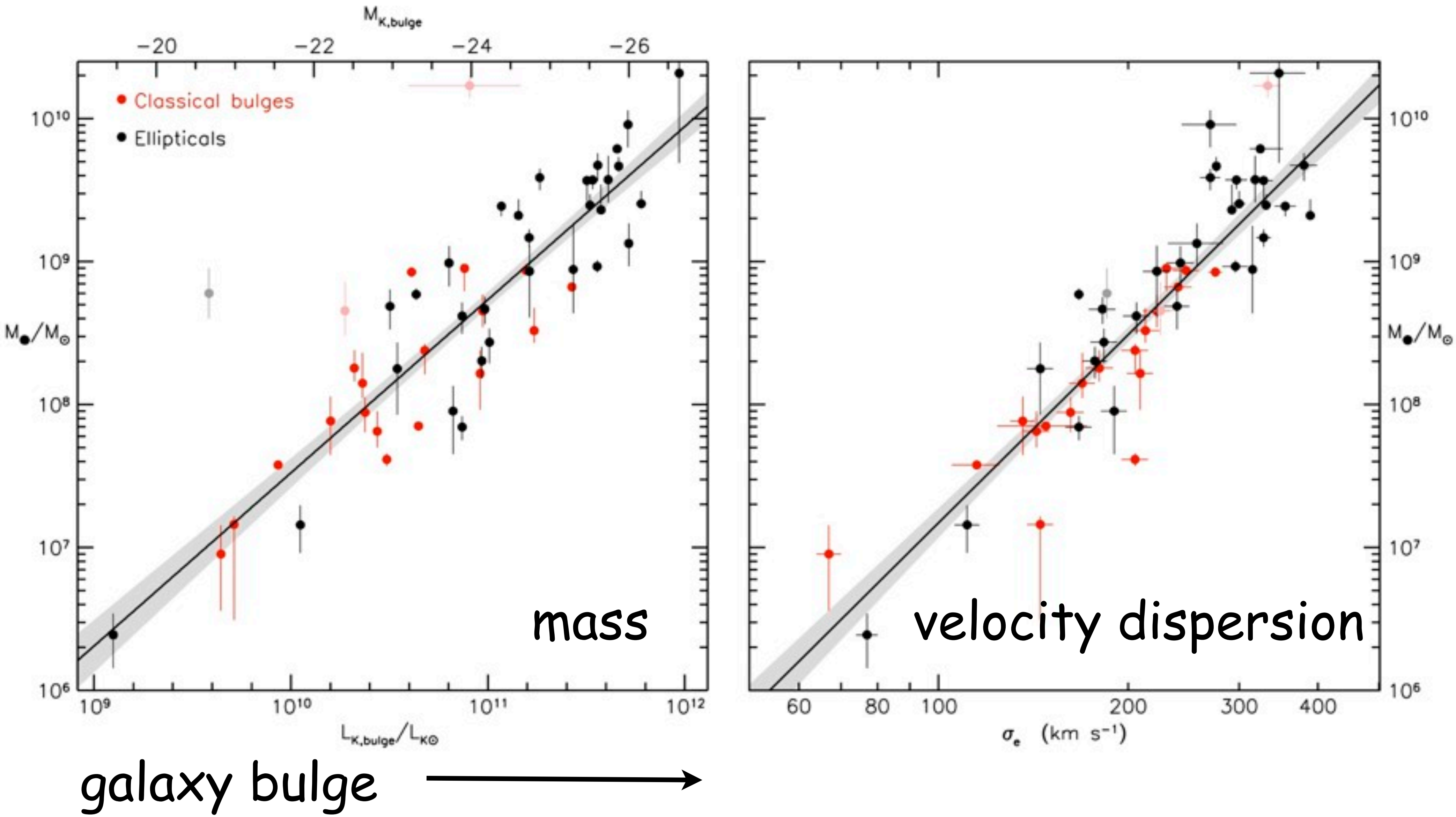


huge range of mass and length scales: numerical treatment impossible

galaxy knows about central SMBH



Kormendy & Ho, 2013

how?

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

so its gravity affects only a region

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

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

- 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'

well....

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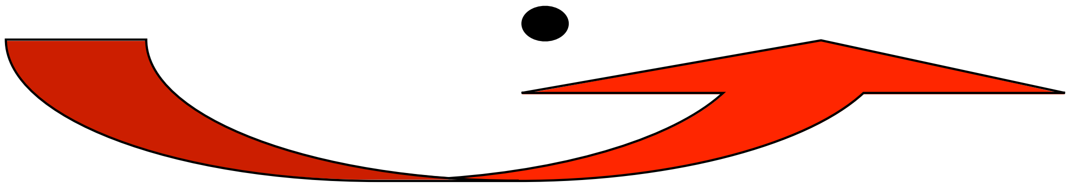
`feedback'

black hole is dangerous for galaxy!

feeding the hole

transferred mass does not hit black hole in general, but must orbit it



— initial orbit is a rosette, but self—intersections → dissipation → energy loss, but no angular momentum loss

Kepler orbit with lowest energy for fixed a.m. is a circle

thus orbit circularizes, with radius such that it retains its orginal specific angular momentum

further energy loss only possible if angular momentum can be removed

accretion disc

disc formation is unavoidable

all accreting gas has enough angular momentum to orbit the hole, so a disc always forms

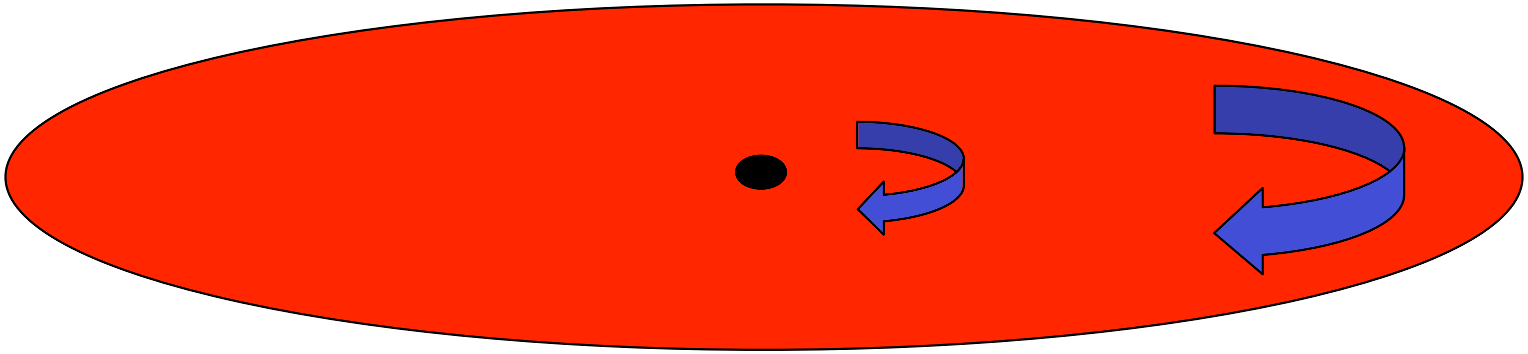
disc must be small enough for matter to accrete on reasonable timescales, i.e. ~ 0.1 pc

this requires any feeding mechanism to produce an accurate `shot' towards the black hole

feeding SMBH is difficult

this may be why $M_{\rm BH} \simeq 10^{-3} M_{\rm bulge}$

accretion disc structure (see APIA Ch 5)



flat, differentially rotating gas disc, thickness $H(R)$

surface density (mass/area) $\Sigma(R) = \rho H$

rotational angular velocity $\Omega(R)$ increases towards centre

angular momentum $R^2\Omega(R)$ *decreases* towards centre

disc is thin, $\frac{H}{R} \sim \frac{c_s}{v_\mathrm{K}} << 1$, Keplerian $R\Omega(R) = v_K = \left(\frac{GM}{R}\right)^{1/2}$

(pressure forces small) if and only if it can cool

accretion disc structure

- driver of accretion is `viscosity' - some dissipative process which transports angular momentum outwards, against a.m. gradient

- currently unknown - but may be magnetic

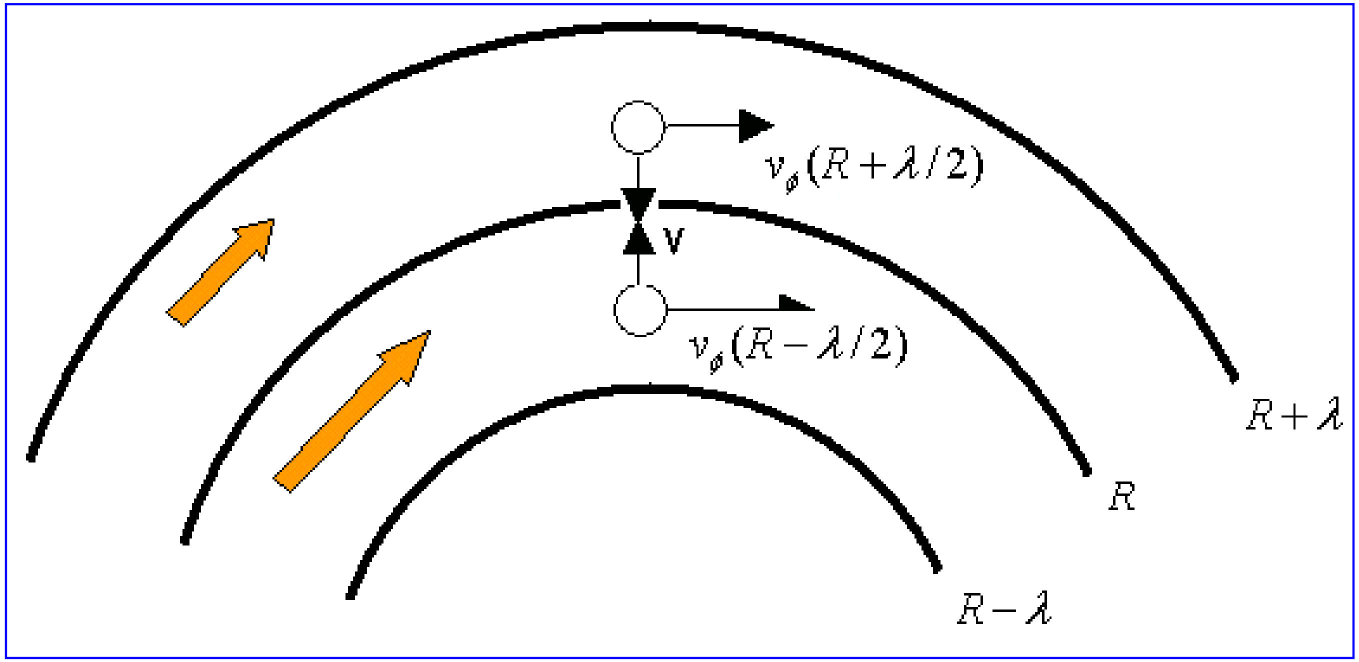
- characterized by a lengthscale λ and a speed v describing random motions around mean streaming (fluid) motion

- e.g. *molecular* viscosity has λ = mean free path, v = thermal speed of molecules (sound): other processes have larger λ, e.g. turbulence

- a viscosity transports fluid momentum and angular momentum within it

- gas spirals in, losing angular momentum and energy

accretion disc structure



torque of inner ring on outer one is $G(R) = 2\pi\nu\Sigma R^3 \dfrac{\mathrm{d}\Omega}{\mathrm{d}R}$, with $\nu \sim \lambda v$

dissipation per unit disc face area of a steady thin disc is

$$D(R) = \frac{3GM\dot{M}}{8\pi R^3}\left[1 - \left(\frac{R_{\rm in}}{R}\right)^{1/2}\right]$$

viscous timescale to lose angular momentum and spiral in is long:

disc surface density $\Sigma(R,t)$ obeys a *diffusion equation*

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left(R^{1/2}\frac{\partial}{\partial R}[\nu \Sigma R^{1/2}]\right)$$

where ν is 'kinematic viscosity': parametrize as $\nu = \alpha c_s H$, with $\alpha < 1$, $\dot{M}(R,t) = 3\pi\nu\Sigma$

Σ spreads on *viscous timescale*

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

where $t_{\rm dyn}$ is the *dynamical timescale* $R/v_K = (R^3/GM)^{1/2}$

this is *long*: $t_{\rm visc} \simeq 10^{10}$ yr for $R \sim 1$ pc $(H/R \lesssim 10^{-2})$

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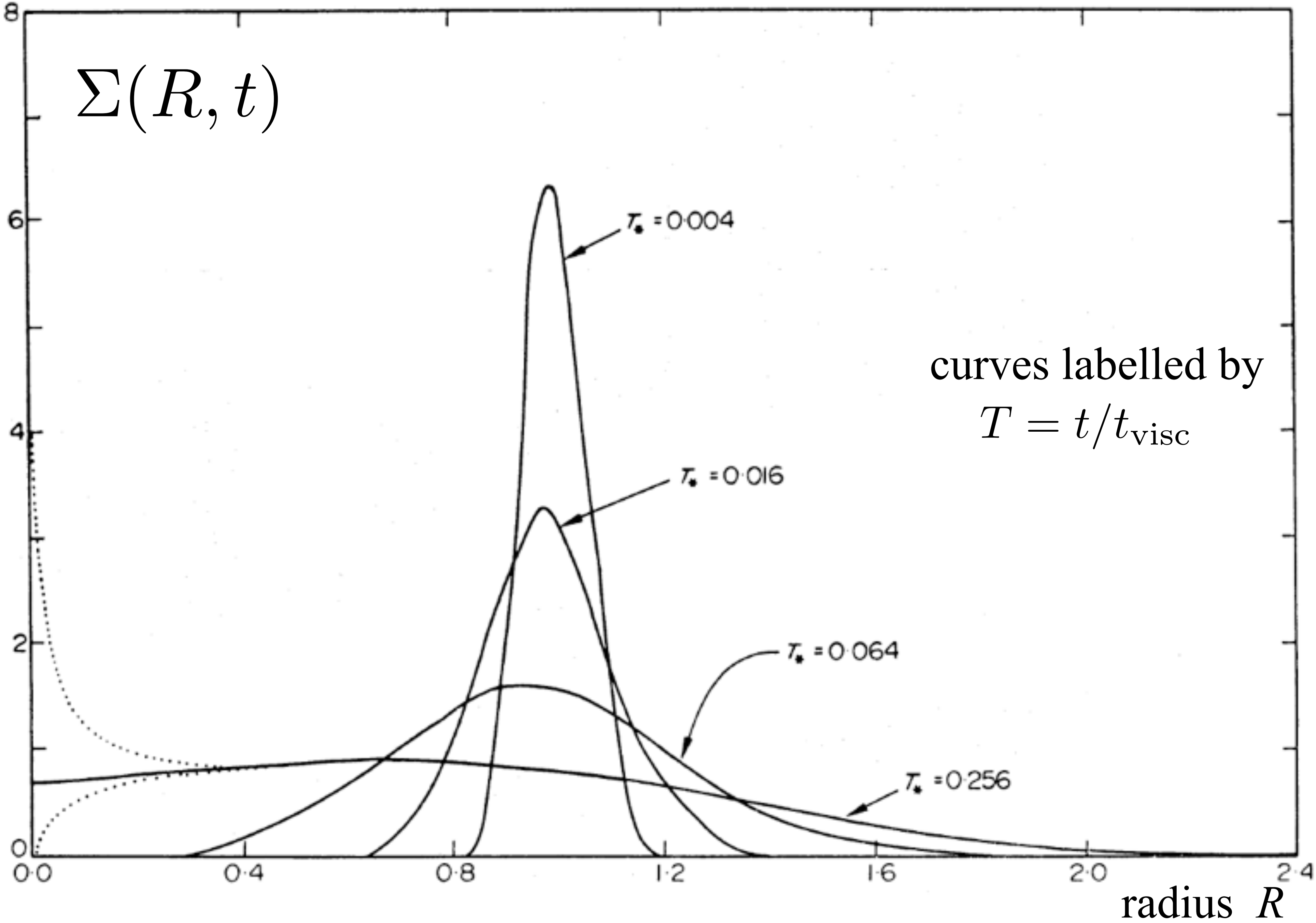
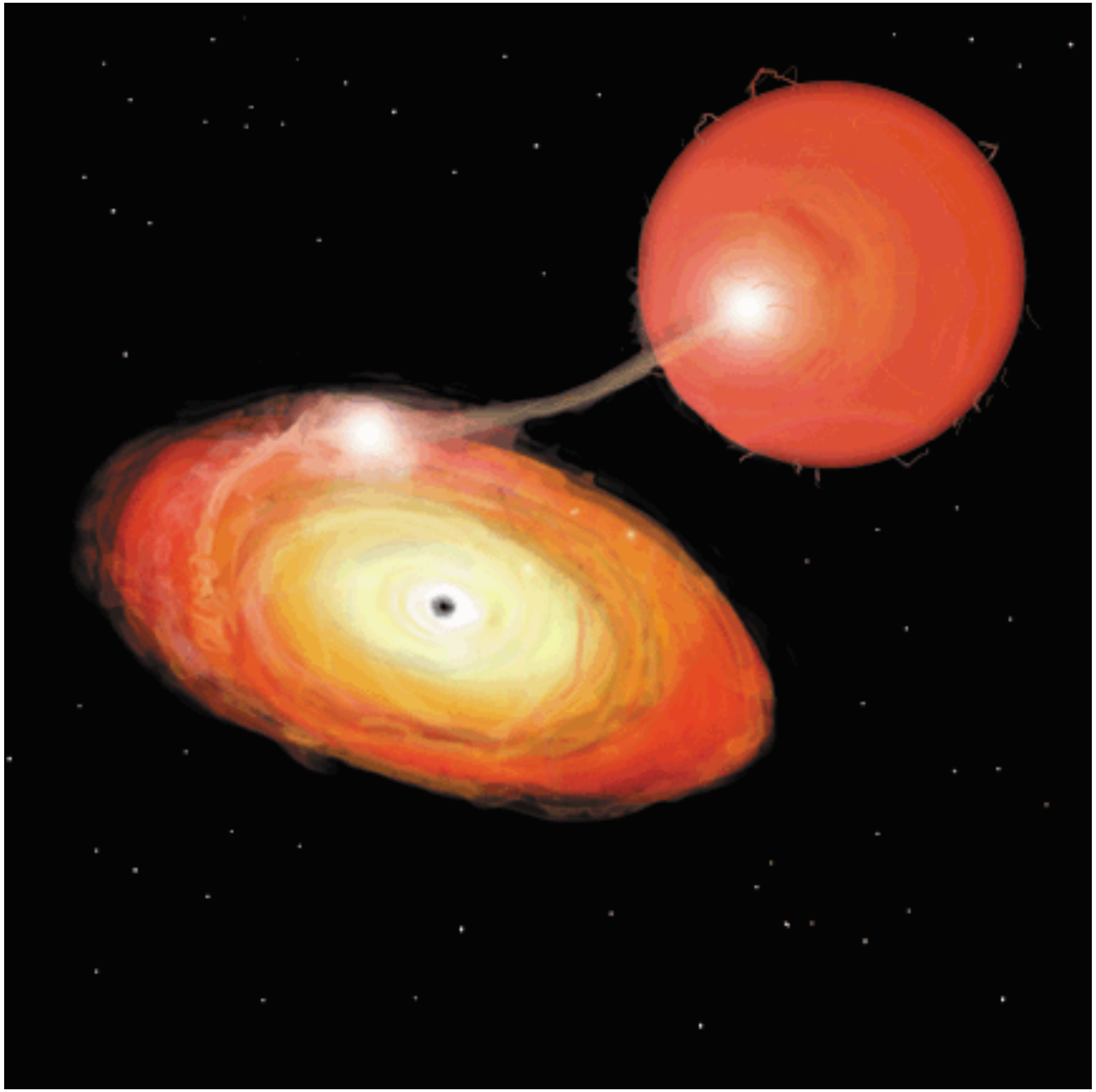
initial ring spreads diffusively to make a disc





close binary system with an accretion disc some phenomena qualitatively independent of viscosity: only specifies *overall timescale* as

$$t_{\rm visc} \sim \frac{R^2}{\nu}$$

e.g. superhumps: requires orbital resonances within disc (Whitehurst & King, 1991; Lubow, 1991, 1992)

