Soft X-ray Transients: how black holes accrete

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the problem

disc instability picture seems to be successful for dwarf nova outbursts

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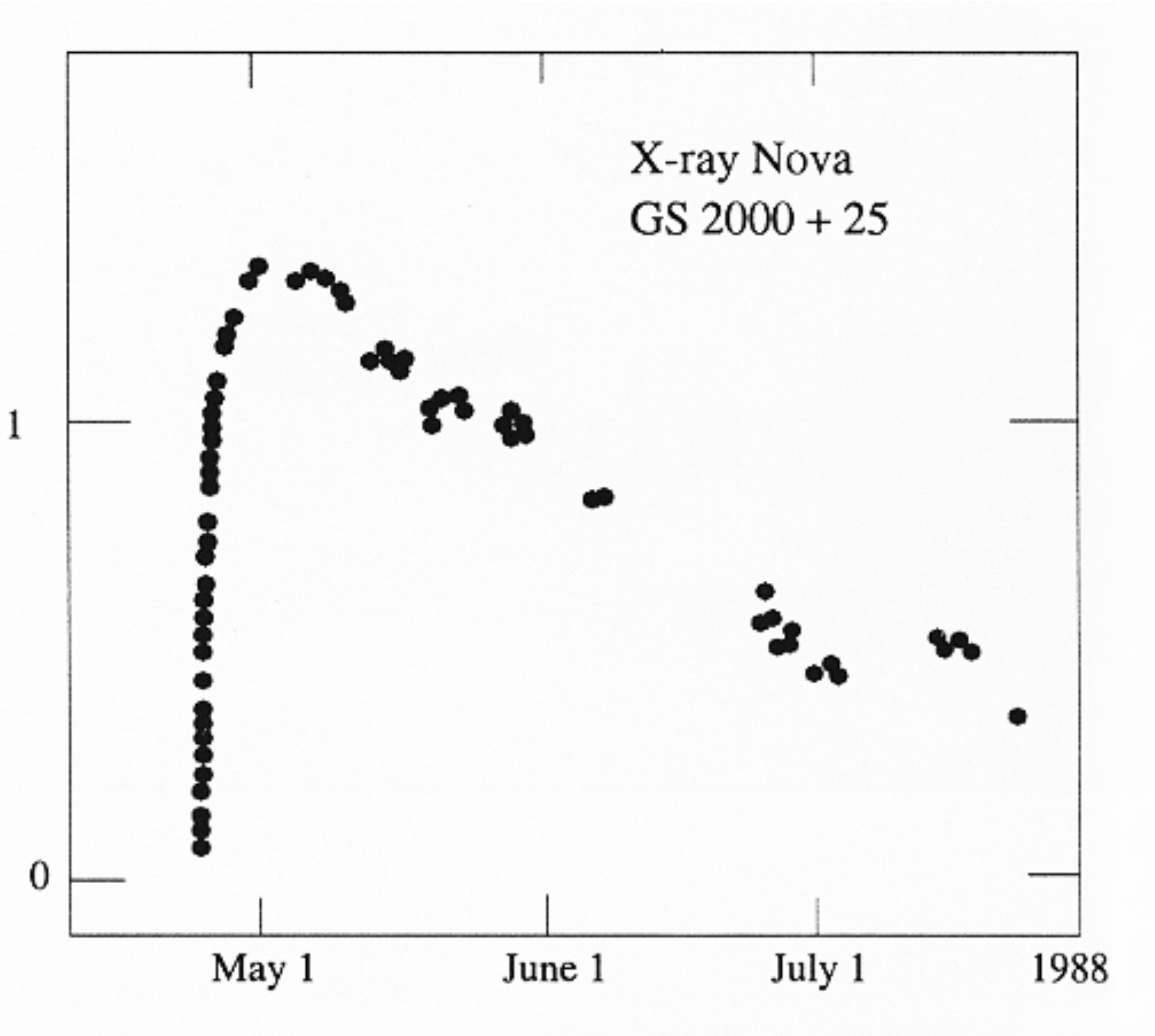