40 *R. Whitehurst*

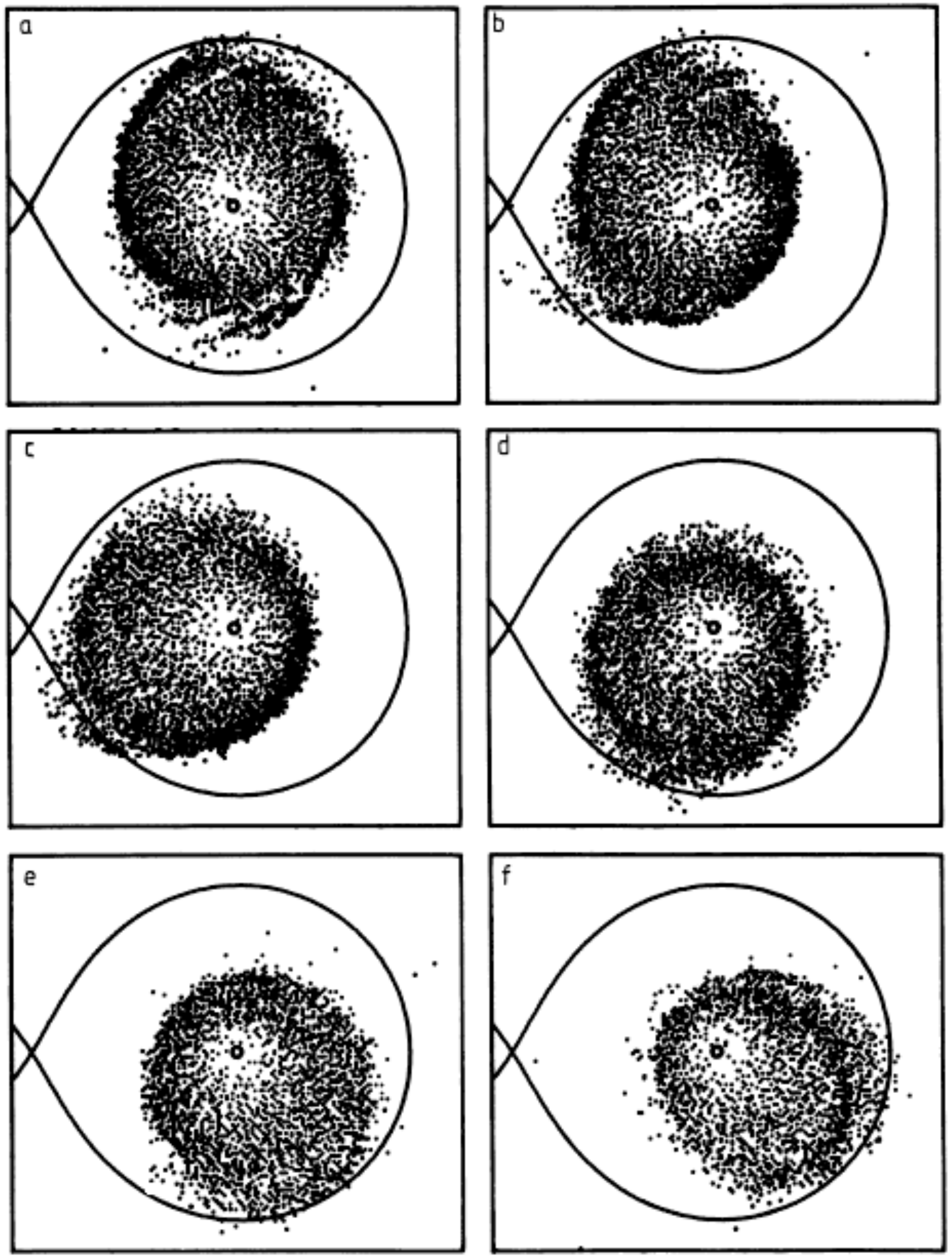
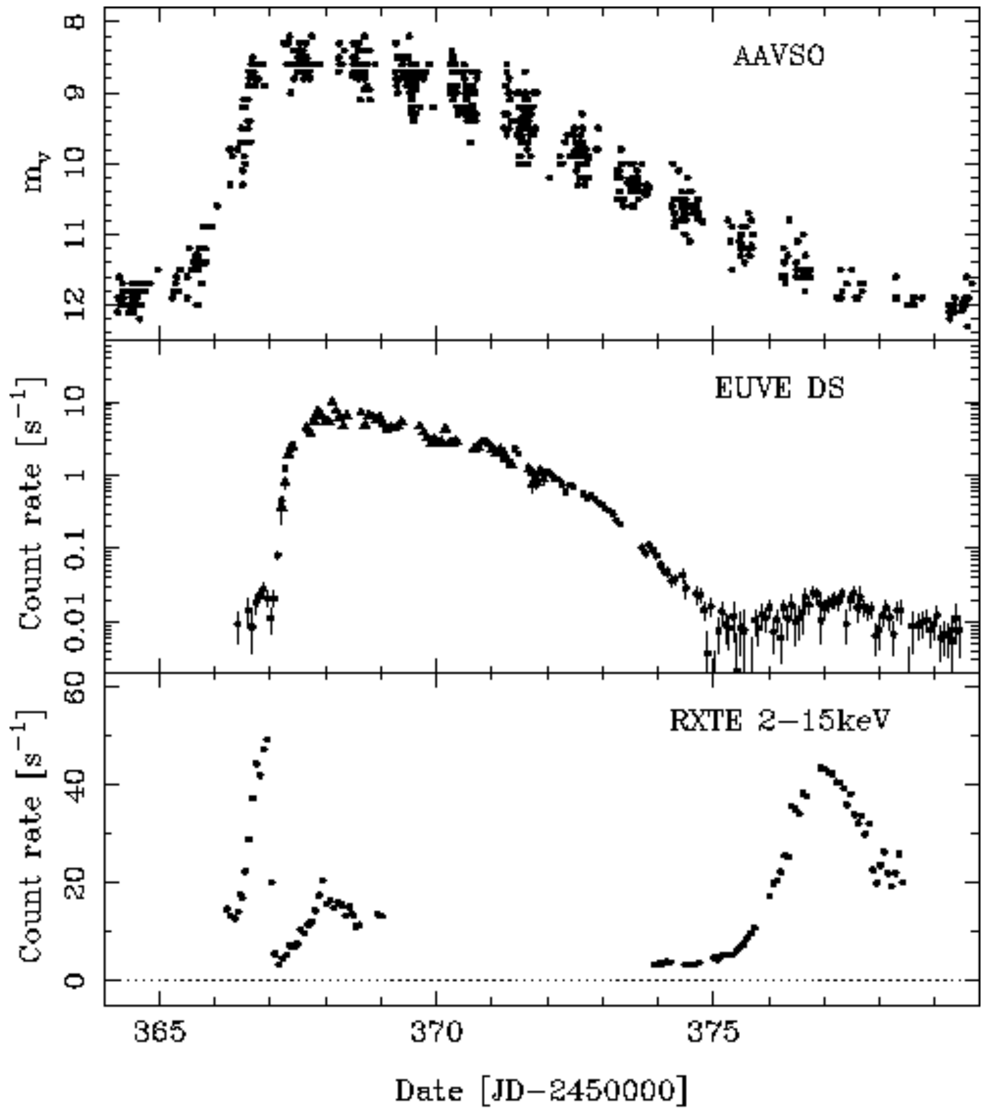
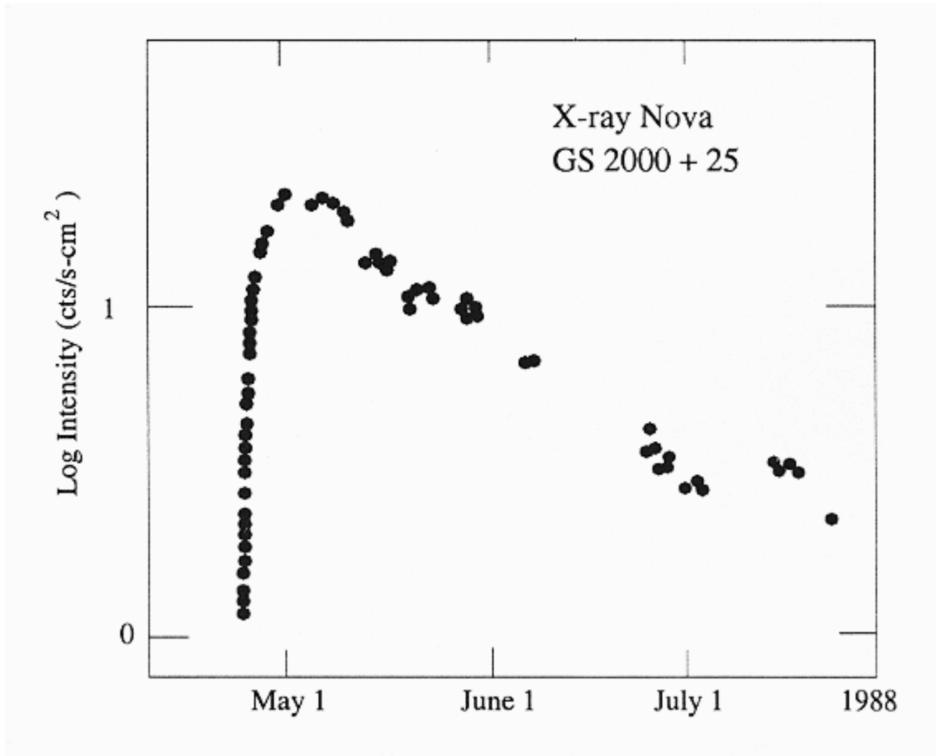


Figure 2. Transformation of the disc from the initial corotating mode to the eccentric 1::1 resonant mode. Each snapshot is precisely three orbital periods apart. Note that the rotation of the disc is clear in snapshots (d), (e) and (f).

or disc instabilities



dwarf nova (unirradiated disc)



soft X-ray transient (irradiated disc)

unirradiated (dwarf nova) case: disc evolves viscously for short time, themal evolution (cooling wave) quickly cuts outburst off (Meyer & Meyer-Hofmeister, 1982)

irradiated (SXT) case: central X-ray irradiation prevents cooling wave, and traps disc in hot state (King & Ritter, 1998) until much of central disc mass depleted – much longer outbursts in SXTs than in dwarf novae, despite similar size discs

exponential outburst if disc fully irradiated (short orbital periods (K & R 98) unirradiated (dwarf nova) case: disc evolves viscously for short time, themal evolution (cooling wave) quickly cuts outburst off (Meyer & Meyer-Hofmeister, 1982)

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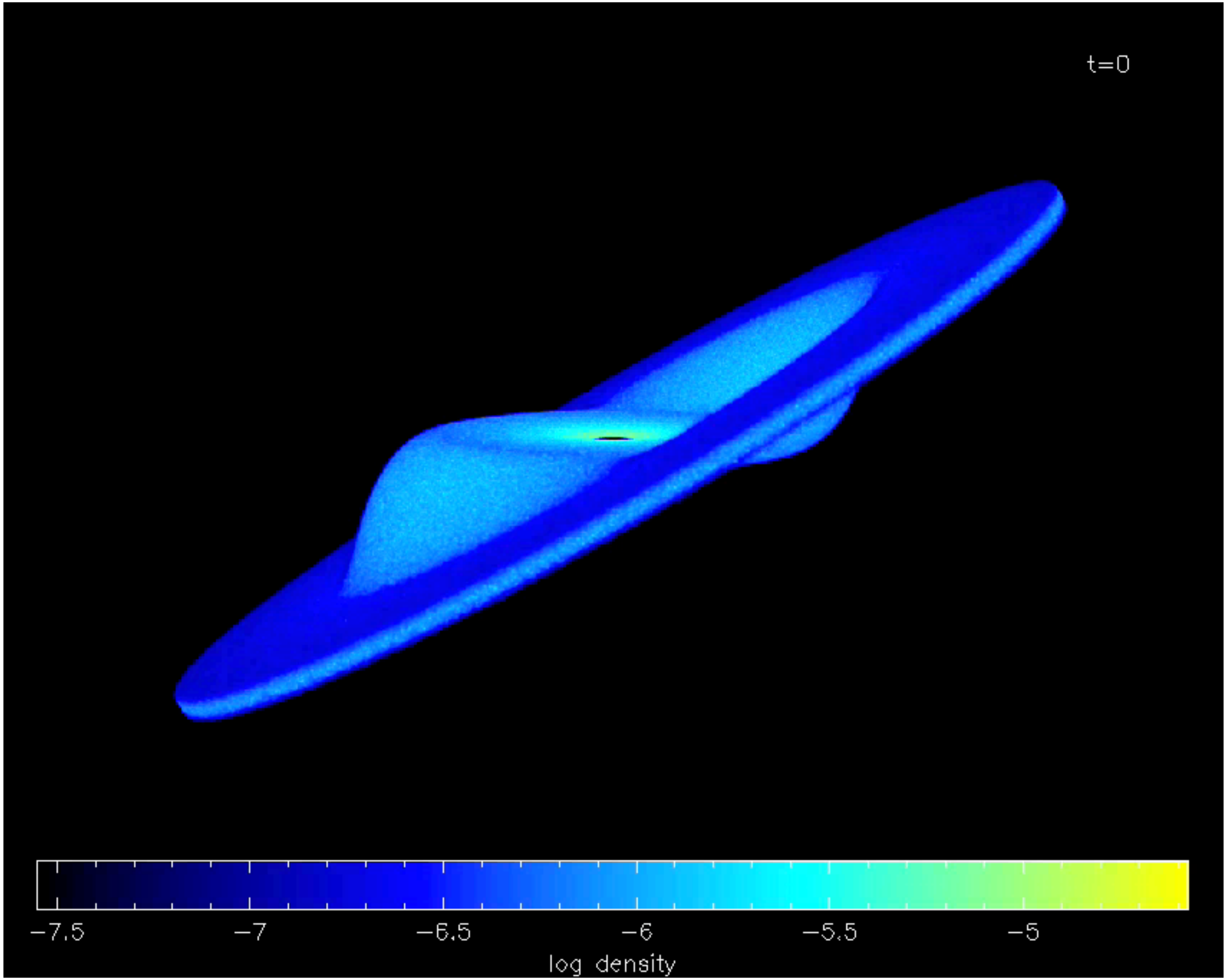
warps

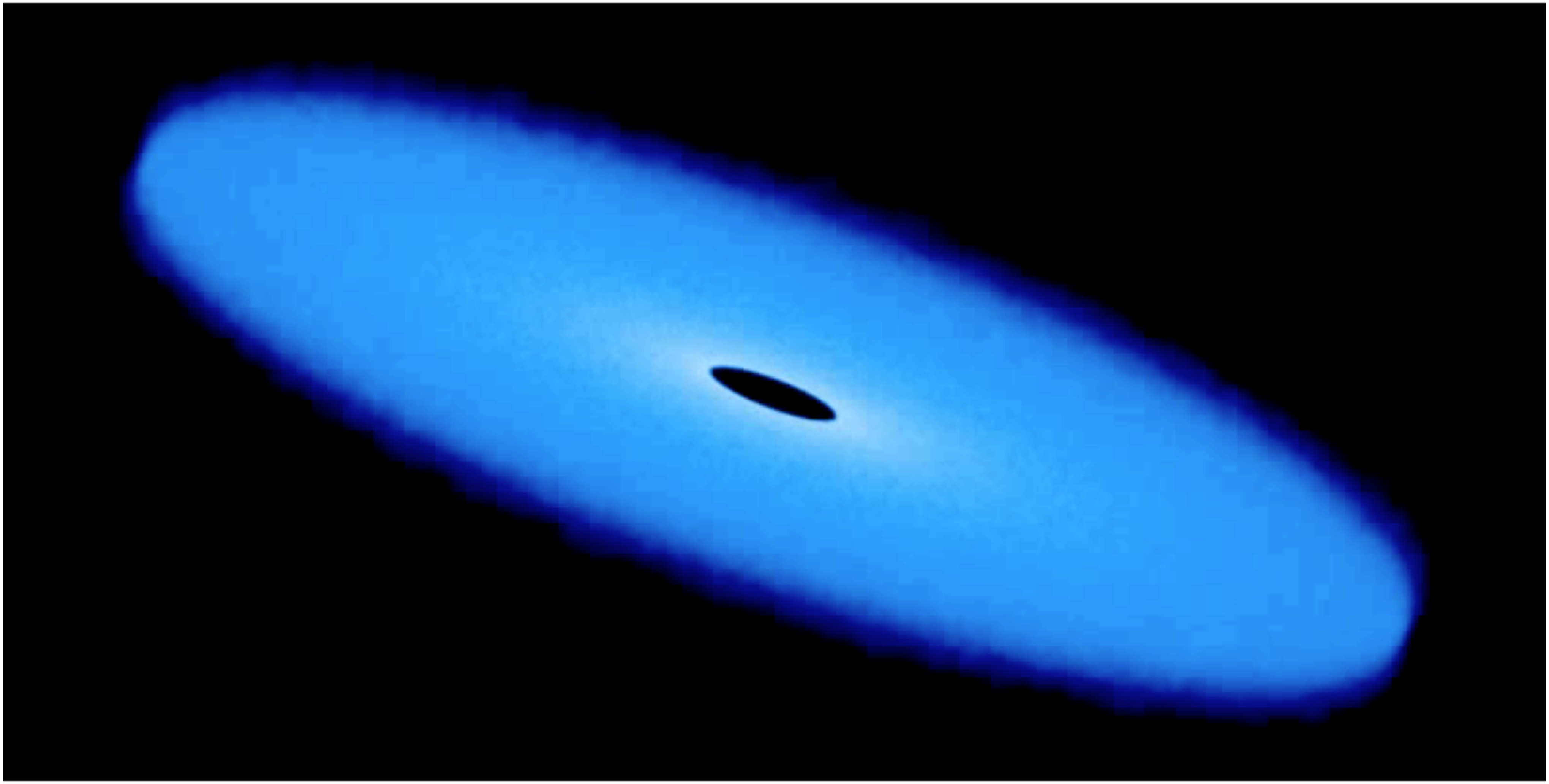
but disc is often *warped :* plane changes with radius, often because accretor is not purely spherical, e.g. accretor is a spinning black hole (Lense-Thirring effect) or binary black hole (quadrupole)

often the disc can accomodate this in a steady warp (`Bardeen - Petterson effect') assumed warp (Lodato & Price 2010)

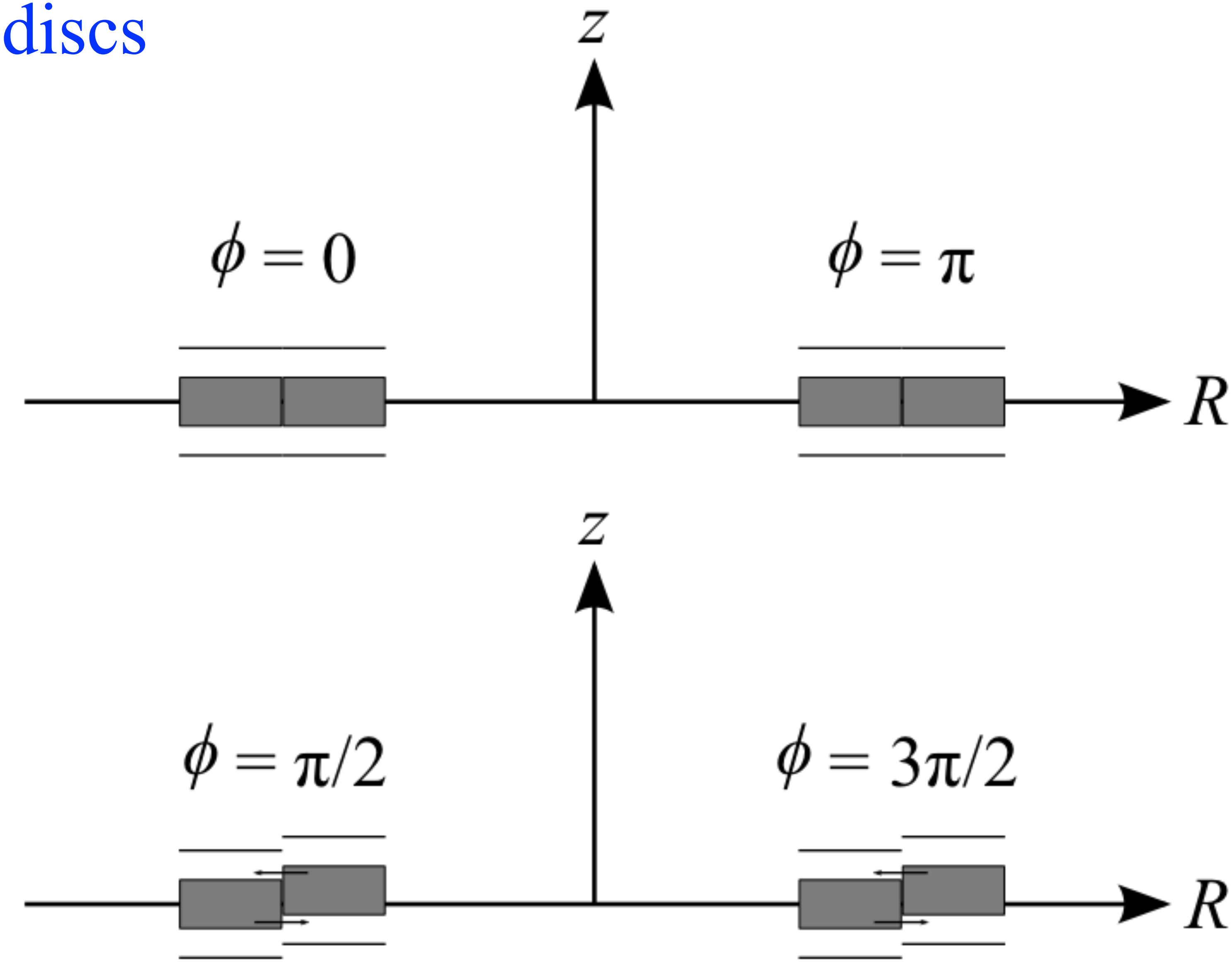


strong warp, significant viscosity

induced warp: Lense-Thirring with small tilt (Nixon & King, 2011)



warped discs



a warped disc: the shaded areas have higher pressure: arrows show pressure gradients induced by the warp: an orbiting fluid element feels a phase-dependent pressure gradient whose amplitude is a function of height

warped discs

but pressure oscillations are *resonant* (epicyclic freq) => large effect

result: if viscosity is locally isotropic, forces trying to hold the disc together actually *weaken* for larger warps

so for a sufficiently large amplitude warp the disc *breaks* general nonlinear theory

Equation (38) at $O(\epsilon^{s+3})$:

$$\left(\Omega\partial_\phi - \frac{v_{\theta 1}}{r}\partial_\zeta\right)p_1 + \left(v_{r1}\partial_r - \frac{v_{\theta 2}}{r}\partial_\zeta + \frac{v_{\phi 1}}{r}\partial_\phi\right)p_0 = \frac{\Gamma p_1}{r}\partial_\zeta v_{\theta 1} - \Gamma p_0\left[\frac{1}{r^2}\partial_r(r^2 v_{r1}) - \frac{1}{r}\partial_\zeta v_{\theta 2} + \frac{1}{r}\partial_\phi v_{\phi 1}\right]. \tag{74}$$

Equation (41) at $O(\epsilon^{s+2})$:

$$\begin{aligned}
&\rho_0\left(\Omega\partial_\phi - \frac{v_{\theta 1}}{r}\partial_\zeta\right)v_{r2} + \rho_0\left(v_{r1}\partial_r - \frac{v_{\theta 2}}{r}\partial_\zeta + \frac{v_{\phi 1}}{r}\partial_\phi\right)v_{r1} + \rho_1\left(\Omega\partial_\phi - \frac{v_{\theta 1}}{r}\partial_\zeta\right)v_{r1} - \frac{\rho_0}{r}\left[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\right]^2 \\
&\quad - 2\rho_0\Omega\left[-\frac{1}{2}r\Omega\zeta^2 + v_{\phi 2} + r(\dot\gamma + v_{r2}\gamma')\cos\beta - r v_{r1}(\beta'\sin\phi - \gamma'\sin\beta\cos\phi)\zeta\right] - \frac{\rho_0}{r}(v_{\phi 1} + r v_{r1}\gamma'\cos\beta)^2 \\
&\quad - 2\rho_1\Omega(v_{\phi 1} + r v_{r1}\gamma'\cos\beta) = -(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta\left\{p_1 - \left(\mu_{b0} + \frac{1}{3}\mu_0\right)\left[\frac{1}{r^2}\partial_r(r^2 v_{r1}) - \frac{1}{r}\partial_\zeta v_{\theta 2} + \frac{1}{r}\partial_\phi v_{\phi 1}\right]\right. \\
&\quad \left. + \left(\mu_{b1} + \frac{1}{3}\mu_1\right)\frac{1}{r}\partial_\zeta v_{\theta 1}\right\} - (\partial_r - \gamma'\cos\beta\,\partial_\phi)\left[p_0 + (\mu_{b0} + \frac{1}{3}\mu_0)\frac{1}{r}\partial_\zeta v_{\theta 1}\right] \\
&\quad + \left[\frac{1}{r^2} + (\beta'\cos\phi + \gamma'\sin\beta\sin\phi)^2\right]\partial_\zeta(\mu_0\partial_\zeta v_{r2} + \mu_1\partial_\zeta v_{r1}) + (\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta\left[\mu_0(\partial_r - \gamma'\cos\beta\,\partial_\phi)v_{r1}\right] \\
&\quad + \frac{1}{r^2}(\partial_r - \gamma'\cos\beta\,\partial_\phi)\left[\mu_0 r^2(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta v_{r1}\right] - \frac{2v_{r1}}{r}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta\mu_0 \\
&\quad + \frac{1}{r^3}\left[(\partial_r - \gamma'\cos\beta\,\partial_\phi)(\mu_0 r^2)\right]\partial_\zeta\left[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\right] \\
&\quad - (\partial_\zeta\mu_0)(\partial_r - \gamma'\cos\beta\,\partial_\phi)\left[\frac{v_{\theta 1}}{r} + v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\right] \\
&\quad - \frac{1}{r}(\partial_\zeta\mu_0)\partial_\phi\left[(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)(v_{\phi 1} + r v_{r1}\gamma'\cos\beta)\right] + \Omega'\partial_\phi\mu_0 \\
&\quad + \frac{1}{r}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)(\partial_\phi\mu_0)\partial_\zeta(v_{\phi 1} + r v_{r1}\gamma'\cos\beta) + \Omega(\beta'\sin\phi - \gamma'\sin\beta\cos\phi)\partial_\zeta\mu_1.
\end{aligned} \tag{75}$$

Equation (42) at $O(\epsilon^{s+2})$:

$$\begin{aligned}
&\rho_0\left(\Omega\partial_\phi - \frac{v_{\theta 1}}{r}\partial_\zeta\right)\left[v_{\theta 2} + r(\dot\beta + v_{r2}\beta')\cos\phi + r(\dot\gamma + v_{r2}\gamma')\sin\beta\sin\phi\right] \\
&\quad + \rho_0\left(v_{r1}\partial_r - \frac{v_{\theta 2}}{r}\partial_\zeta + \frac{v_{\phi 1}}{r}\partial_\phi\right)\left[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\right]
\end{aligned}$$

$$- \frac{1}{r}(\partial_\zeta \mu_0)\partial_\phi\big[(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)(v_{\phi 1} + r v_{r1}\gamma'\cos\beta)\big] + \Omega'\partial_\phi\mu_0$$

$$+ \frac{1}{r}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)(\partial_\phi\mu_0)\partial_\zeta(v_{\phi 1} + r v_{r1}\gamma'\cos\beta) + \Omega(\beta'\sin\phi - \gamma'\sin\beta\cos\phi)\partial_\zeta\mu_1. \tag{75}$$

Equation (42) at $O(\epsilon^{s+2})$:

$$\rho_0\left(\Omega\partial_\phi - \frac{v_{\theta 1}}{r}\partial_\zeta\right)\big[v_{\theta 2} + r(\dot\beta + v_{r2}\beta')\cos\phi + r(\dot\gamma + v_{r2}\gamma')\sin\beta\sin\phi\big]$$

$$+ \rho_0\left(v_{r1}\partial_r - \frac{v_{\theta 2}}{r}\partial_\zeta + \frac{v_{\phi 1}}{r}\partial_\phi\right)\big[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\big]$$

$$+ \rho_1\left(\Omega\partial_\phi - \frac{v_{\theta 1}}{r}\partial_\zeta\right)\big[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\big] + \frac{\rho_0 v_{r1}}{r}\big[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\big]$$

$$- \rho_0\Omega\big[(v_{\phi 1} + r v_{r1}\gamma'\cos\beta)\zeta + r(\dot\beta + v_{r2}\beta')\sin\phi - r(\dot\gamma + v_{r2}\gamma')\sin\beta\cos\phi\big]$$

$$- \frac{\rho_0}{r}(v_{\phi 1} + r v_{r1}\gamma'\cos\beta)\big[r\Omega\zeta + r v_{r1}(\beta'\sin\phi - \gamma'\sin\beta\cos\phi)\big] - \rho_1\Omega\big[r\Omega\zeta + r v_{r1}(\beta'\sin\phi - \gamma'\sin\beta\cos\phi)\big]$$

$$= \frac{1}{r}\partial_\zeta\left\{p_1 - \left(\mu_{\mathrm{b}0} + \frac{1}{3}\mu_0\right)\left[\frac{1}{r^2}\partial_r(r^2 v_{r1}) - \frac{1}{r}\partial_\zeta v_{\theta 2} + \frac{1}{r}\partial_\phi v_{\phi 1}\right] + \left(\mu_{\mathrm{b}1} + \frac{1}{3}\mu_1\right)\frac{1}{r}\partial_\zeta v_{\theta 1}\right\}$$

$$+ \left[\frac{1}{r^2} + (\beta'\cos\phi + \gamma'\sin\beta\sin\phi)^2\right]\partial_\zeta\big\{\mu_0\partial_\zeta\big[v_{\theta 2} + r(\dot\beta + v_{r2}\beta')\cos\phi + r(\dot\gamma + v_{r2}\gamma')\sin\beta\sin\phi\big]$$

$$+ \mu_1\partial_\zeta\big[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\big]\big\}$$

$$+ (\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta\big\{\mu_0(\partial_r - \gamma'\cos\beta\,\partial_\phi)\big[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\big]\big\}$$

$$+ \frac{1}{r^2}(\partial_r - \gamma'\cos\beta\,\partial_\phi)\big\{\mu_0 r^2(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta\big[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\big]\big\}$$

$$- \frac{1}{r}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)(\partial_\zeta\mu_0)\big[v_{\theta 1} + r v_{r1}(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\big] - \frac{1}{r^3}(\partial_\zeta v_{r1})(\partial_r - \gamma'\cos\beta\,\partial_\phi)(\mu_0 r^2)$$

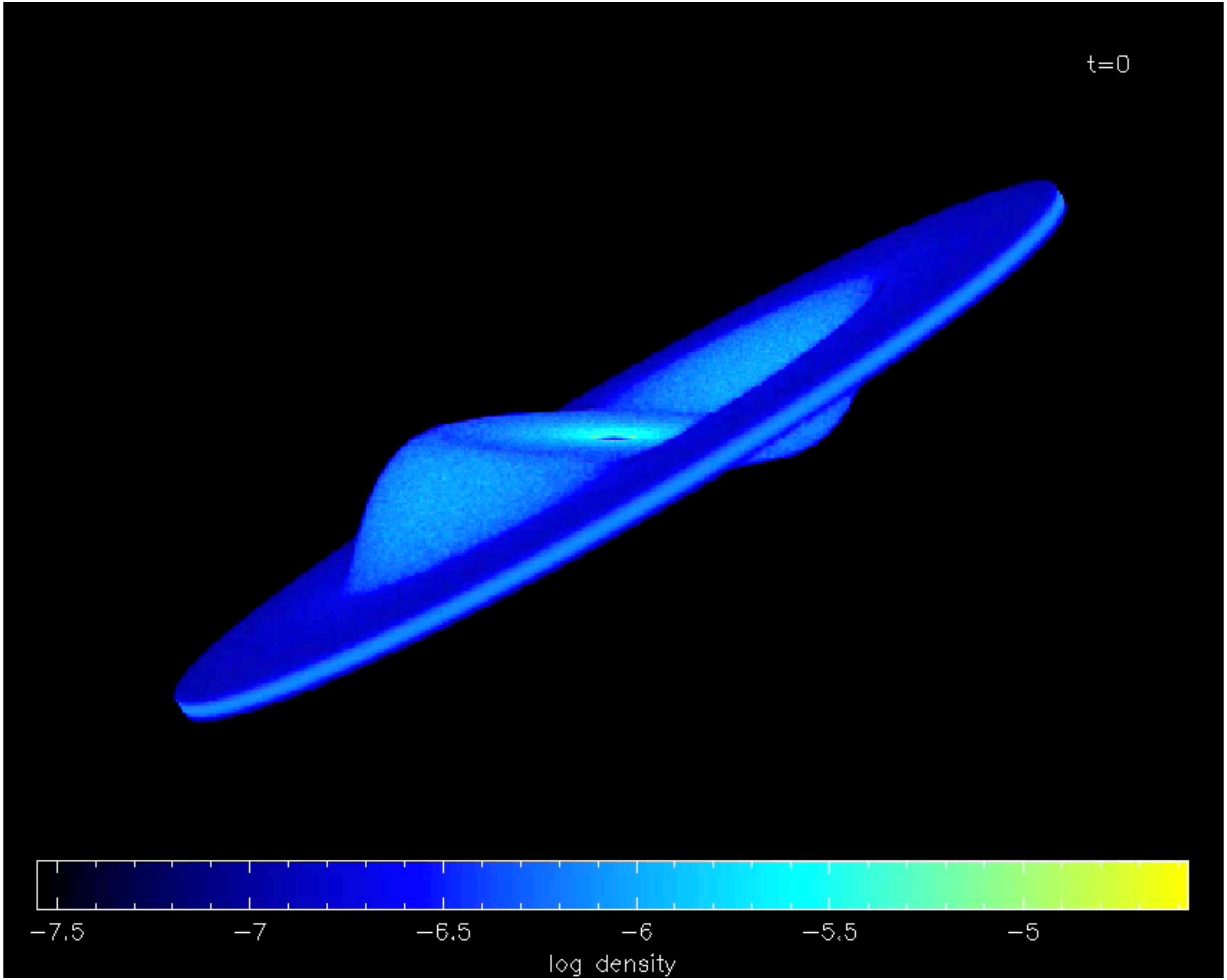
$$+ \frac{1}{r}(\partial_\zeta\mu_0)(\partial_r - \gamma'\cos\beta\,\partial_\phi)v_{r1} + \frac{1}{r^2}(\partial_\zeta\mu_0)\partial_\phi(v_{\phi 1} + r v_{r1}\gamma'\cos\beta)$$

$$- \frac{1}{r^2}(\partial_\phi\mu_0)\partial_\zeta(v_{\phi 1} + r v_{r1}\gamma'\cos\beta) - (\beta'\sin\phi - \gamma'\sin\beta\cos\phi)(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta\big[\mu_0(v_{\phi 1} + r v_{r1}\gamma'\cos\beta)\big]$$

$$- r\Omega(\beta'\sin\phi - \gamma'\sin\beta\cos\phi)(\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta\mu_1 - \frac{1}{r^2}(\partial_r - \gamma'\cos\beta\,\partial_\phi)\big[\mu_0 r^3\Omega(\beta'\sin\phi - \gamma'\sin\beta\cos\phi)\big]$$

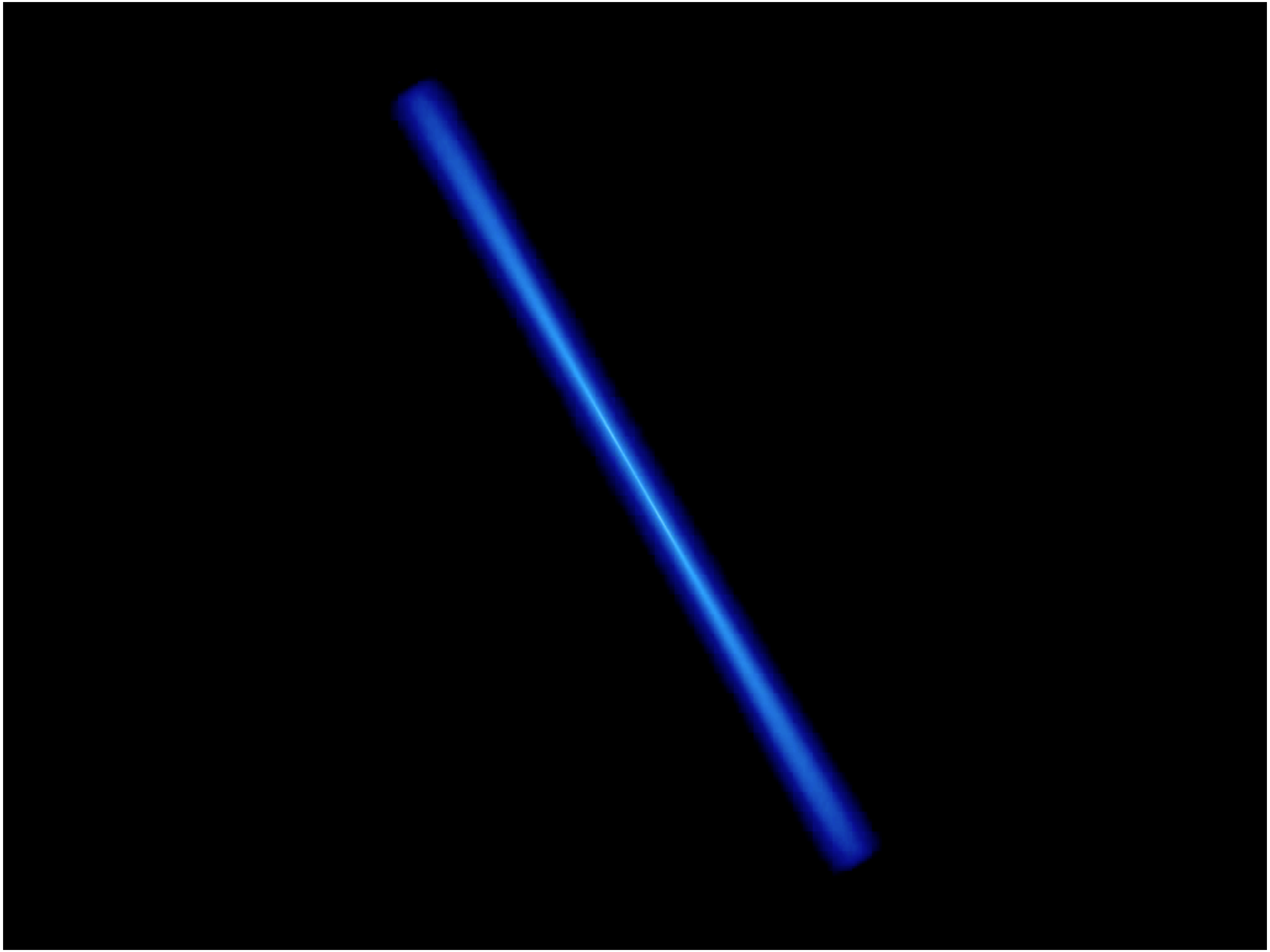
$$- \mu_0(\beta'\sin\phi - \gamma'\sin\beta\cos\phi)\big[(r\Omega)' + (\beta'\cos\phi + \gamma'\sin\beta\sin\phi)\partial_\zeta(v_{\phi 1} + r v_{r1}\gamma'\cos\beta)\big]. \tag{76}$$

larger assumed warp (Lodato & Price, 2010)



strong warp, viscosity relatively weaker: disc breaks!

Lense-Thirring: big tilt ==> rapid accretion (King & Nixon 2012



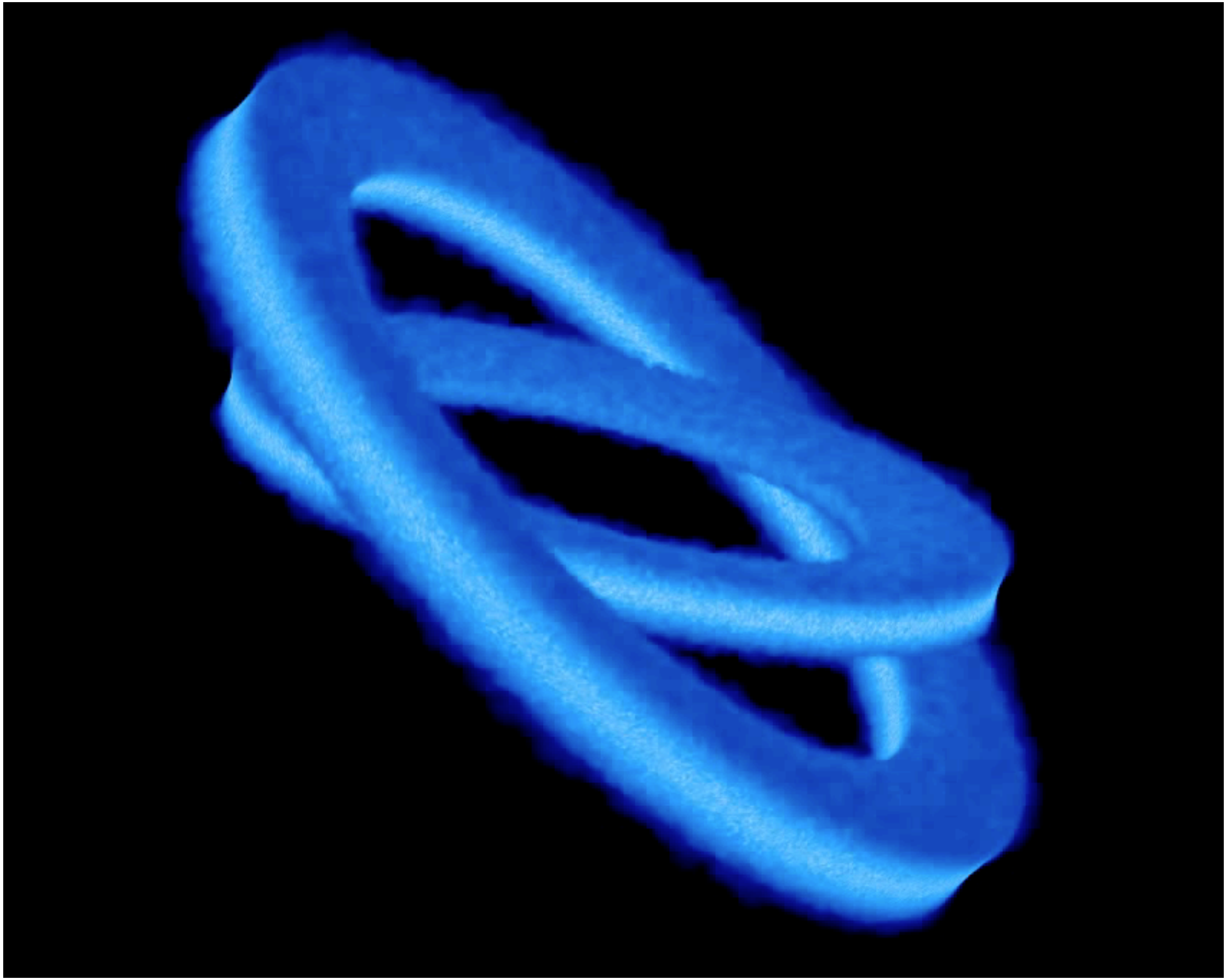
broken discs tear

why does disc behave in this complex way?
why is accretion so rapid?

inclined discs => disc *breaking*

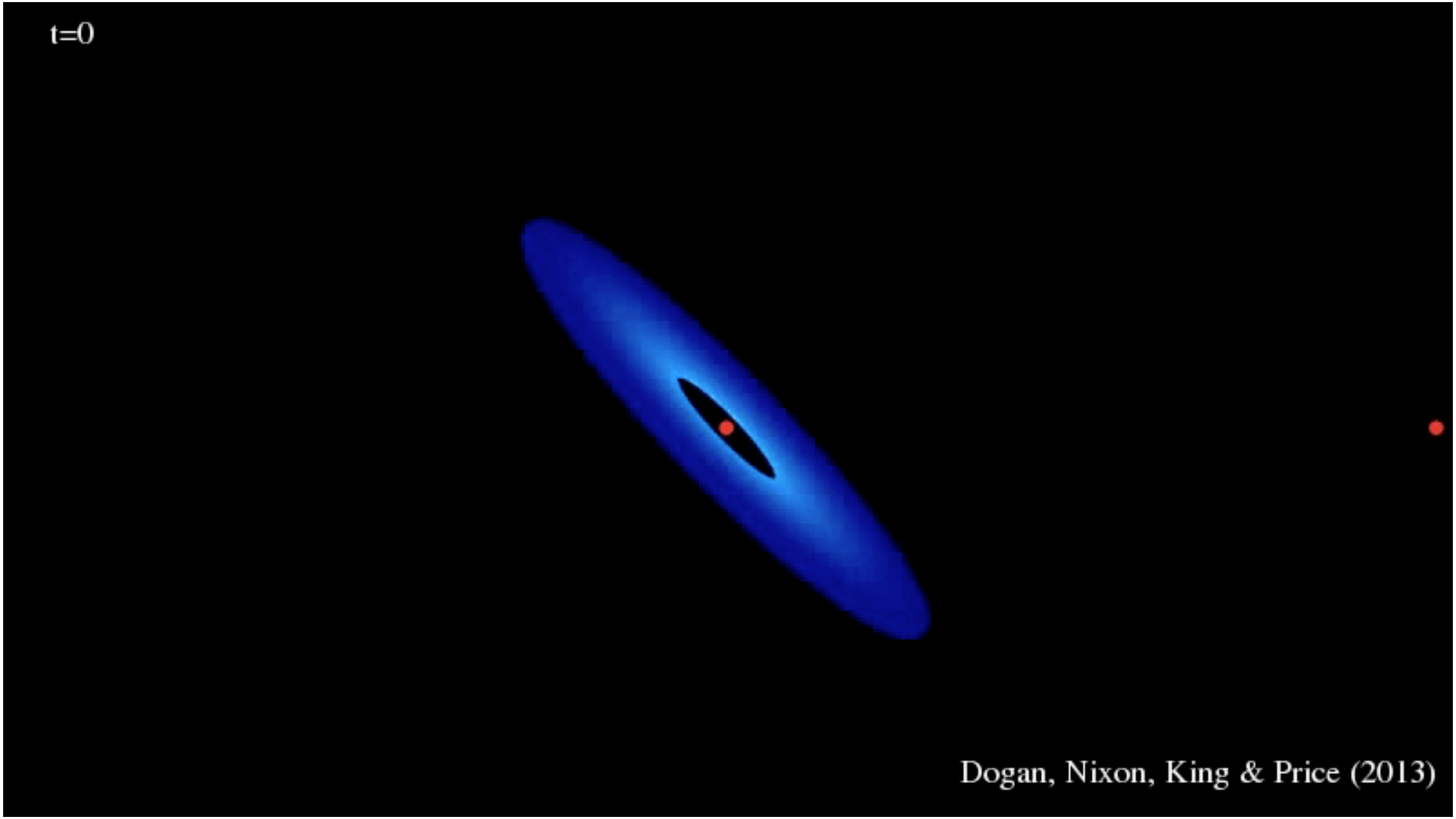
now broken disc components *precess* independently

=> opposed accretion => rapid accretion: `tearing' rapid accretion: counterrotating discs (Nixon & King, 2012)



circumprimary tearing:

Dogan et al. (2015)



warped, broken and tearing discs

mild warps => smooth bending of disc plane (Bardeen-Petterson effect)

but for a sufficiently large (few degrees) warp the disc *breaks*

broken disc components precess into opposition

rapid (dynamical) accretion

disc gas has borrowed angular momentum from the accretor in order
to cancel its own, and so fall in dynamically

can overcome angular momentum barrier to black hole growth

many more consequences, e.g. state changes in X-ray binaries, merging of supermassive black hole binaries......