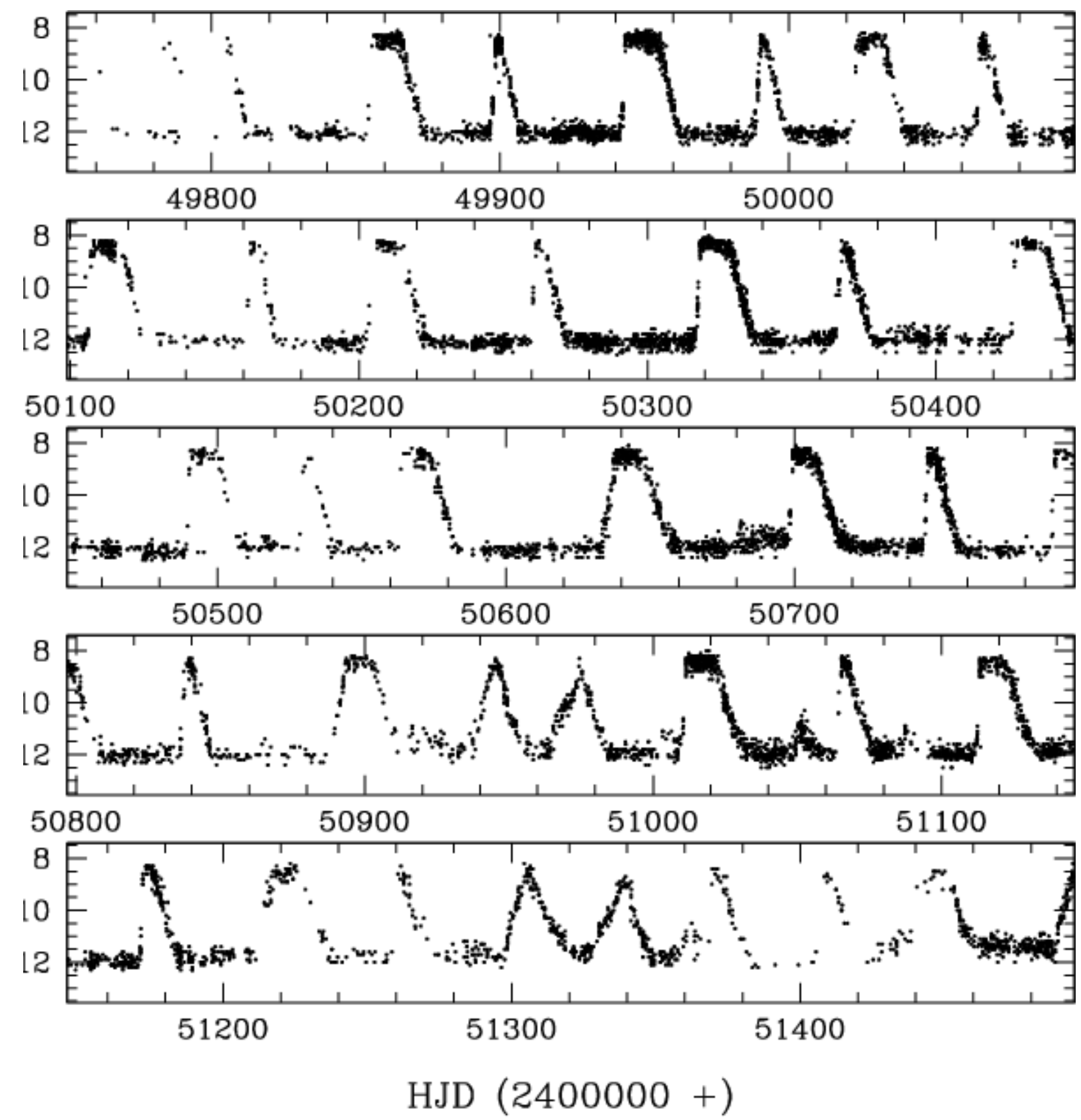
soft X-ray transients also have outbursts, but timescales are much longer





outbursts last months

outbursts last days

yet binary systems and accretion discs similar - periods of a few hours - why?