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

$$F_{\rm grav} = \frac{GM(m_p + m_e)}{r^2} \simeq \frac{GMm_p}{r^2}, \ (m_p >> m_e)$$

Eddington limit

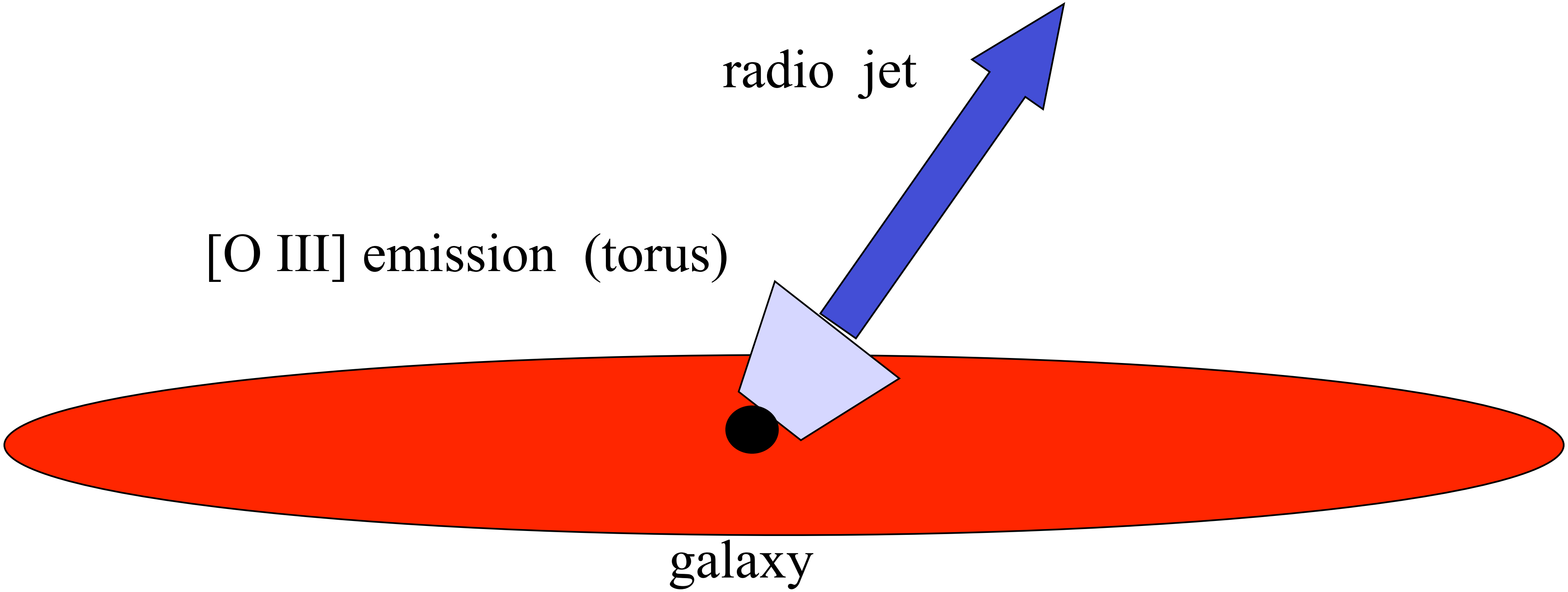
accretion is inhibited once $F_{\rm rad} \geq F_{\rm grav}$, i.e. once

$$L \geq L_{\rm Edd} = \frac{4\pi G M c}{\kappa} = 1.3 \times 10^{46} M_8 \ {\rm erg\ s^{-1}}$$

Eddington limit: luminosity requires minimum mass

$$(\kappa = \sigma_T / m_p = \textit{electron scattering opacity} \simeq 0.34 \ {\rm cm^2\ g^{-1}})$$

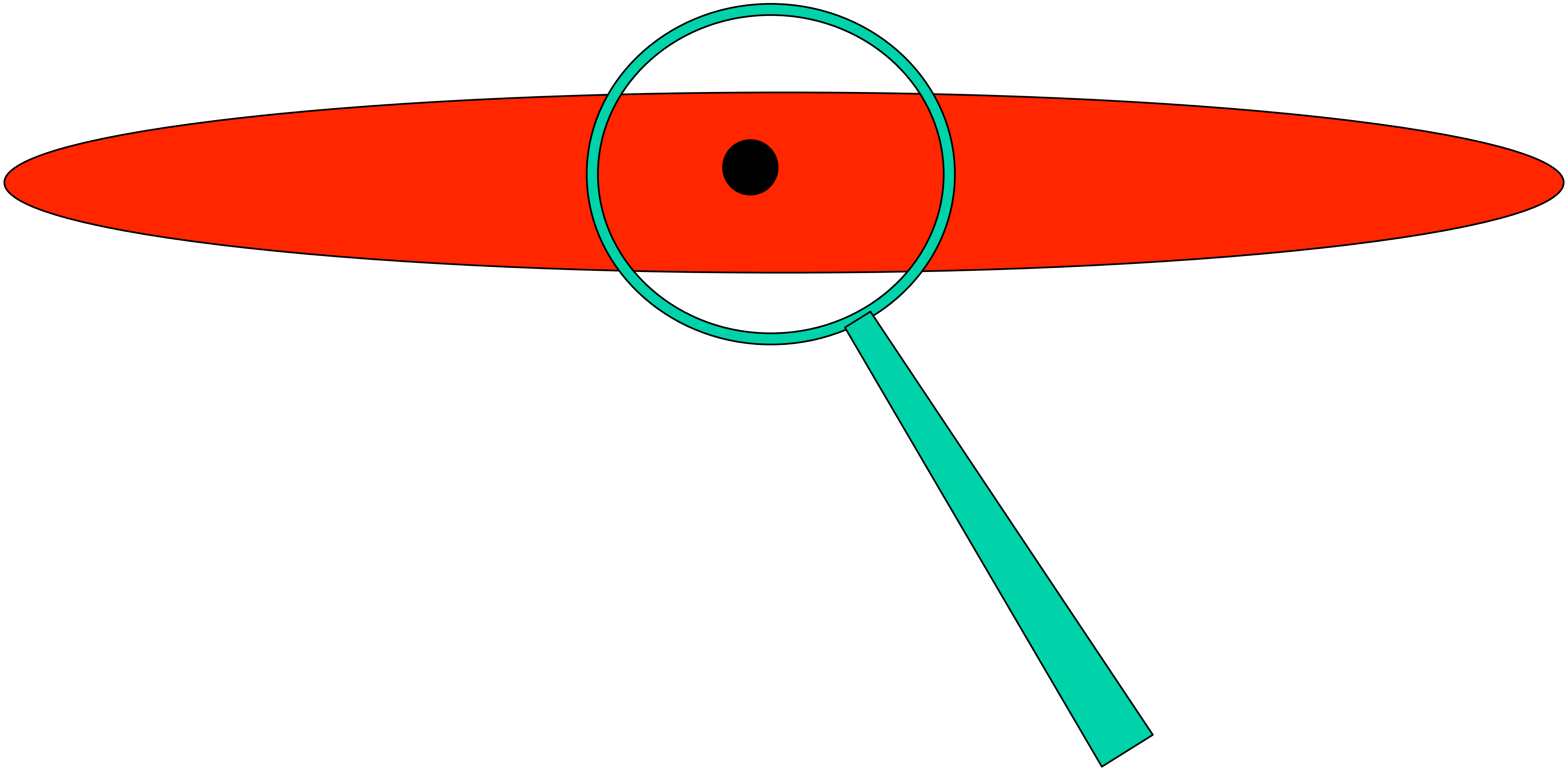
orientations



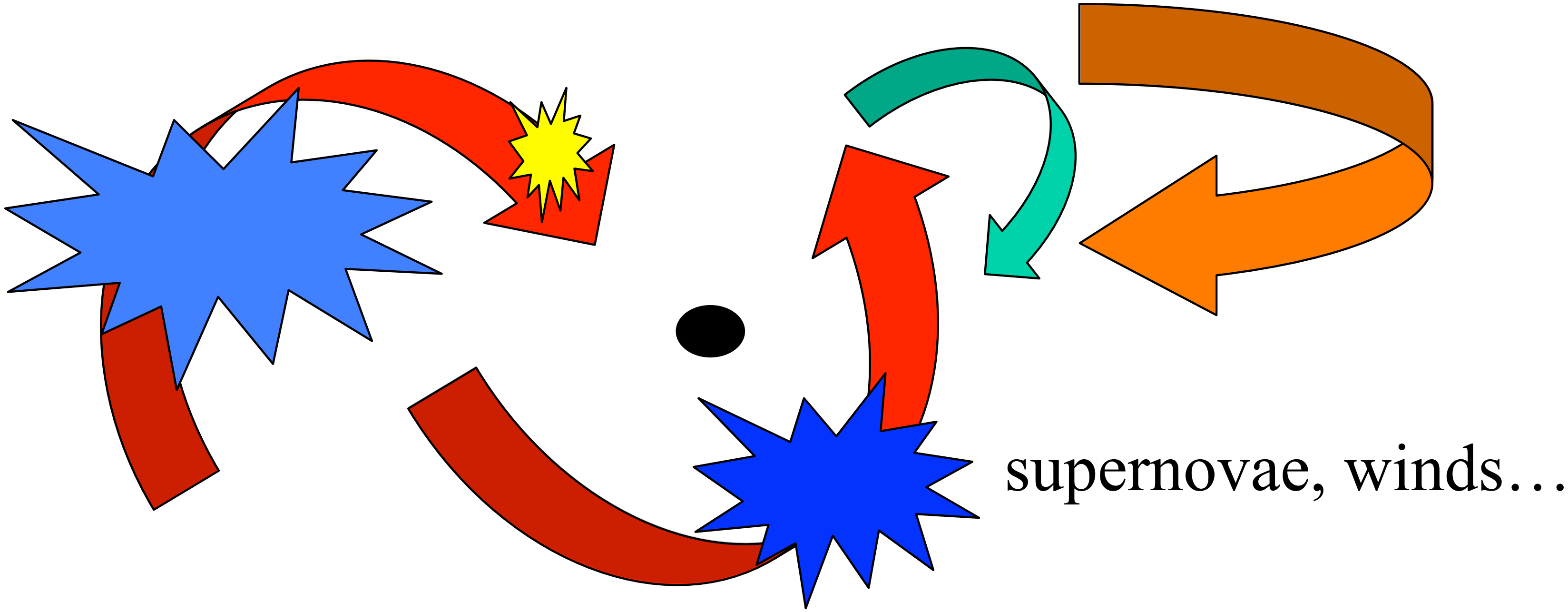
jet and torus directions correlate with each other, but are
uncorrelated with galaxy major axis
(Kinney et al., 2000; Nagar & Wilson, 1999; Schmitt et al, 2003)

➔ central disc flow has angular momentum unrelated to host
accretion disc is `warped' - centre and edge have different planes

zoom in to nucleus



central accretion flow



chaotic – no relation to large—scale structure of host

accretion is via a sequence of randomly oriented discs

huge range of length and mass scales: numerical treatment impossible

black hole growth

can BH grow in line with galaxy?

can we grow masses $M > 5 \times 10^9\ M_\odot$

at redshifts $z = 6$ (Barth et al., 2003; Willott et al., 2003),

only 10^9 years after the Big Bang?

accretion rate limited by Eddington (radiation pressure) limit:

$$\eta c^2 \dot{M}_{\rm acc} \le L_{\rm Edd} = \frac{4\pi G M c}{\kappa}$$

and some of rest–mass energy goes into radiation, i.e.

$$\dot{M} = (1-\eta)\dot{M}_{\rm acc}$$

$$=> \dot{M} \le \frac{1-\eta}{\eta}\frac{M}{t_{\rm Edd}}$$

where

$$t_{\rm Edd} = \frac{\kappa c}{4\pi G} = 4.5 \times 10^8 \ {\rm yr}$$

so

$$\frac{M}{M_0} \le \exp\left[\quad \left(\frac{1}{\eta} - 1\right)\frac{t}{t_{\rm Edd}}\right]$$

$$\frac{M}{M_0} \leq \exp\left[\left(\frac{1}{\eta} - 1\right)\frac{t}{t_{\rm Edd}}\right]$$

so

$$a = 1 => \eta = 0.42 => \frac{M}{M_0} \leq 21$$

whereas

$$a = 0 => \eta = 0.057 => \frac{M}{M_0} \leq 8 \times 10^{15} \ !$$

$$\frac{M}{M_0} \leq \exp\left[\left(\frac{1}{\eta} - 1\right)\frac{t}{t_{\rm Edd}}\right]$$

so

$$a = 1 => \eta = 0.42 => \frac{M}{M_0} \leq 21$$

whereas

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holes with high spin require \`seeds' with masses > 0.05 x current mass — greater than some current SMBH!

$$\frac{M}{M_0} \leq \exp\left[\left(\frac{1}{\eta} - 1\right)\frac{t}{t_{\rm Edd}}\right]$$

so

$$a = 1 => \eta = 0.42 => \frac{M}{M_0} \leq 21$$

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$$a = 0 => \eta = 0.057 => \frac{M}{M_0} \leq 8 \times 10^{15} \ !$$

holes with high spin require `seeds' with masses > 0.05 x current mass — greater than some current SMBH!

holes with low spin can grow *much* faster –

(and are easier to retain if they coalesce)

$$\frac{M}{M_0} \leq \exp\left[\left(\frac{1}{\eta} - 1\right)\frac{t}{t_{\rm Edd}}\right]$$

so

$$a = 1 => \eta = 0.42 => \frac{M}{M_0} \leq 21 \qquad (e^3)$$

whereas

$$a = 0 => \eta = 0.057 => \frac{M}{M_0} \leq 8 \times 10^{15}\ ! \qquad (e^{36})$$

holes with high spin require `seeds' with masses > 0.05 x current mass — greater than some current SMBH!

holes with low spin can grow *much* faster –

(and are easier to retain if they coalesce)

so need to understand spin evolution of SMBH **

$\eta = 0.1$:

$$\frac{M}{M_0} \leq \exp\left[2.2\left(\frac{1}{\eta} - 1\right)\right]$$

$$= e^{19.8}$$

$$= 4 \times 10^8$$

so the standard `ballpark' $\eta = 0.1$ is *borderline* for growing large QSO masses at z = 6 from stellar seeds, with maximal feeding

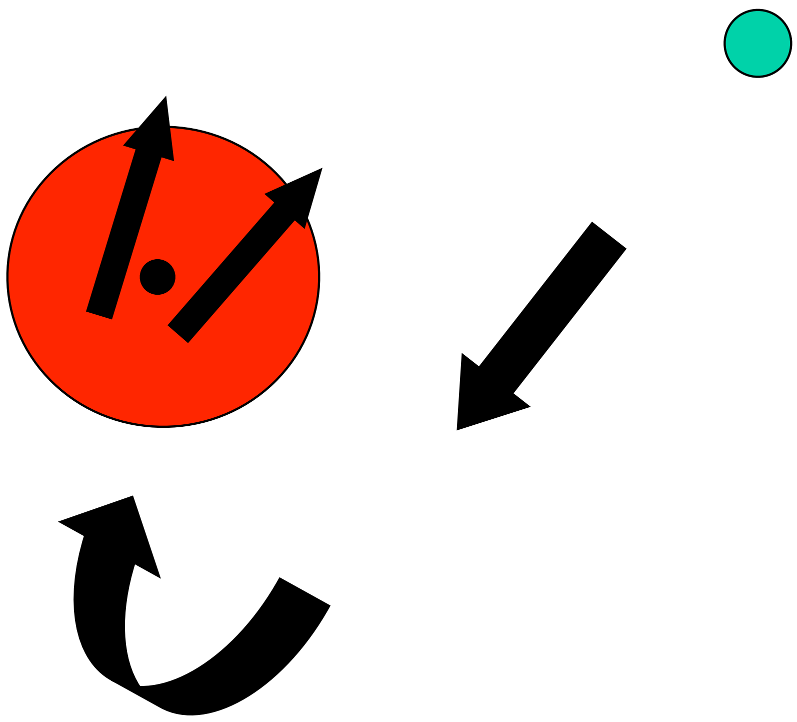
accretion to central black hole

central object gains a.m. and spins up

➔ reaches maximum spin rate $a \sim 1$ after accreting $\sim M$,
if accretion always has same sense

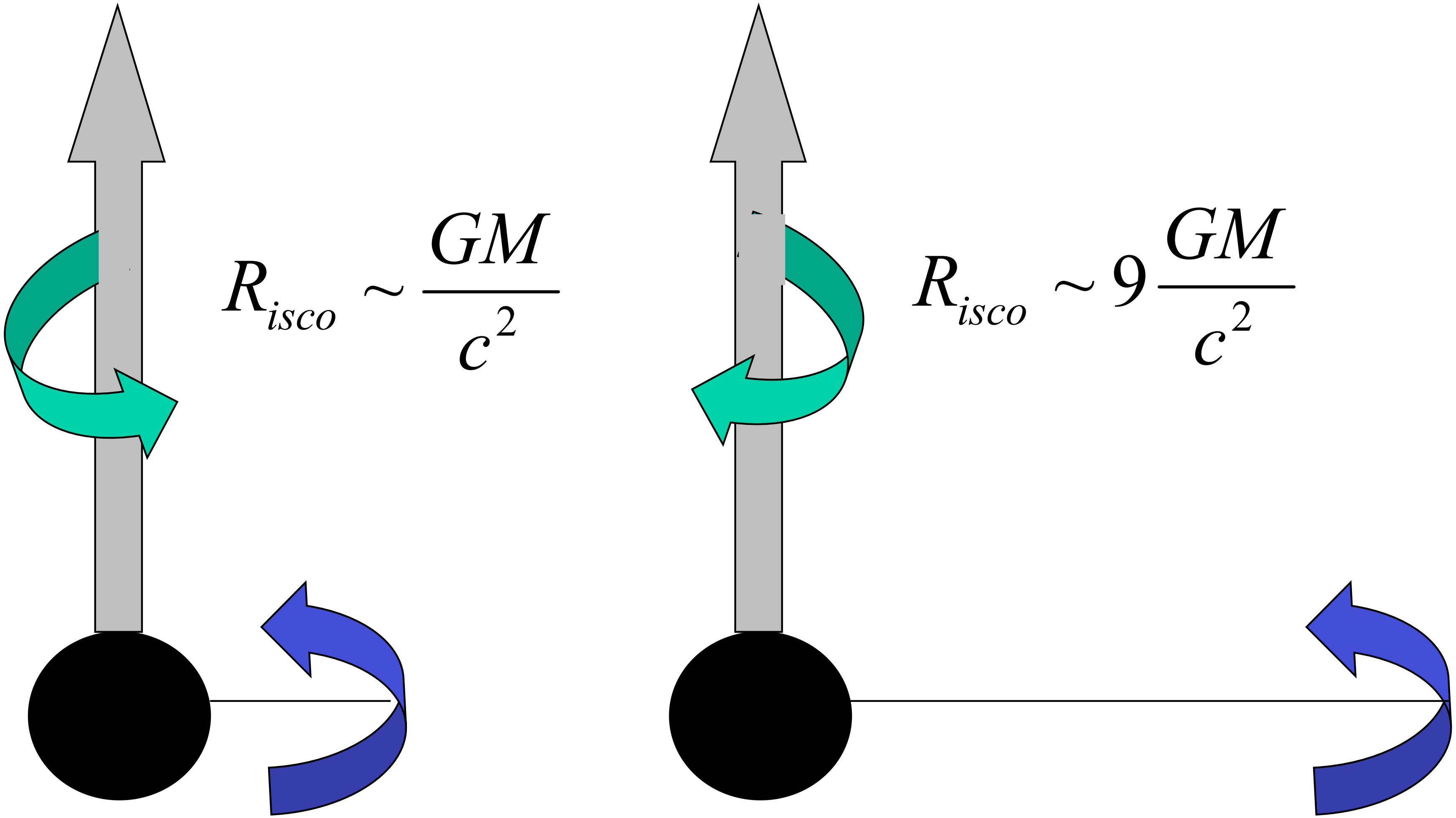
hole gains mass significantly – does it spin up?

gas infall can be both prograde and retrograde



with equal probability

accreting (or coalescing) from a retrograde orbit has a bigger effect since last stable orbit has larger lever arm than prograde one



BH area theorem

BH event horizon area is

$$A = 8\pi \left(\frac{GM}{c^2}\right)^2 [1 + (1 - a^2)^{1/2}]$$

this behaves like (is!) the *entropy* of the hole - so A cannot decrease

e.g. spin up from $a = 0$ to $a = 1$: M must increase to prevent decrease of A - rotational energy adds to mass!

spindown - extraction of rotational energy, so M decreases: but cannot decrease so much that area A drops, hence maximum mass decrease is from M to $M/\sqrt{2}$ (as a goes from 1 to 0)

maximum rotational energy extraction is $(1 - 1/\sqrt{2})Mc^2 \simeq 0.29Mc^2$

thus can give up angular momentum and still increase area, i.e. release rotational energy – e.g. as gravitational radiation

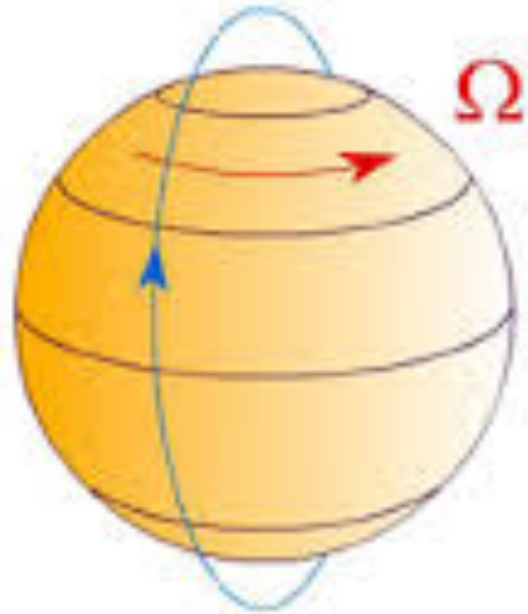
then mass M decreases!

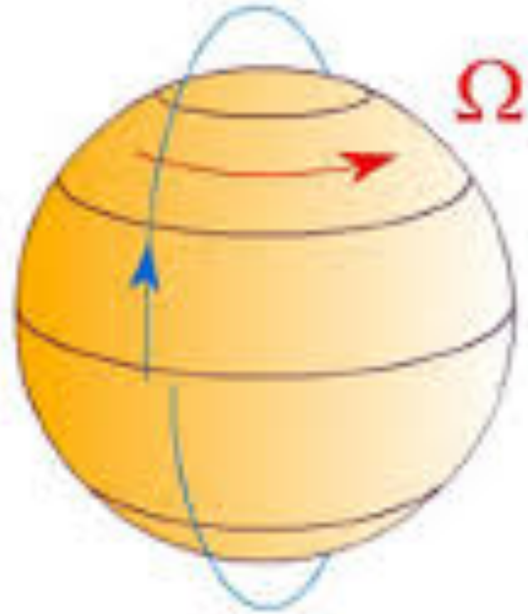
BH coalescence can be both prograde and retrograde wrt spin of merged hole, i.e. orbital opposite to spin a.m.

long—term effect of black-hole coalescences is spindown, since last stable circular orbit has larger a.m. in retrograde case.

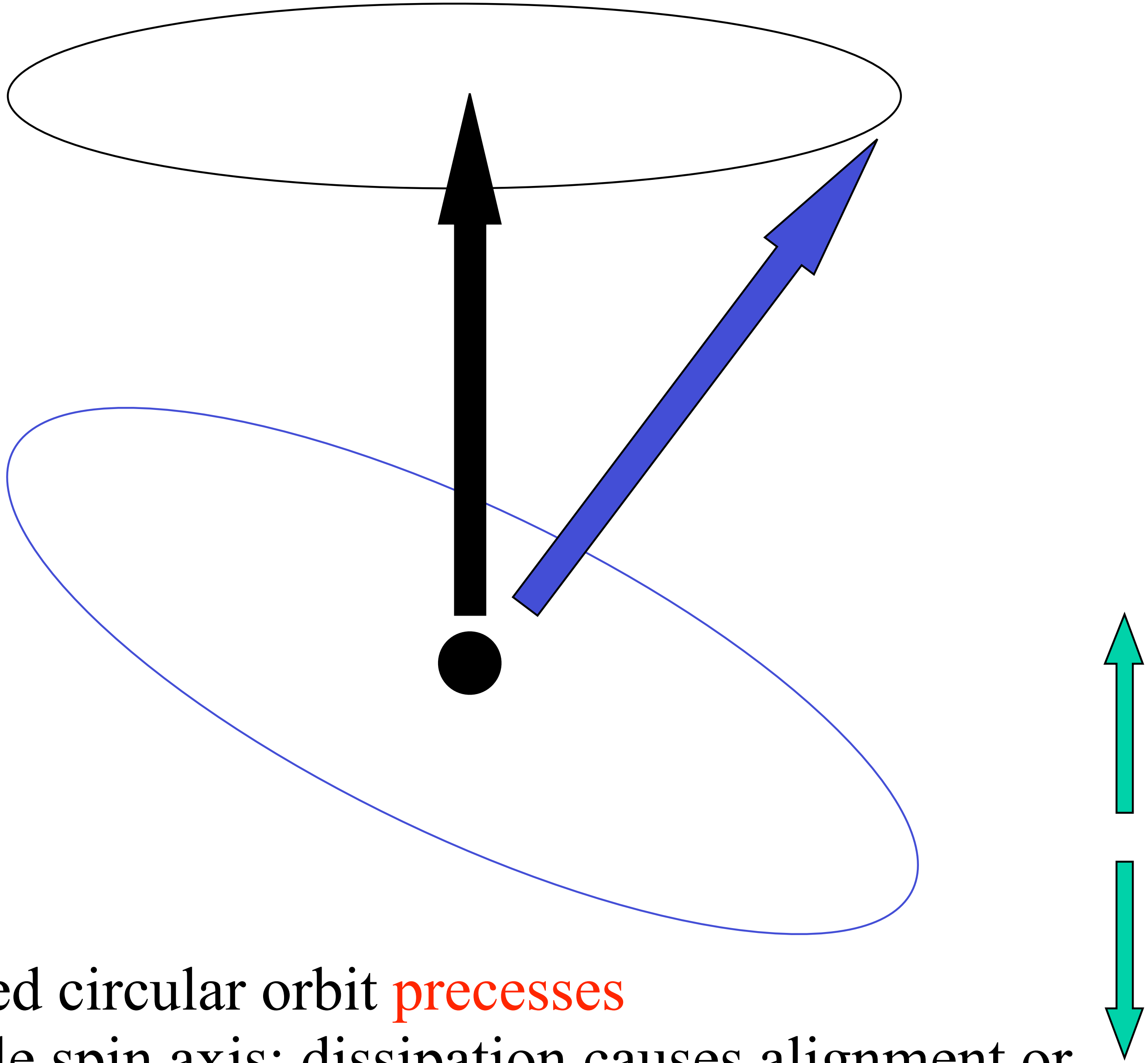
- black hole coalescences cause net spindown because of this
- is this true of accretion?
- actually *yes*, but disc warping effect complicates things

Lense-Thirring effect





Lense-Thirring effect



plane of inclined circular orbit precesses
about black hole spin axis: dissipation causes alignment or
counteralignment

gas torques on hole:

- two main types: 1. accretion – spinup or spindown – hole mass has to double to change *a* significantly — slow

  2. Lense—Thirring from misaligned disc

  viscous timescale — fast in inner disc

- old argument: alignment via Lense—Thirring occurs rapidly, hole spins up to keep a ~ 1, accretion efficiency is high

- but L—T also vanishes for counteralignment

- alignment or not? (King, Lubow, Ogilvie & Pringle 05)

**

torque on hole is pure precession, so orthogonal to spin.

thus general equation for spin evolution is

$$\frac{d\mathbf{J}_h}{dt} = -K_1[\mathbf{J_h} \wedge \mathbf{J_d}] - K_2[\mathbf{J}_h \wedge (\mathbf{J}_h \wedge \mathbf{J}_d)]$$

here $K_1, K_2 > 0$ depend on disc properties: first term specifies precession, second alignment

clearly magnitude J_h is constant, and vector sum $\boldsymbol{J}_t$ of $\boldsymbol{J}_h$, $\boldsymbol{J}_d$ is constant. Thus *$\boldsymbol{J}_t$ stays fixed, while tip of $\boldsymbol{J}_h$ moves on a sphere during alignment* using these, we have

$$\frac{d}{dt}(\mathbf{J}_h.\mathbf{J}_t) = \mathbf{J}_t.\frac{d\mathbf{J}_h}{dt} = \mathbf{J}_d.\frac{d\mathbf{J}_h}{dt}$$

so

$$\frac{d}{dt}(\mathbf{J}_h.\mathbf{J}_t) = K_2[J_d^2 J_h^2 - (\mathbf{J}_d.\mathbf{J}_h)^2] > 0$$

Exercise!

but J_h, J_t are constant, so angle θ_h between them obeys

$$\frac{d}{dt}(\cos\theta_h) > 0$$

— *hole spin always aligns with total angular momentum* can further show that J_d^2 always decreases during this process – dissipation

thus viewed in frame precessing with $\boldsymbol{J}_h$, $\boldsymbol{J}_d$,

$\boldsymbol{J}_t$ stays fixed: $\boldsymbol{J}_h$ aligns with it while keeping its length constant

J_d^2 decreases monotonically because of dissipation since if θ is the angle between $\mathbf{J}_h$ and $\mathbf{J}_d$ the cosine theorem gives

$$J_t^2 = J_h^2 + J_d^2 + 2J_h J_d \cos(\theta)$$

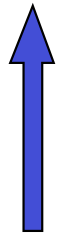
disc and hole a.m. counteralign $(J_t^2 < J_h^2)$ if and only if

$$\cos\theta < -\frac{J_d}{2J_h}$$

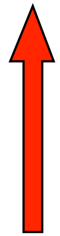
counteralignment occurs *often* if the disc's angular momentum is always comparable to or smaller than the hole's, i.e. in most cases where $\mathbf{J}_d$ and $\mathbf{J}_h$ are initially opposed (i.e. $\theta > \pi/2$)

older treatments *assumed* disc fixed, i.e. $J_d \to \infty$
so $J_t^2 > J_h^2$ always: so *always* found alignment!

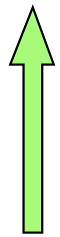
$$\boldsymbol{J}_h =$$



$$\boldsymbol{J}_d =$$



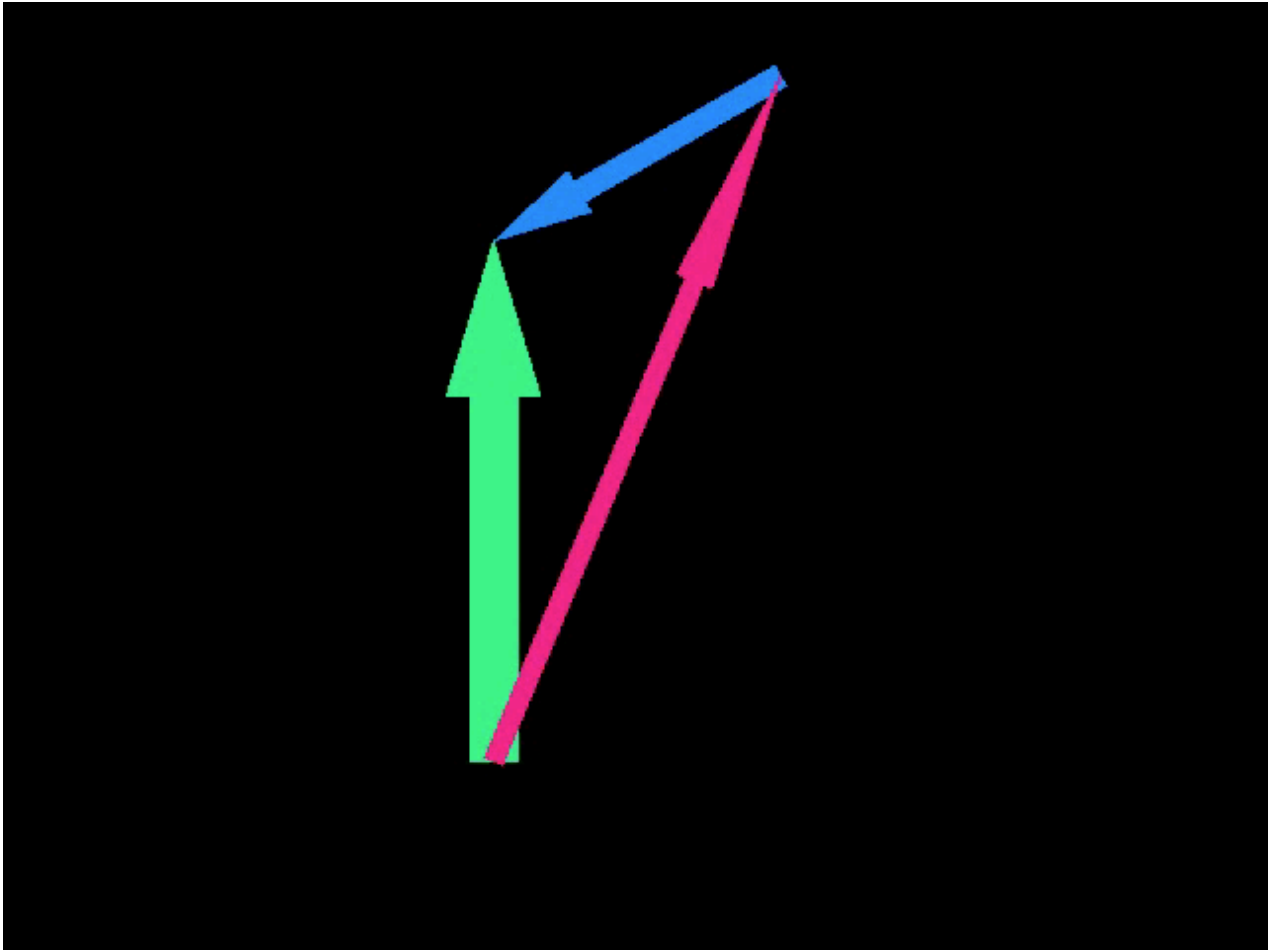
$$\boldsymbol{J}_t = \boldsymbol{J}_h + \boldsymbol{J}_d =$$



so if

$$\cos\theta > -\frac{J_d}{2J_h}$$

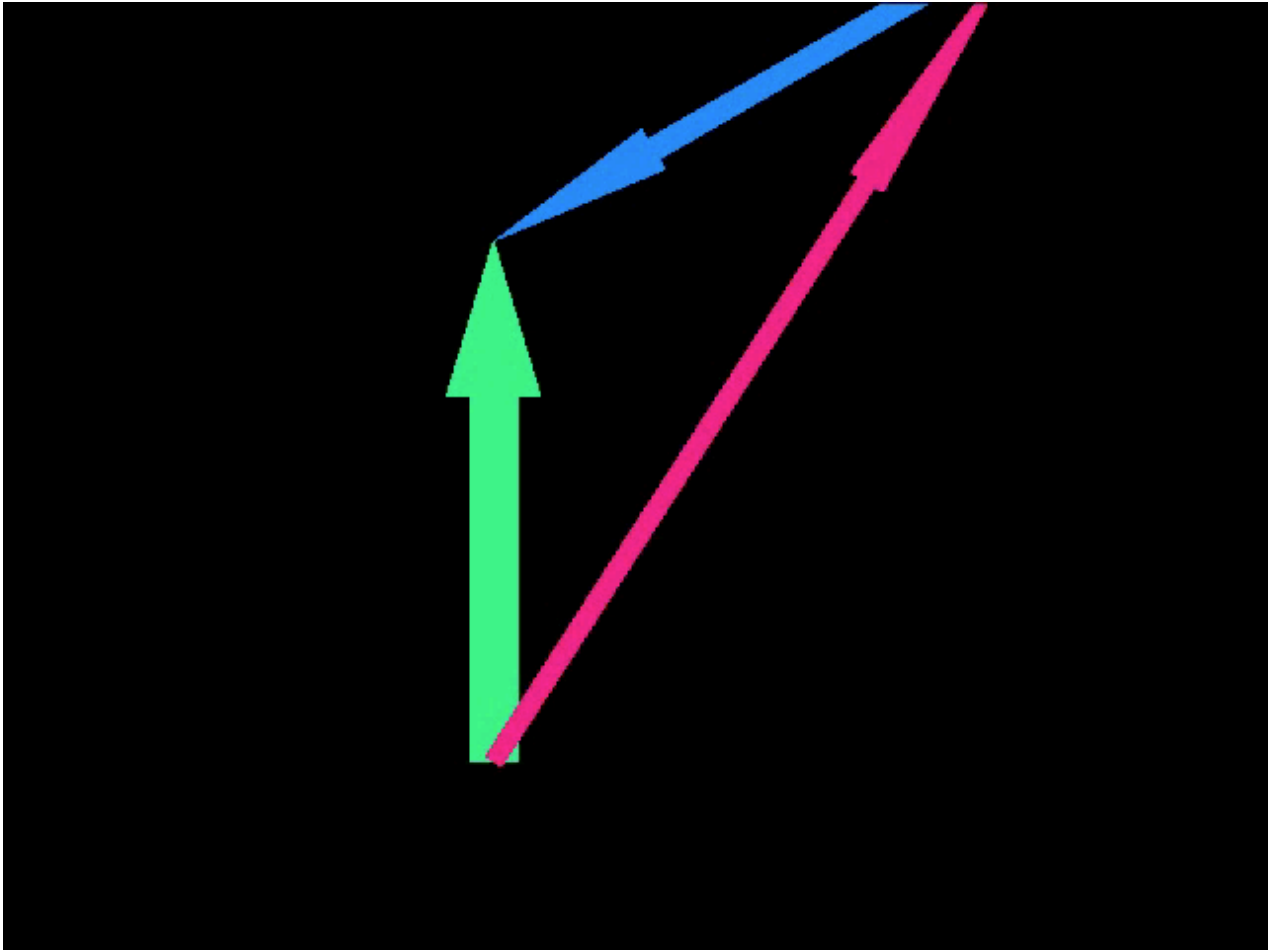
alignment follows



but if instead

$$\cos\theta < -\frac{J_d}{2J_h}$$

counteralignment follows



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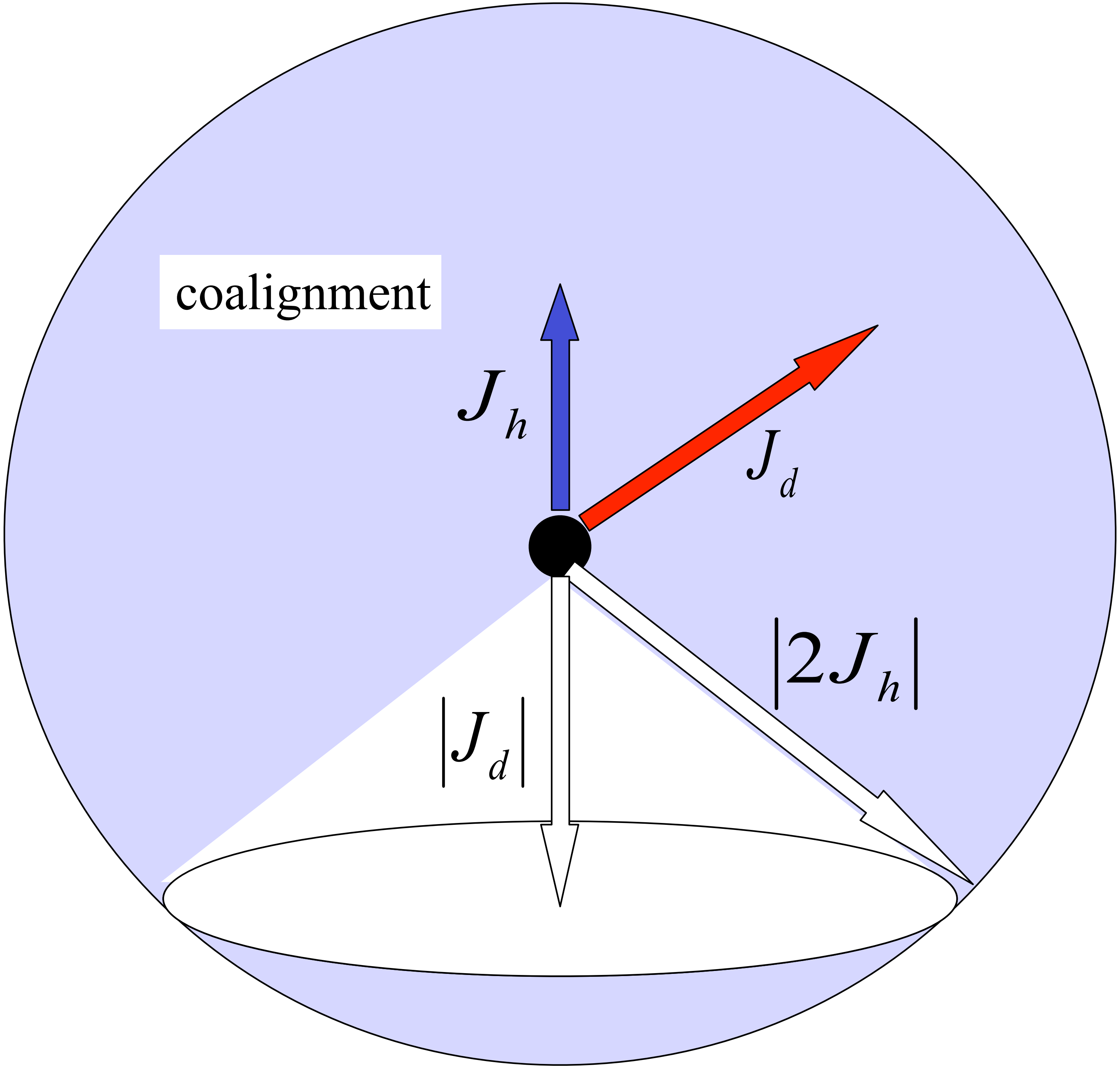
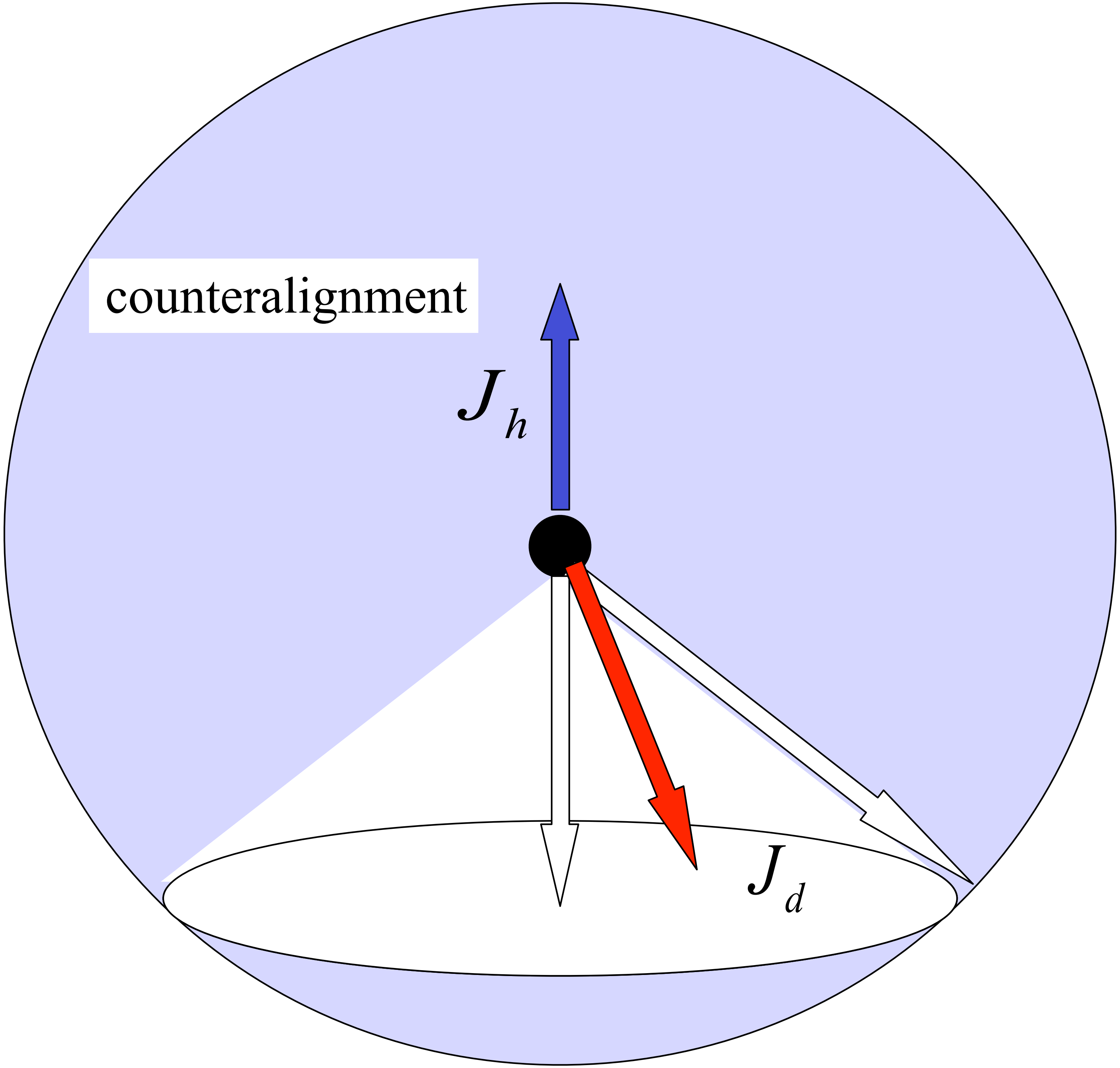
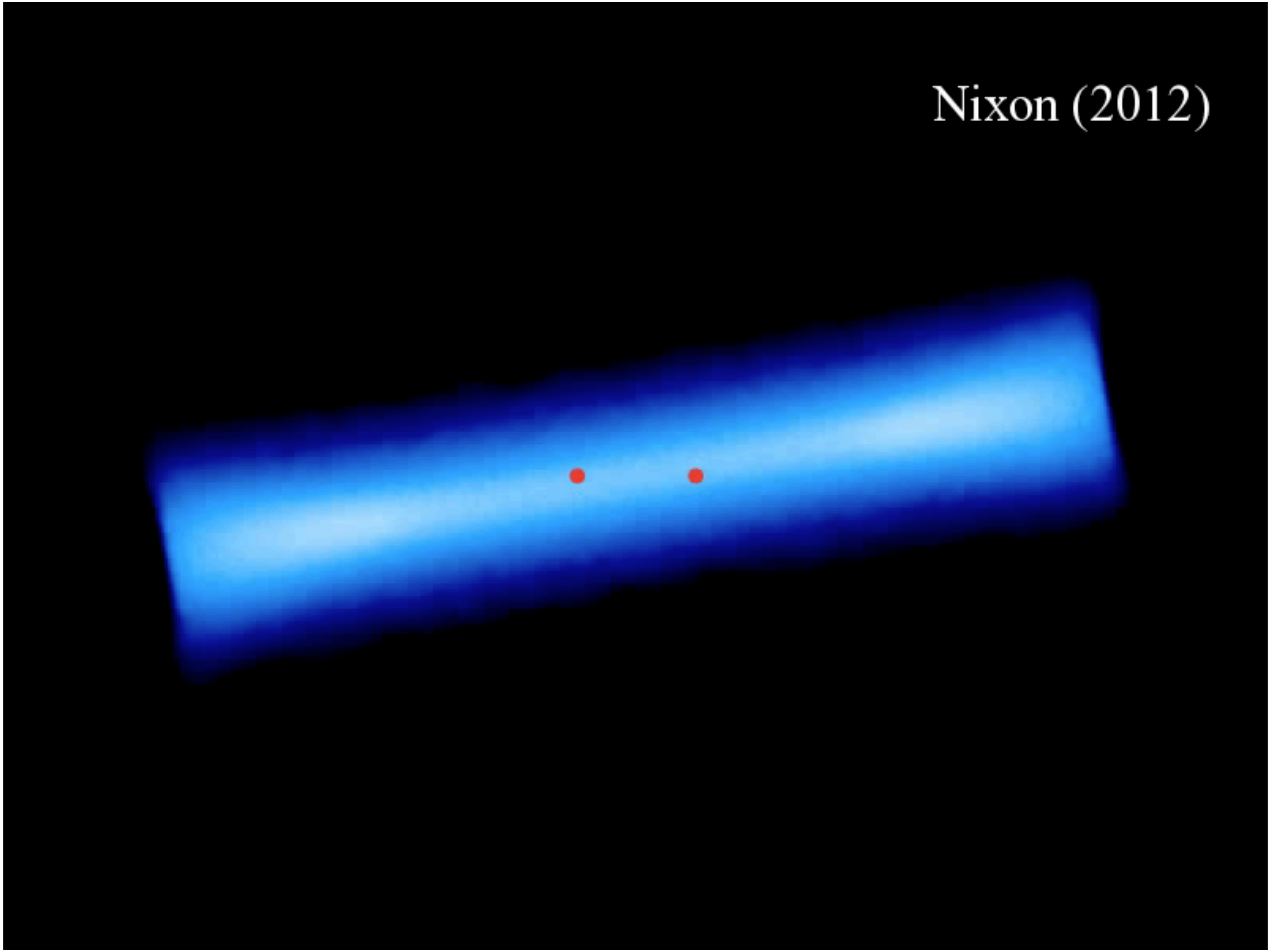