observation

van Paradijs & McClintock (1994):

visual luminosity of LMXBs scales as
$L_V \propto L_X^{1/2} P^{2/3} \propto L_X^{1/2} a$

since $L_V \propto a^2 T^2$, we have $a^2 T^2 \propto L^{1/2} a$, and so

$$\boxed{a^2 T^4 \propto L_X}$$

i.e. visual luminosity proportional to X-ray luminosity

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accretion disc is irradiated

thermal state controlled by central X-ray source, *not* locally

irradiation affects disc stability

van Paradijs, 1996

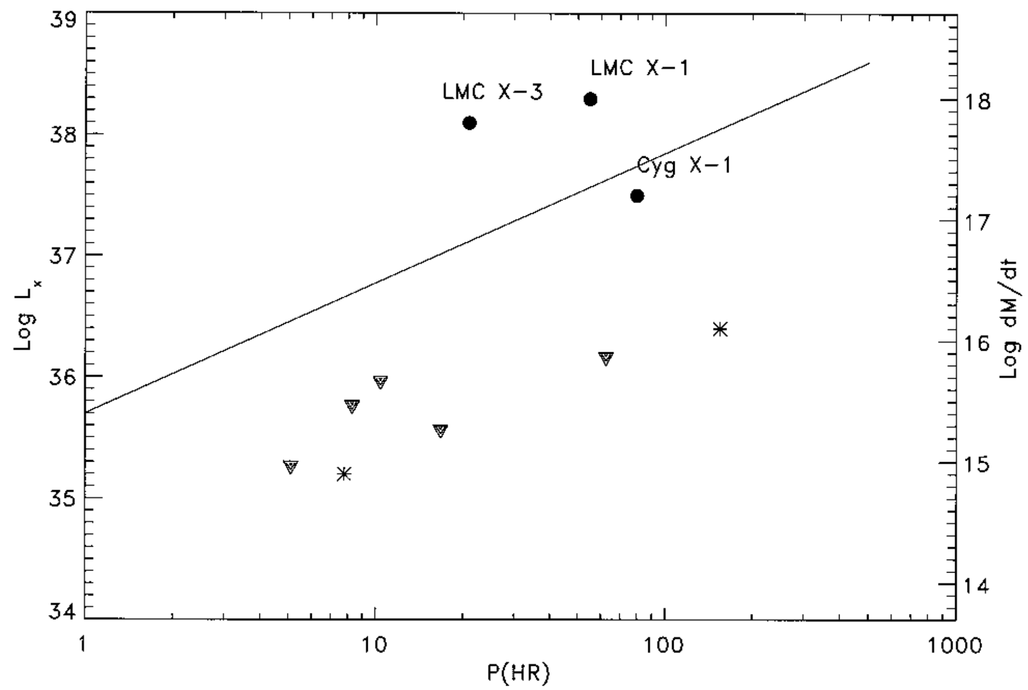

FIG. 2.—X-ray luminosity (and average mass transfer rate) as a function of orbital period for persistent and transient LMXBs with black holes. The transients with known recurrence times have been indicated with asterisks, the other transients with triangles. The straight line indicates the separation between persistent and transient sources derived here for black holes of 10 $M_\odot$ (eq. [3]). The figure also includes (*filled circles*) the three persistent high-mass X-ray binaries Cyg X-1, LMC X-1, and LMC X-3, at the fiducial positions that they would have occupied if they had been LMXBs with an equally large accretion disk, i.e., Roche lobe of the X-ray source. Since LMC X-1 and Cyg X-1 likely transfer mass by a (possibly focused) stellar wind instead of fully developed Roche lobe overflow, the radius of any accretion disk in these systems is likely to be smaller than the 80% of the Roche lobe radius assumed in the calculations (see text); as a result their fiducial positions are likely to be too far to the right in this diagram.

main effect of X-ray heating is to make the flow through the accretion disk stable down to substantially lower mass transfer rates than for DNs. It is interesting that the transient that is closest to the instability line is Aql X-1, also the one with (by far) the shortest outburst intervals.