coalignment
J_h
J_d
$|J_d|$
$|2J_h|$


counteralignment
J_h
J_d

alignment/counteralignment *with a binary*: Nixon (2012)



accretion to central black hole

central object gains a.m. and spins up

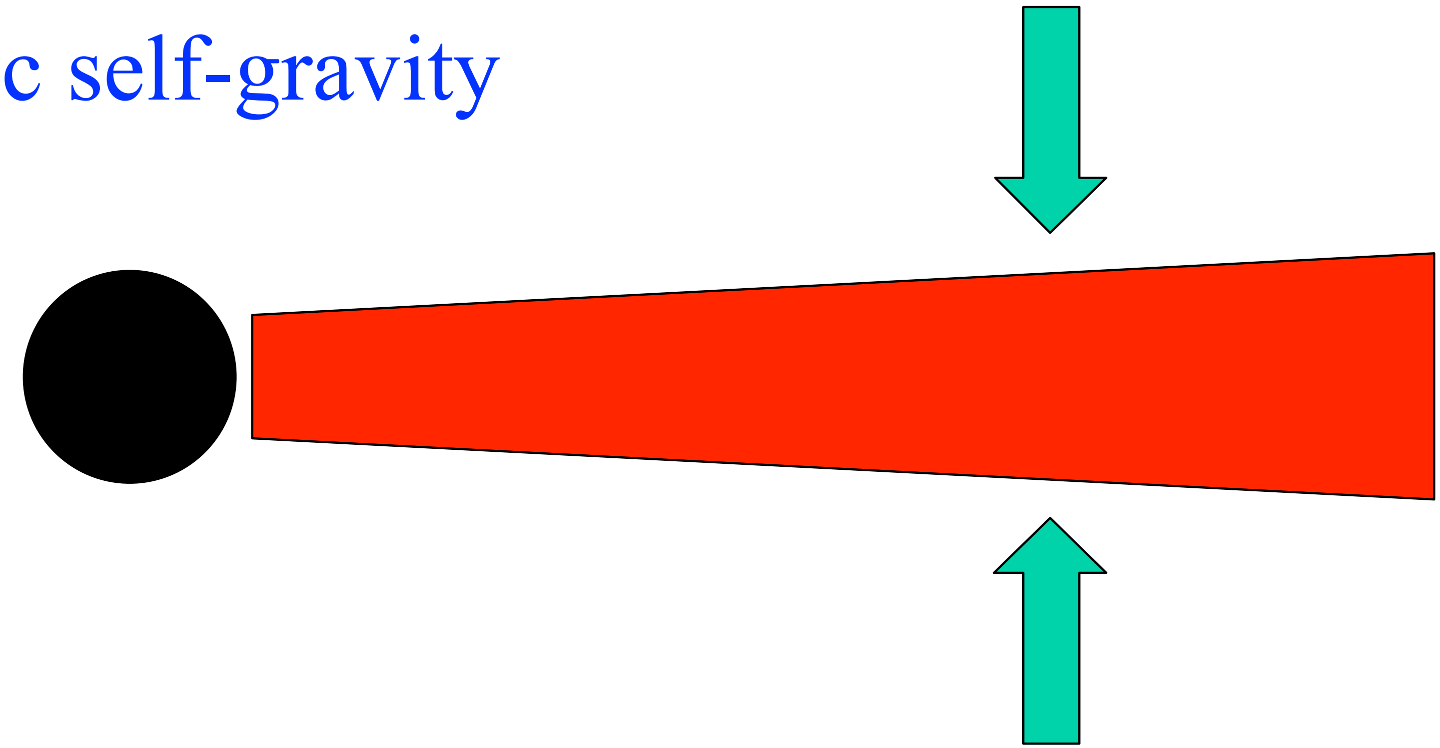
➔ reaches maximum spin rate $a \sim 1$ after accreting $\sim M$,
if accretion always has same sense

hole gains mass significantly – does it spin up?

alignment/counteralignment depends on J_d/J_h

so how large is this quantity?

disc self-gravity

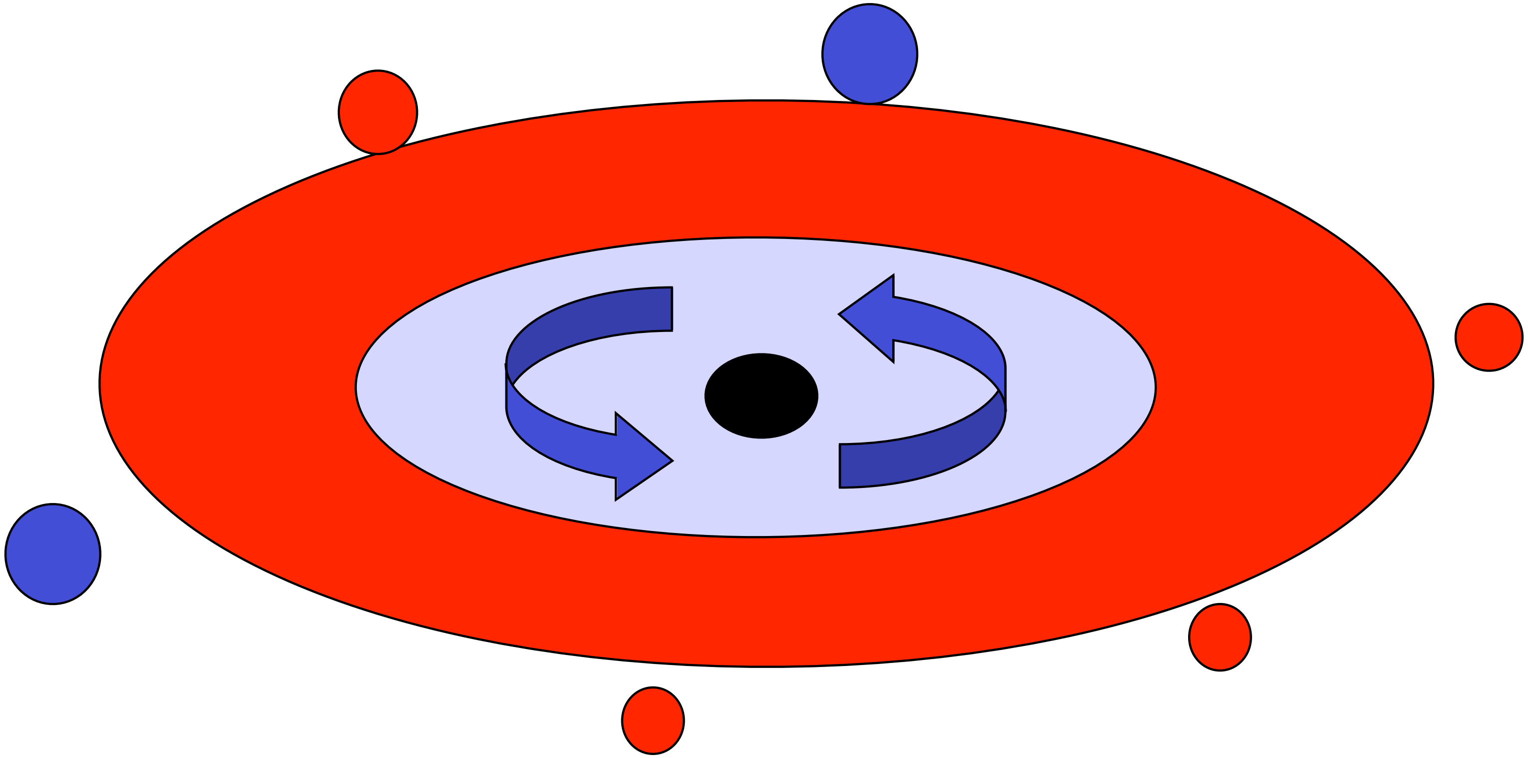


important if gravity force from local disc matter > BH tidal field, i.e.

$$\frac{G\rho H^3}{H^2} > \frac{GMH}{R^3} => \rho > \frac{M}{R^3}$$

so self gravity is important (disc may fragment) if

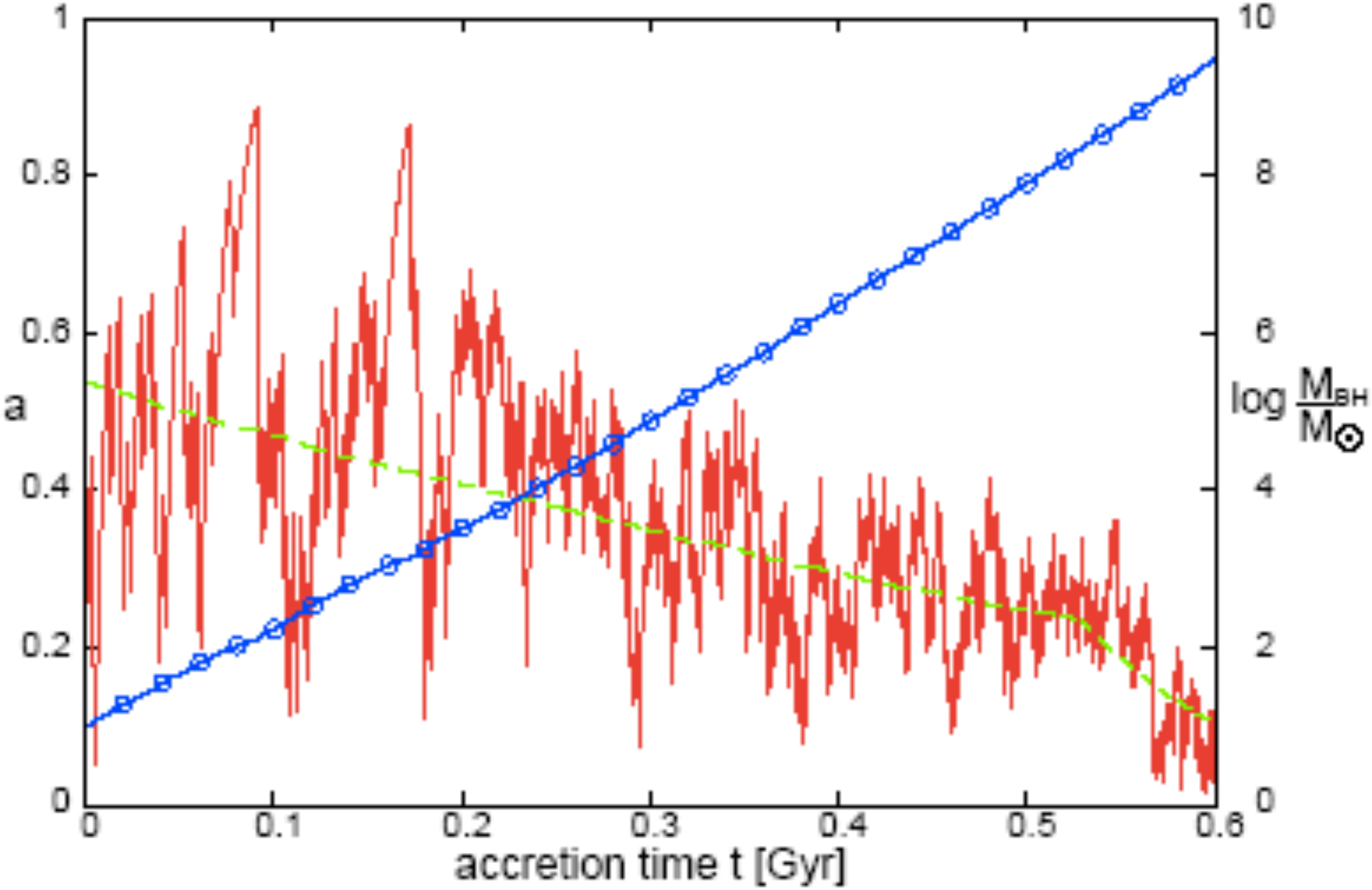
$$M_{\rm disc} > R^2 H\rho \gtrsim \frac{H}{R}M$$



self—gravity limit on disc mass and size implies $J_d/J_h < 1$
gas outside $R_{\rm sg}$ *forms stars and disconnects from the disc*

condition $\cos\theta < -\frac{J_d}{2J_h}$ is easy to satisfy

spinup and spindown alternate – spin becomes small so given a sufficient mass supply, black holes can grow to observed high—redshift masses from small beginnings



King, Pringle & Hofmann, MNRAS 2008

- *coalescences* lift SMBH discontinuously above curve

- curve is an attractor, so SMBH return to it once they have doubled their masses by accretion

- doubling is unlikely for largest SMBH — giant ellipticals

- so *some* of these galaxies *can* have SMBH with *high spin*

how big can a black hole grow?

self-gravity radius is almost independent of parameters:

$$R_{\rm sg} = 3 \times 10^{14} \alpha_{0.1}^{14/27} \eta_{0.1}^{8/27} (L/L_{\rm Edd})^{-8/27} M_8^{1/27}\ {\rm m}$$

or

$$R_{\rm sg} \simeq C \simeq 3 \times 10^{14}\ {\rm m}$$

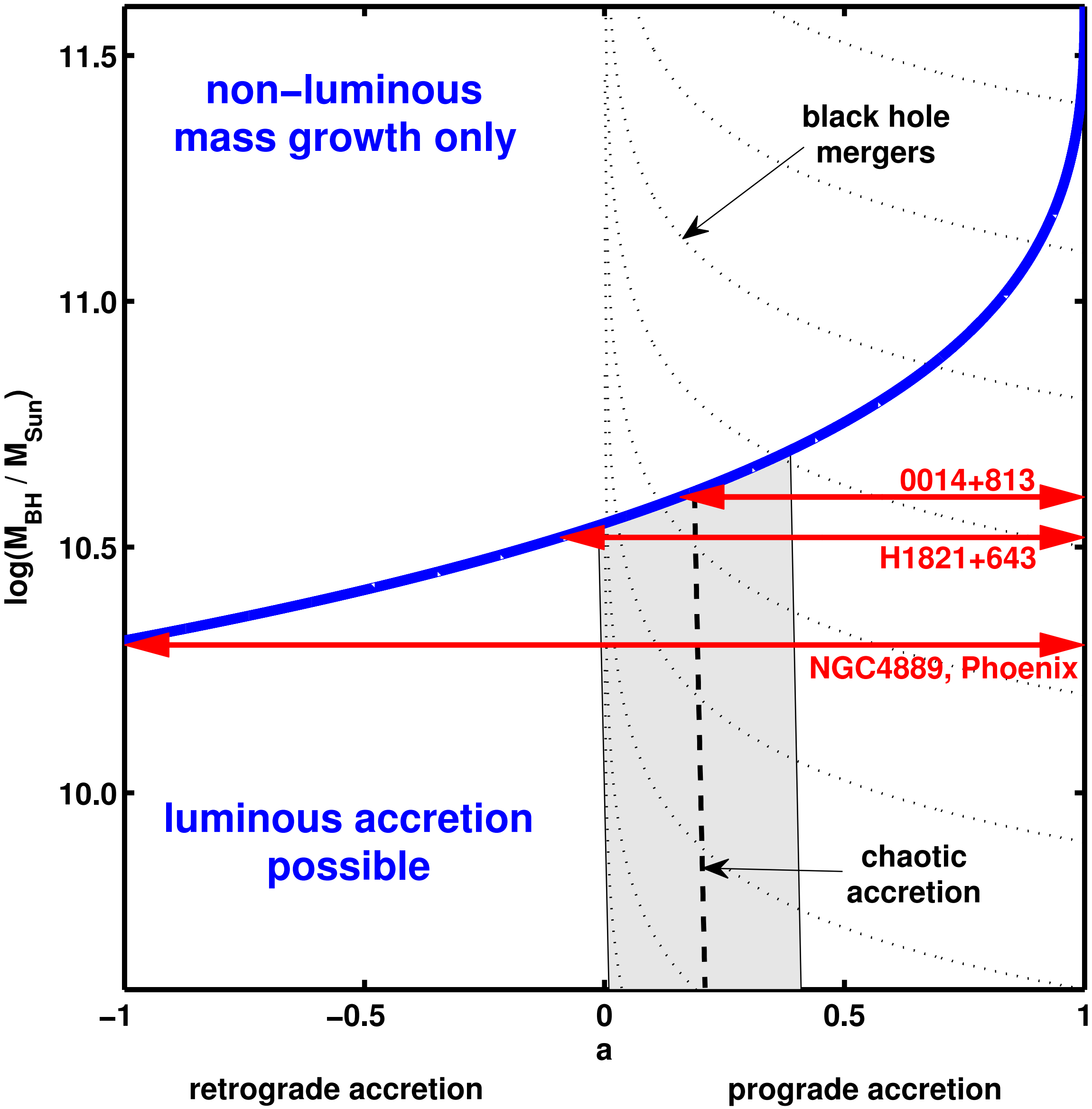
so disc radius must be smaller than this

but disc must be bigger than ISCO:

$$R_{\rm ISCO} = f(a) \frac{GM}{c^2} = 7.7 \times 10^{11} M_8 f_5\ {\rm m}$$

requiring $R_{\rm ISCO} < R_{\rm sg}$ shows that to have a luminous disc

$$M < M_{\rm max} \simeq \frac{c^2 R_{\rm sg}}{G} \simeq 5 \times 10^{10} {\rm M}_\odot$$



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

➔ *AGN should show outflows*

Eddington limit

accretion is inhibited once $F_{\mathrm{rad}} \geq F_{\mathrm{grav}}$, i.e. once

$$L \geq L_{\mathrm{Edd}} = \frac{4\pi G M c}{\kappa} = 1.3 \times 10^{46} M_8 \ \mathrm{erg\ s^{-1}}$$

Eddington limit: luminosity requires minimum mass

$$(\kappa = \sigma_T / m_p = \textit{electron scattering opacity} \simeq 0.34\ \mathrm{cm^2\ g^{-1}})$$

Can a black hole *ignore* the Eddington limit?

accretion would *not* be limited by the Eddington rate

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2}$$

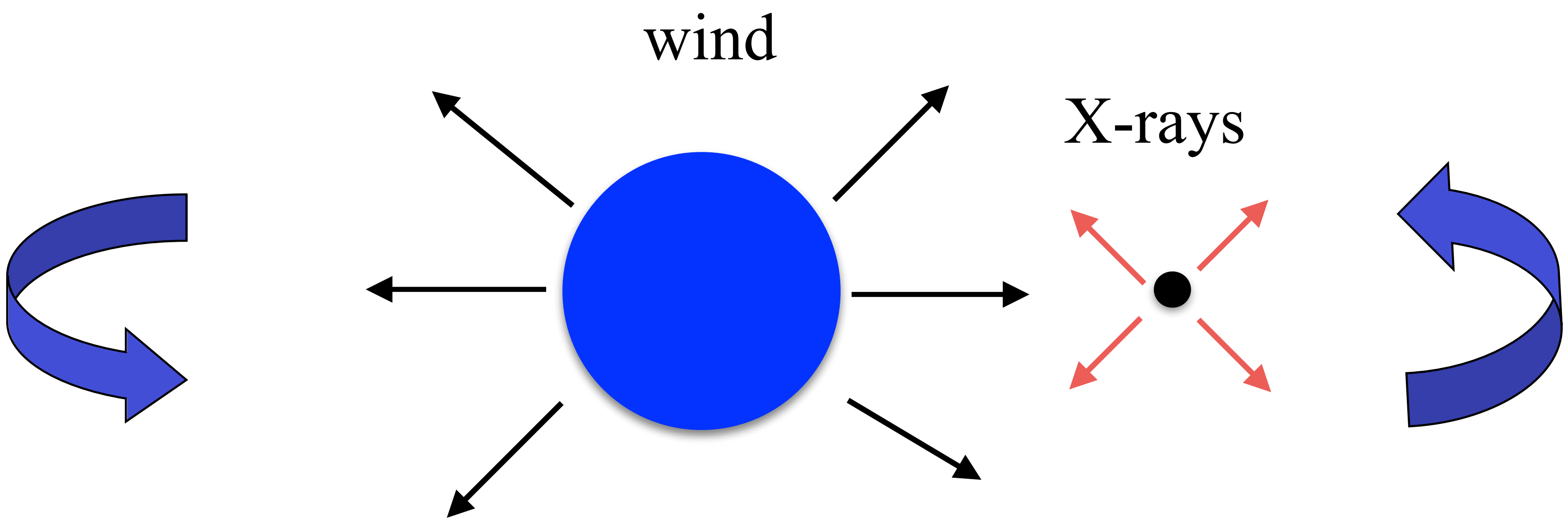
if radiation could somehow escape without pushing matter away.

radiative transfer calculations sometimes suggest this

Can a black hole *ignore* the Eddington limit?

observational constraint: compact binary systems in our Galaxy do not do this

high-mass X-ray binary (HMXB): BH or NS accretes from stellar wind of blue supergiant

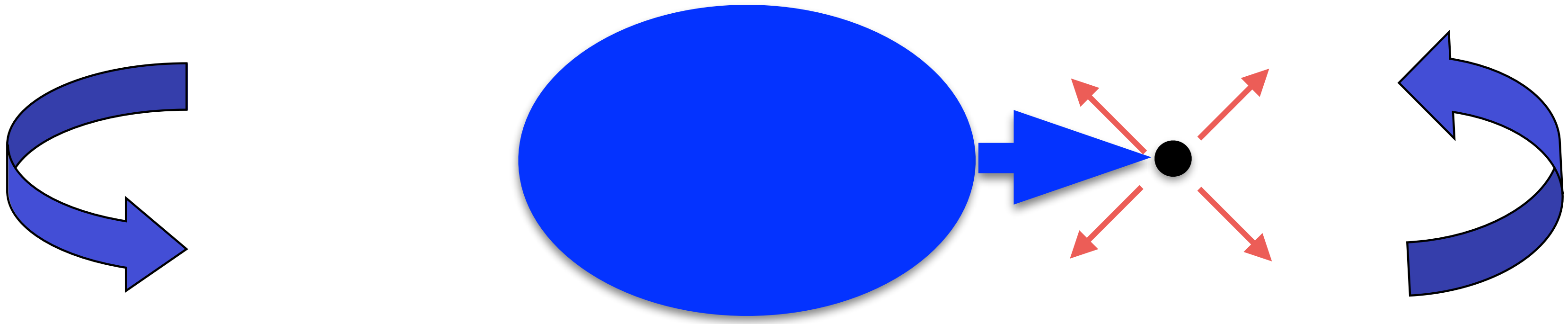


$\sim$ 30 such systems in the Galaxy: they live $\sim 10^5\,\mathrm{yr}$, with luminosities $\sim 10^{37}\,\mathrm{erg\,s^{-1}}$

eventually supergiant fills its Roche lobe and transfers mass at

a rate $\sim 10^5\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ to the BH/NS, i.e $\sim 10^2 - 10^3\,\dot{M}_{\rm Edd}$:

lifetime in this state is $\sim 10^6\,\mathrm{yr}$



so if BH can ignore the Eddington limit,
there should be ~ 300 binaries in the Galaxy with $L >> L_{\rm Edd}$

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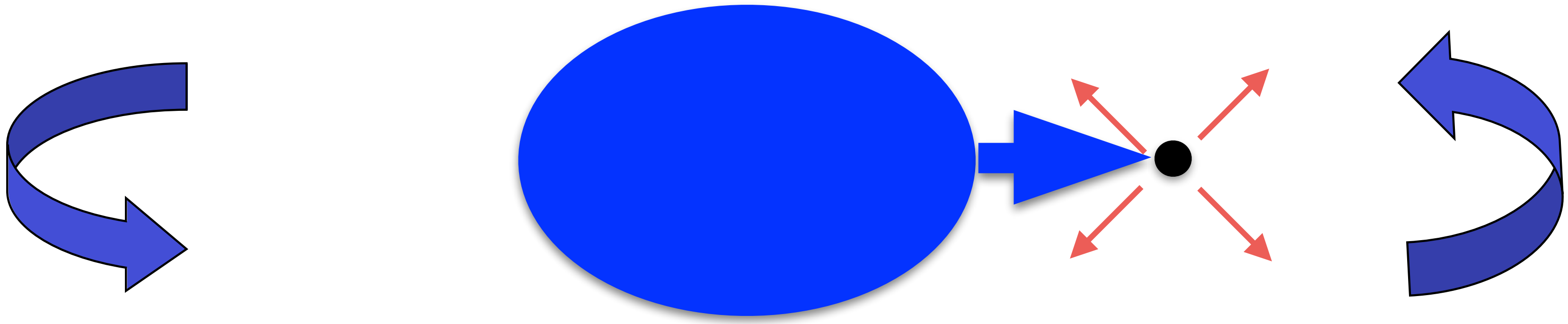
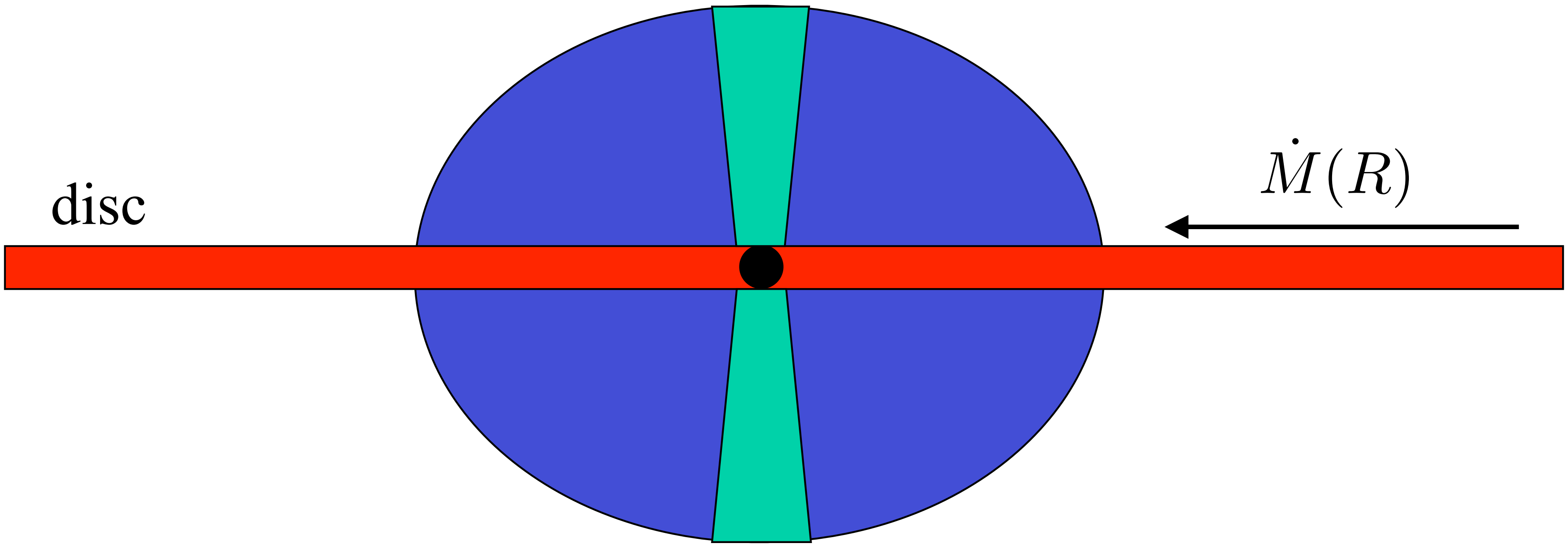


so if BH can ignore the Eddington limit,
there should be ~ 300 binaries in the Galaxy with $L >> L_{\rm Edd}$
there are none:

luminosities do not dramatically exceed $L_{\rm Edd}$
[ULXs are beamed, so *intrinsic* luminosities are $\lesssim L_{\rm Edd}$]

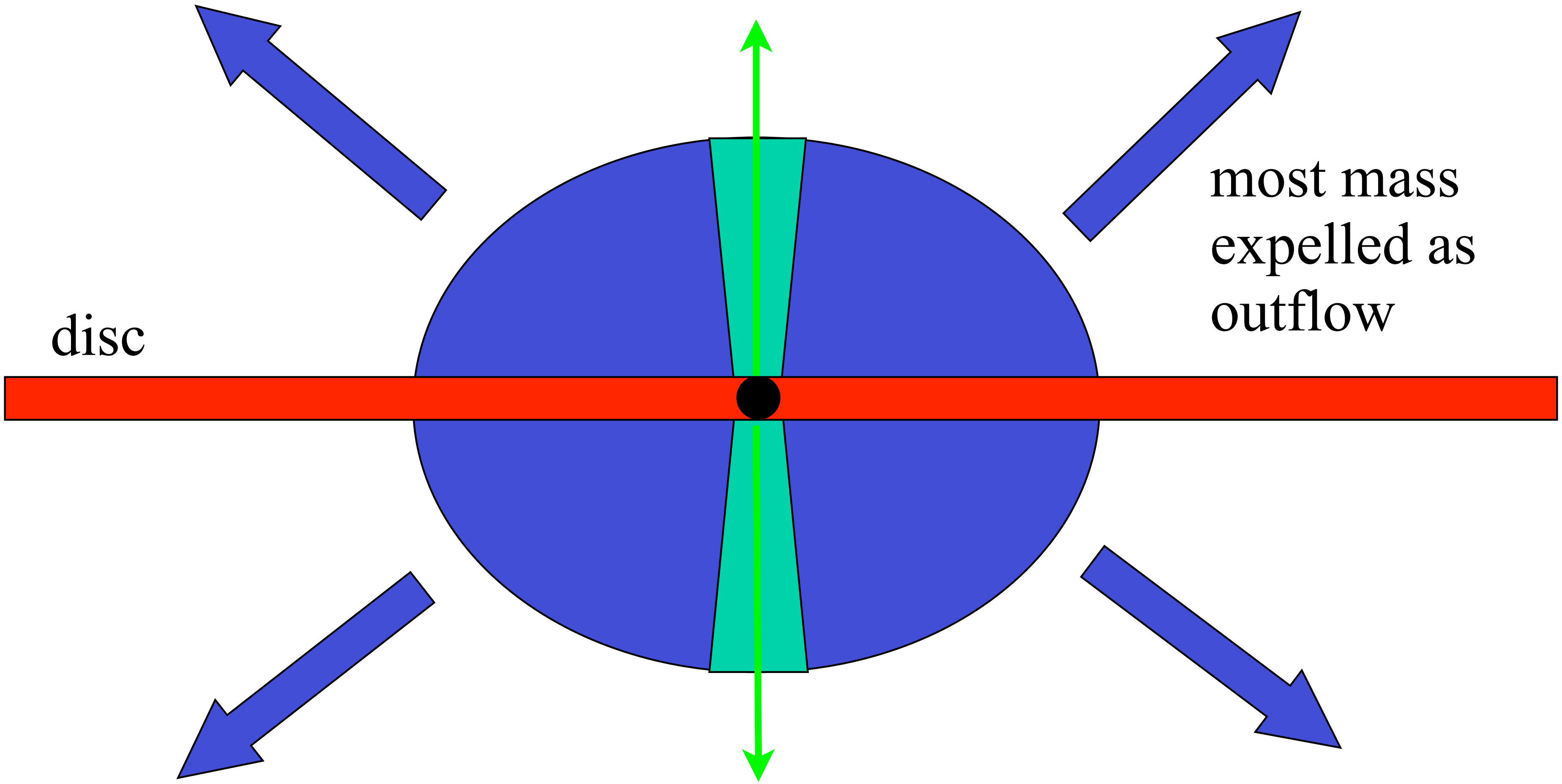
Super-Eddington Accretion

$\dot{M}(R)$ adjusts to keep $GM\dot{M}(R)/R = L_{\rm Edd}$



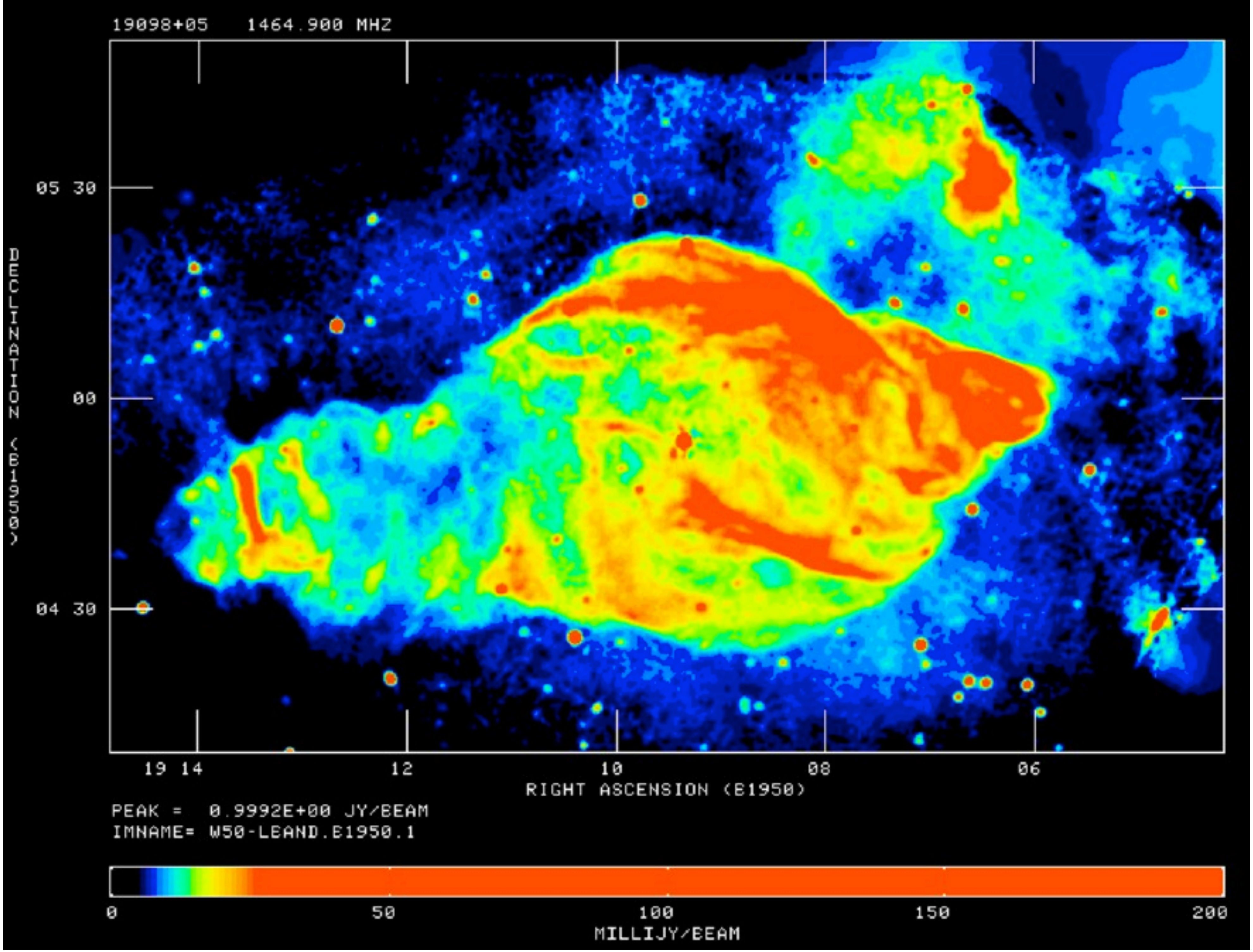
so $\dot{M}(R) \propto R$

Super-Eddington Accretion



$$L = L_{\rm Edd}[1 + \ln(\dot{M}/\dot{M}_{\rm Edd})]$$ (beamed)

compare with SS433


19098+05 1464.900 MHZ
DECLINATION (B1950)
05 30
00
04 30
19 14
12
10
08
06
RIGHT ASCENSION (B1950)
PEAK = 0.9992E+00 JY/BEAM
IMNAME= W50-LBAND.B1950.1
0
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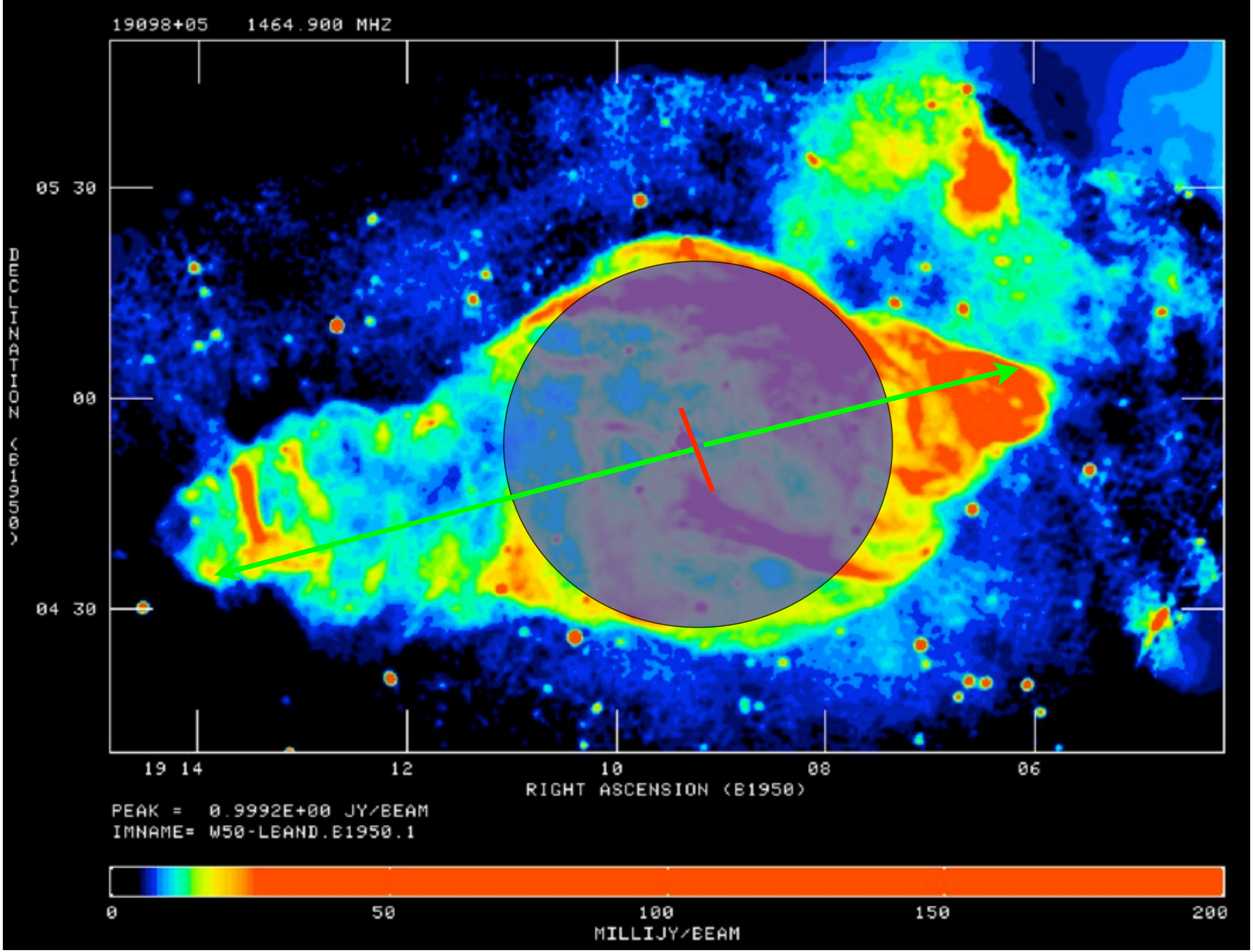
MILLIJY/BEAM



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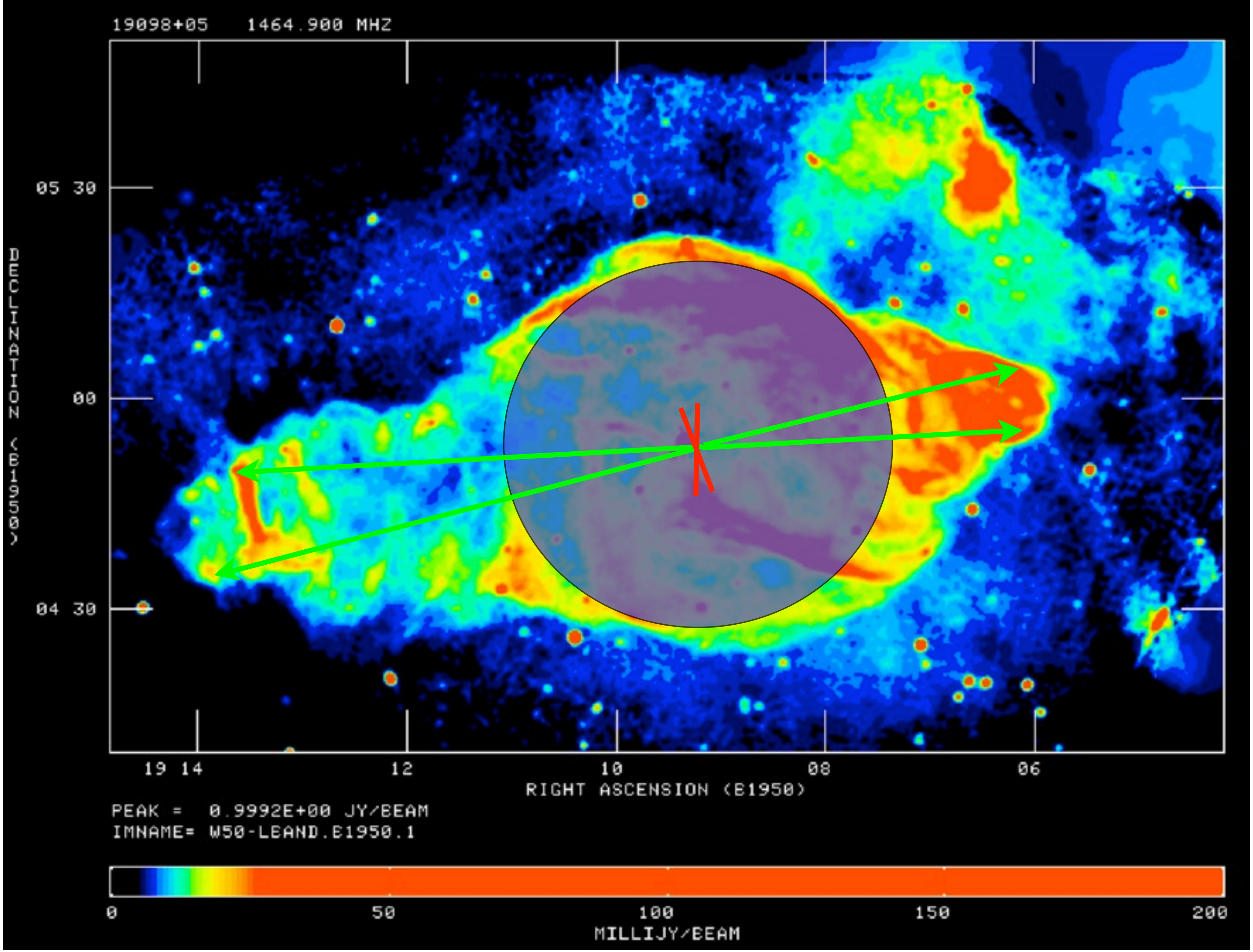