The structure of X-ray–heated disks is different from those

4. DISCUSSION

SXTs with neutron stars are relatively rare, but almost all LMXBs with black holes are transients. The above results indicate that the reason for this is that the black hole systems have very low mass transfer rates. Possible answers to the question why this is so may be found in the different evolutionary histories of these systems and in the effect of a larger mass of the accretor on the mass transfer rate.

It is striking that none of the time-averaged mass transfer rates in the BHXTs is far from 10^{-10} $M_\odot$, i.e., close to the value expected if gravitational radiation is the sole mechanism for loss of orbital angular momentum driving the mass transfer (Savonije 1983). This would suggest that in BHXTs loss of orbital angular momentum by magnetic braking (Verbunt & Zwaan 1981) is not very effective. For given M_2 and P_{orb} the replacement of a neutron star by a black hole will not directly influence the rate at which the secondary spins down due to magnetic braking. In the expression for the tidal torques (Campbell & Papaloizou 1983) the main factors $(M_1/M_2)^2$ and $(R_2/a)^6$ cancel each other, as can be seen by using Paczyński's (1971) expression for R_2/a. Thus, also the rate at which tidal torques keep the secondary star in corotation is not much affected by this replacement. Therefore, both in systems with black holes and in those with neutron stars, the secondary remains very close to corotation, and the corresponding rates of loss of orbital angular momentum do not differ much. However, for given M_2 and P_{orb}, the orbital angular momentum of the systems with black holes is larger than that of systems with neutron stars by a factor $\sim(M_{BH}/M_{NS})^{2/3}$ (here M_{BH} and M_{NS} are the mass of the black hole and the neutron star, respectively), which equals ~4 for a 10 $M_\odot$ black hole and a 1.4 $M_\odot$ neutron star. Since $\dot{M}/M_2 \sim \dot{J}_{orb}/J_{orb}$ (Savonije 1983), one expects the rate of mass transfer for a black hole system to be

irradiation affects disc stability

TABLE 1

SXTs among LMXBs

Secondary	Primary: Neutron Star	Primary: Black Hole
Main sequence	All persistent	Persistent/some SXTs?
Evolved	Persistent/SXTs	All SXTs

29); see King et al. (1996) or McClintock (1996). Table 1 shows that this must mean that sufficiently evolved companions are more common in black hole than in neutron star systems. There is an obvious explanation for this: in the precontact phase (see § 3), the orbital evolution time $t_{\rm AML}$ of black hole systems is significantly longer (by a factor $m_1^{2/3} \sim 4$) than for neutron star systems, for the same reason that the postcontact mass transfer rate is lower for black holes, i.e., that $(\dot{J}/J)_{\rm MB}$ is smaller (see the first term of eq. [9]). The secondaries in black hole systems have on average 4 times as long to evolve along or off the main sequence before there is any possibility of their being driven to short periods by angular momentum losses. Yet equation (10) requires that the secondaries in neutron star systems should be significantly *more* evolved ($\hat{m}_2 \lesssim 0.25$) than in black hole systems ($\hat{m}_2 \lesssim 0.75$) for SXT behavior to occur. Thus, for similar initial separations, a considerably smaller fraction of neutron star than black hole binaries will become SXTs. Of course, a full population synthesis will be required to demonstrate that this conclusion is quantitatively as well as qualitatively valid. A further consequence of the low value of $\hat{m}_2$ in neutron star SXTs is that the mass ratio must be very small in both types of transient: for $P \lesssim 2$ days, we have $M_2/M_1 \simeq 0.33 P_3 \hat{m}_2/m_1$, giving $M_2/M_1 \lesssim 0.059 P_3$ and $M_2/M_2 \lesssim 0.025\ P_3$ for neutron star transients with $M_1 = 1.4\ M_\odot$ and black hole systems with $M_1 = 10\ M_\odot$, respectively. Such extreme mass ratios are a ubiquitous feature of observed SXTs, which lends support to the picture presented here.