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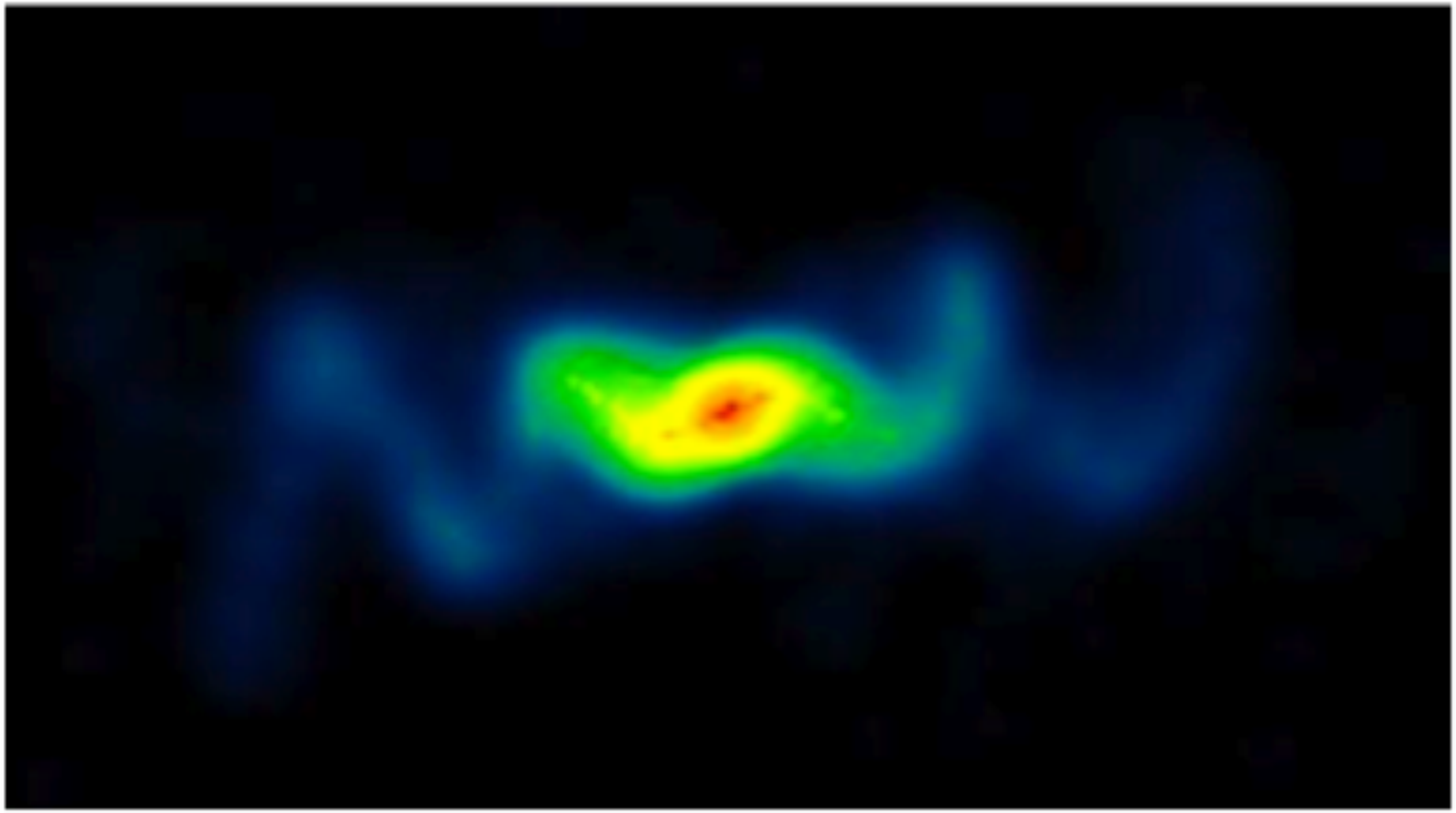
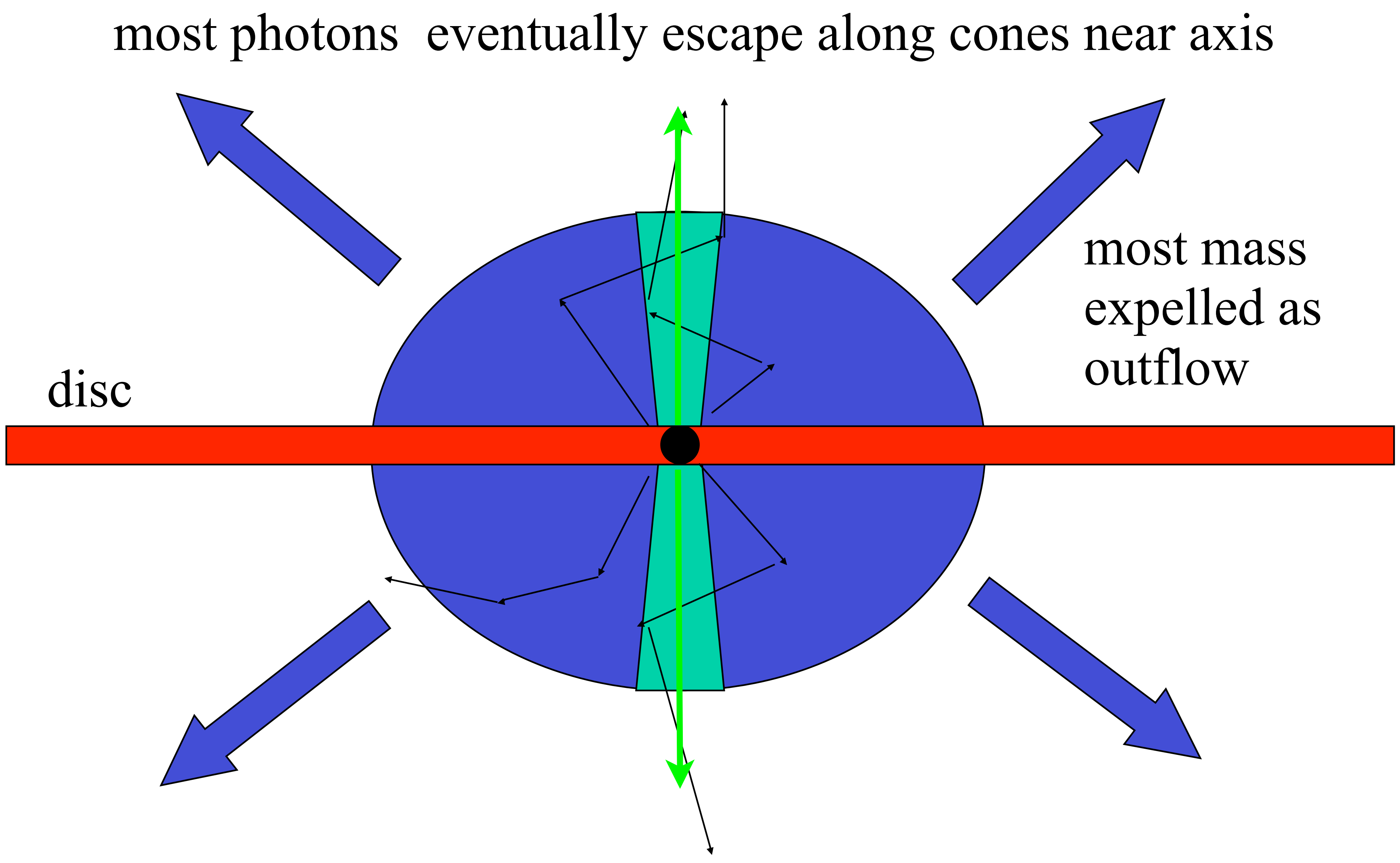
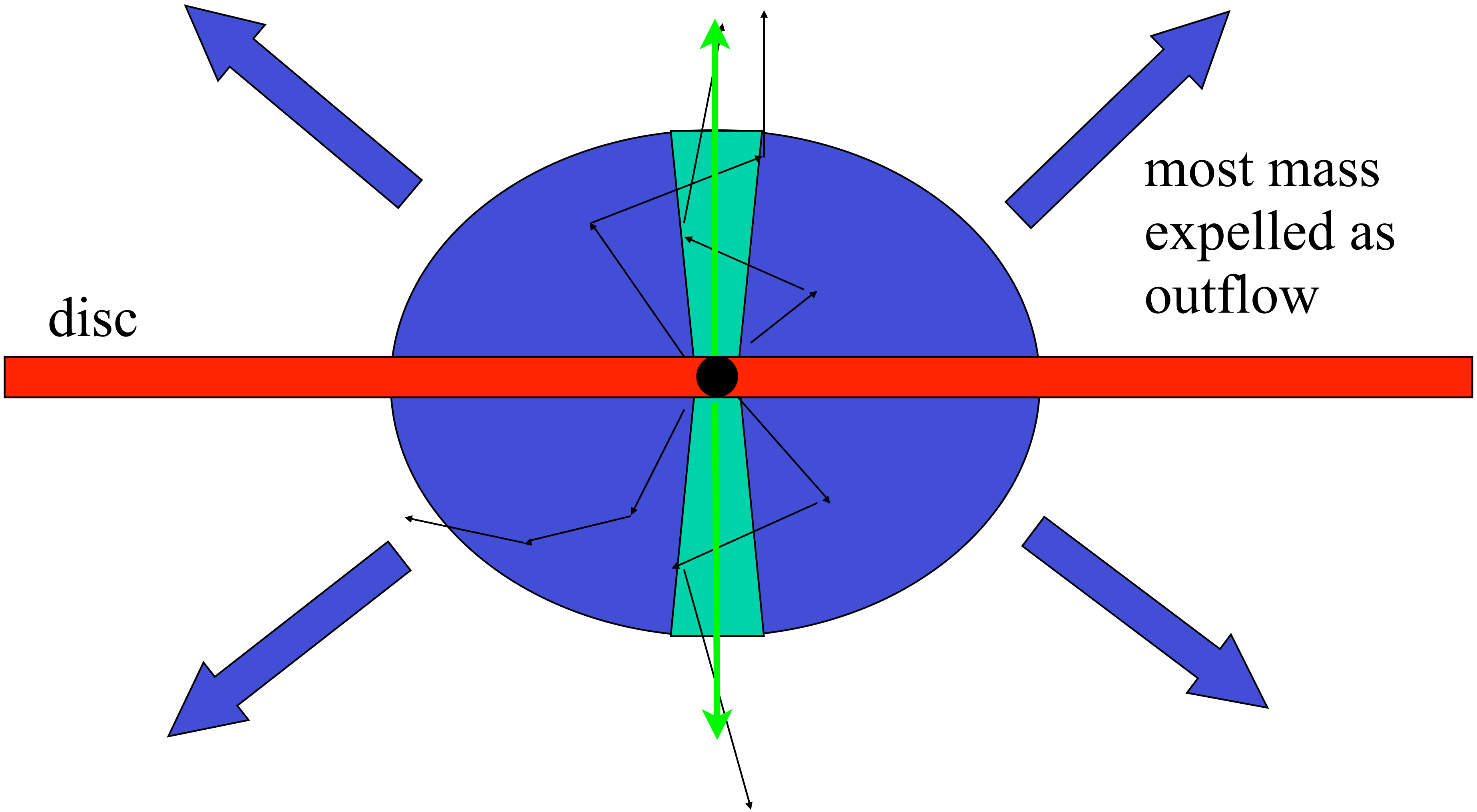


Super-Eddington Accretion



Super-Eddington Accretion

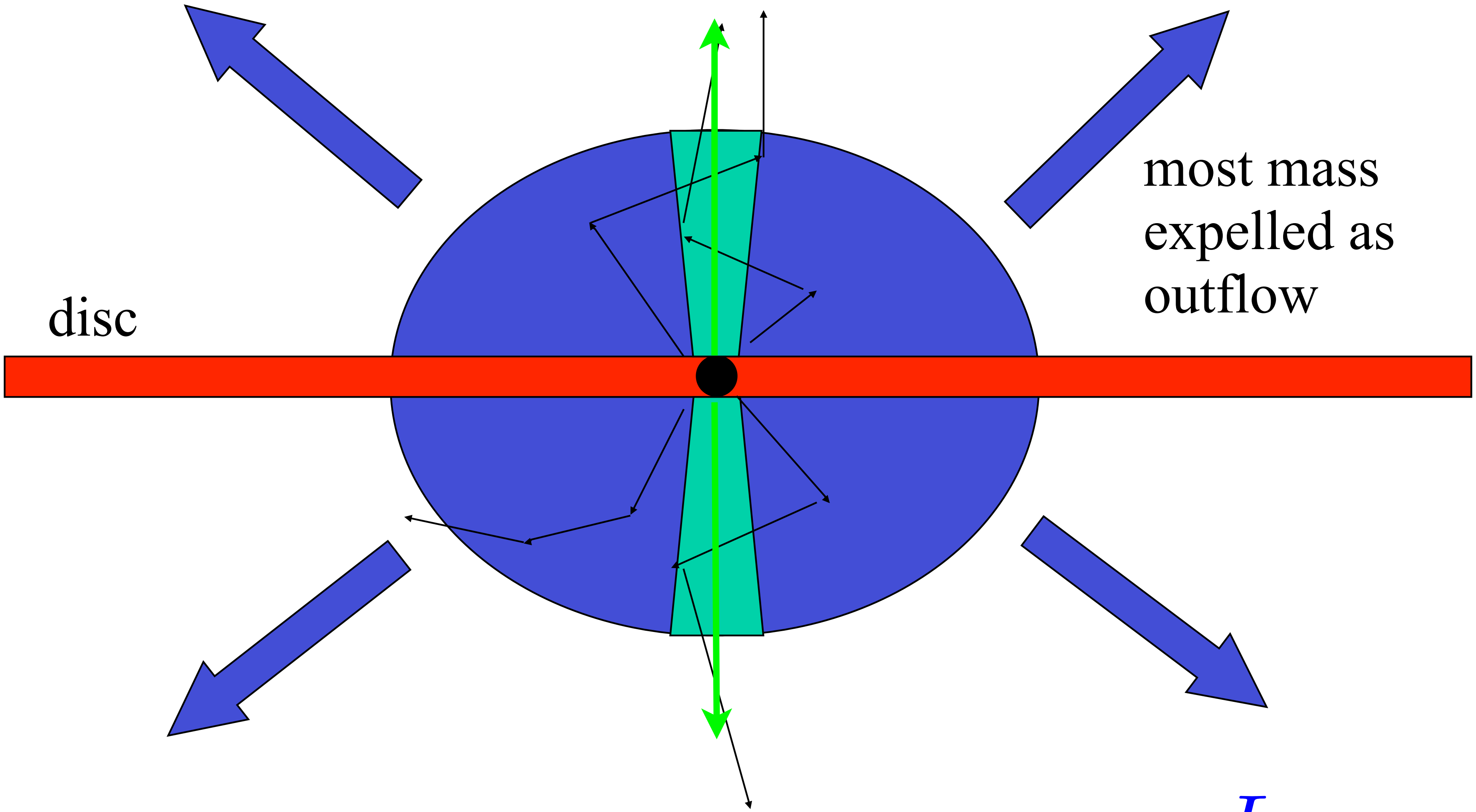
most photons eventually escape along cones near axis



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

Super-Eddington Accretion

most photons eventually escape along cones near axis

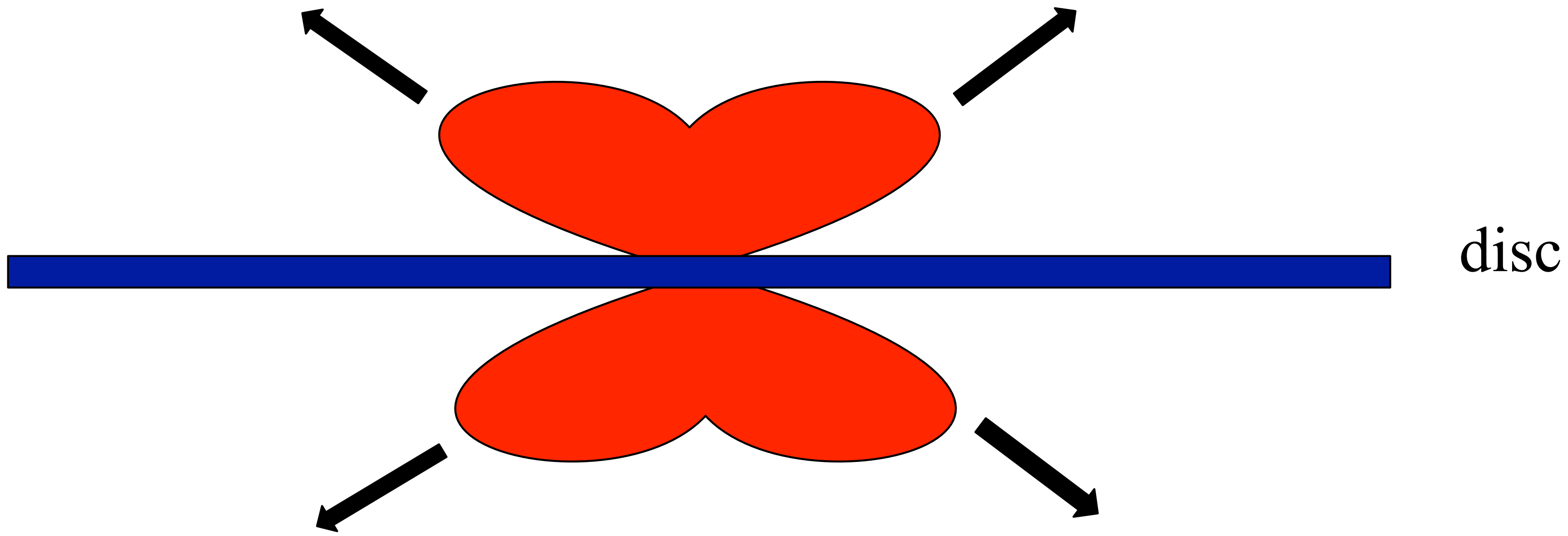


on average photons give up all momentum to outflow after ~ 1 scattering

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

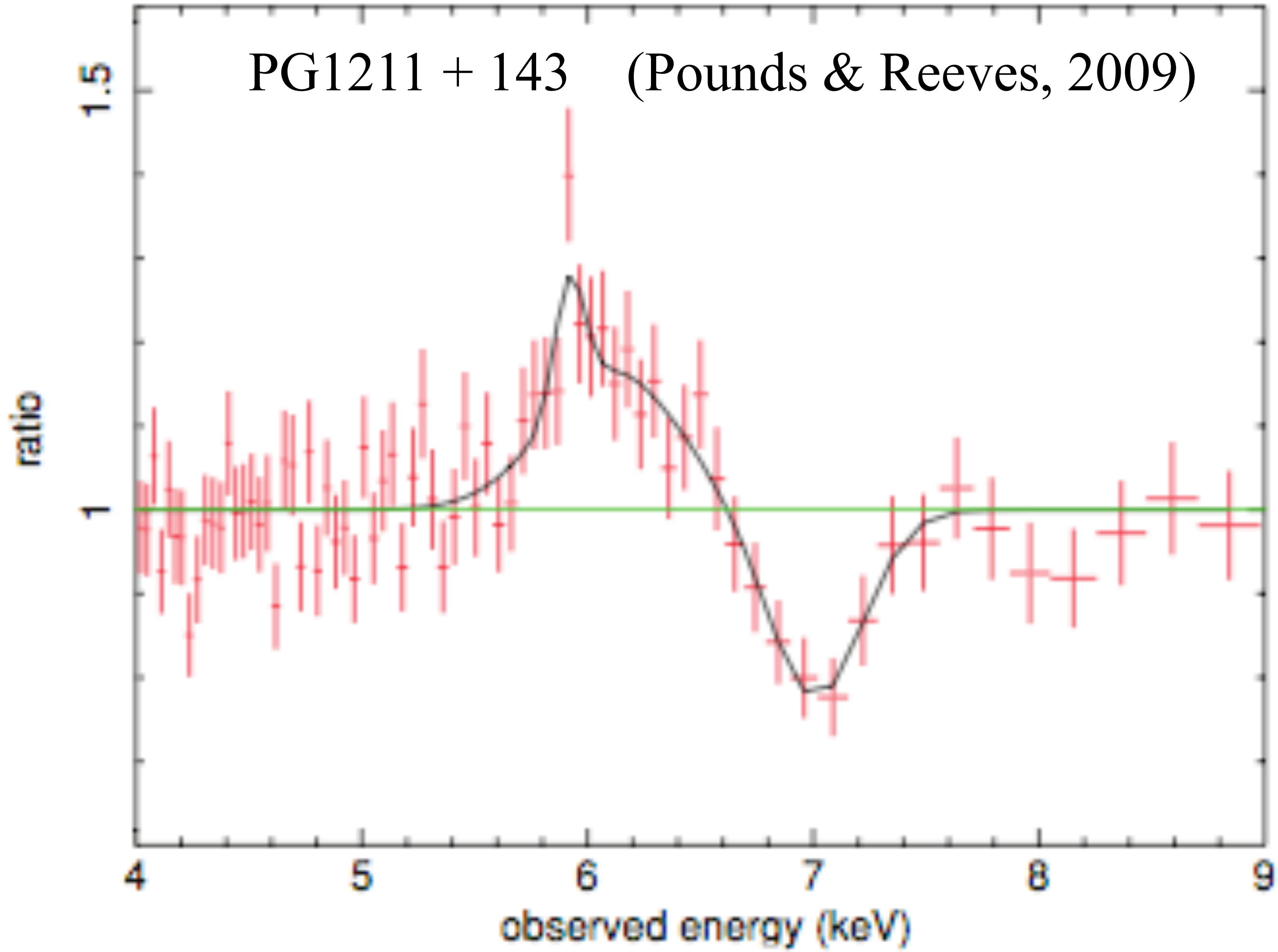
outflows have effectively spherical geometry since

(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

(a) 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 $\frac{L_{\rm Edd}}{c}$