We conclude that soft X-ray transient events probably result from accretion disk instabilities. In line with this, King & Ritter (1996) find outburst and recurrence times of SXTs in good accord with those expected from simple extrapolations from dwarf nova outbursts, provided that due account is taken of the larger disk size in SXTs. The arguments presented here show that the high incidence of black hole identifications in SXTs given by dynamical mass estimates directly reflects the underlying population rather than observational selection.

We thank Jan van Paradijs for providing us with a copy of his paper in advance of publication and for very helpful comments on an earlier version of this Letter, which led to significant improvements. This work was supported by the UK Particle Physics and Astronomy Research Council through a Senior Fellowship (A. R. K.) and a Rolling Grant to the Leicester Astronomy Group.

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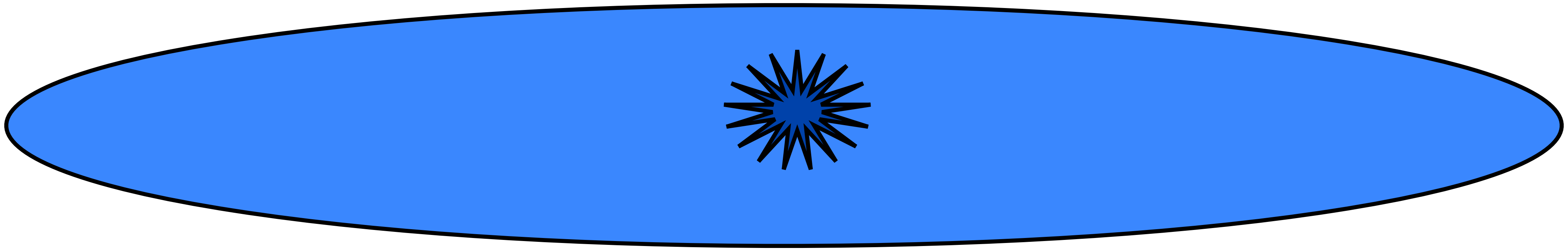
Cannizzo, J. K., Wheeler, J. C., & Ghosh, P. 1982, in Pulsations in Classical and

McClintock, J. E. 1996, talk at Aspen Workshop on Black Hole Soft X-Ray

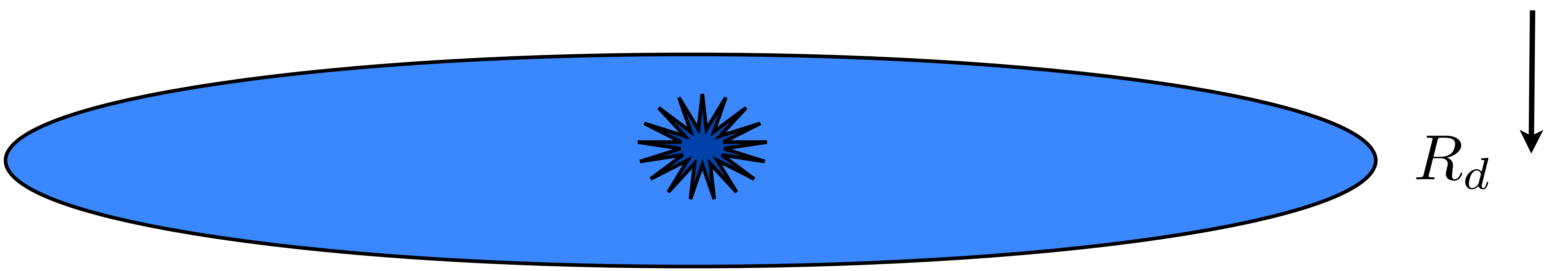
irradiated discs are different



non-local behaviour means the disc can be trapped in the hot state by a high central accretion rate: disc must change globally to escape this state

simple theory of an irradiated outburst

(King & Ritter 1998)



disc is kept in hot state by central accretion luminosity within a radius R_h, with $R_h^2 \propto \dot{M}_c$ = central accretion rate

for a small disc $R_h >$ disc radius R_d: whole disc is hot, with surface density

$$\Sigma \simeq \frac{\dot{M}_c}{3\pi\nu}$$

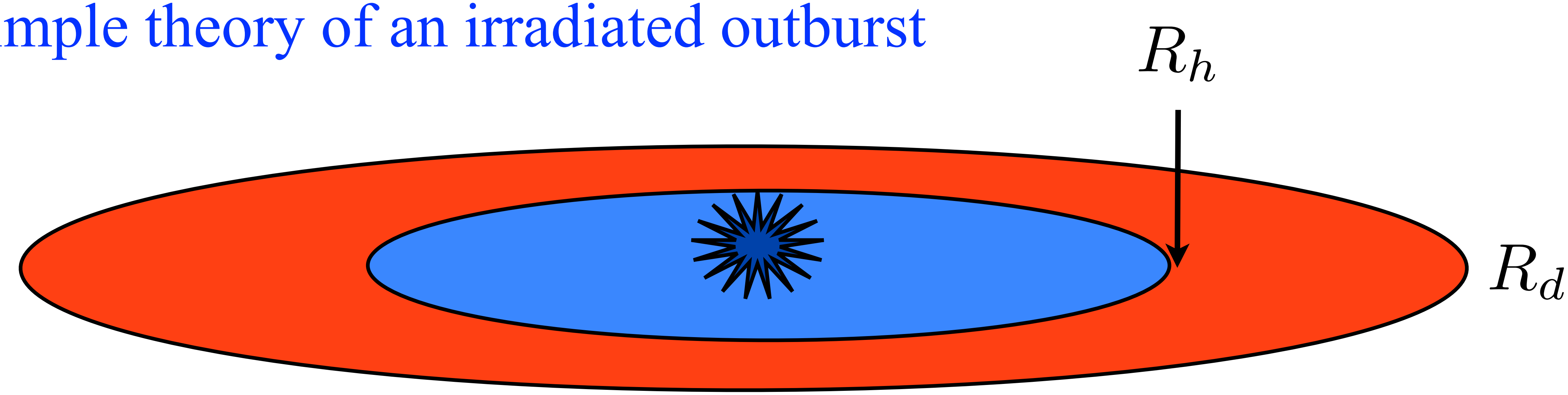
total hot-state mass is

$$M_h \simeq 2\pi \int_0^{R_h} \Sigma R \mathrm{d}R \simeq \dot{M}_c \frac{R_h^2}{3\nu} = \dot{M}_c \tau$$

this can *only* decrease through central accretion, so $\dot{M}_c = -\dot{M}_h, \; M_h \propto e^{-\tau}$ and

$$\dot{M}_c \propto e^{-\tau}$$

simple theory of an irradiated outburst



eventually (or even from the start for a large disc), $R_h < R_d$, so hot mass decreases because R_h shrinks as well as central accretion, i.e.

$$\dot{M}_h = -\dot{M}_c + 2\pi R_h \dot{R}_h \Sigma = -\dot{M}_c + \frac{B}{3\nu}\dot{M}_c \ddot{M}_c$$

$$\text{but} \quad M_h = \dot{M}_c \frac{R_h^2}{3\nu} = \frac{B}{3\nu}\dot{M}_c^2, \quad \text{so}$$

$$\dot{M}_h \equiv \frac{2B}{3\nu}\dot{M}_c \ddot{M}_c = -\dot{M}_c + \frac{B}{3\nu}\dot{M}_c \ddot{M}_c$$

$$\text{and} \quad \frac{B}{3\nu}\ddot{M}_c = -1$$

$$\text{which implies} \quad \frac{\dot{M}_c}{\dot{M}_{c0}} = 1 - \frac{3\nu}{B\dot{M}_{c0}}t, \quad \text{or}$$

$$\frac{\dot{M}_c}{\dot{M}_{c0}} = 1 - \frac{t}{\tau}$$

simple theory of an irradiated outburst

optical should decay more slowly, as spectrum shifts to longer wavelengths

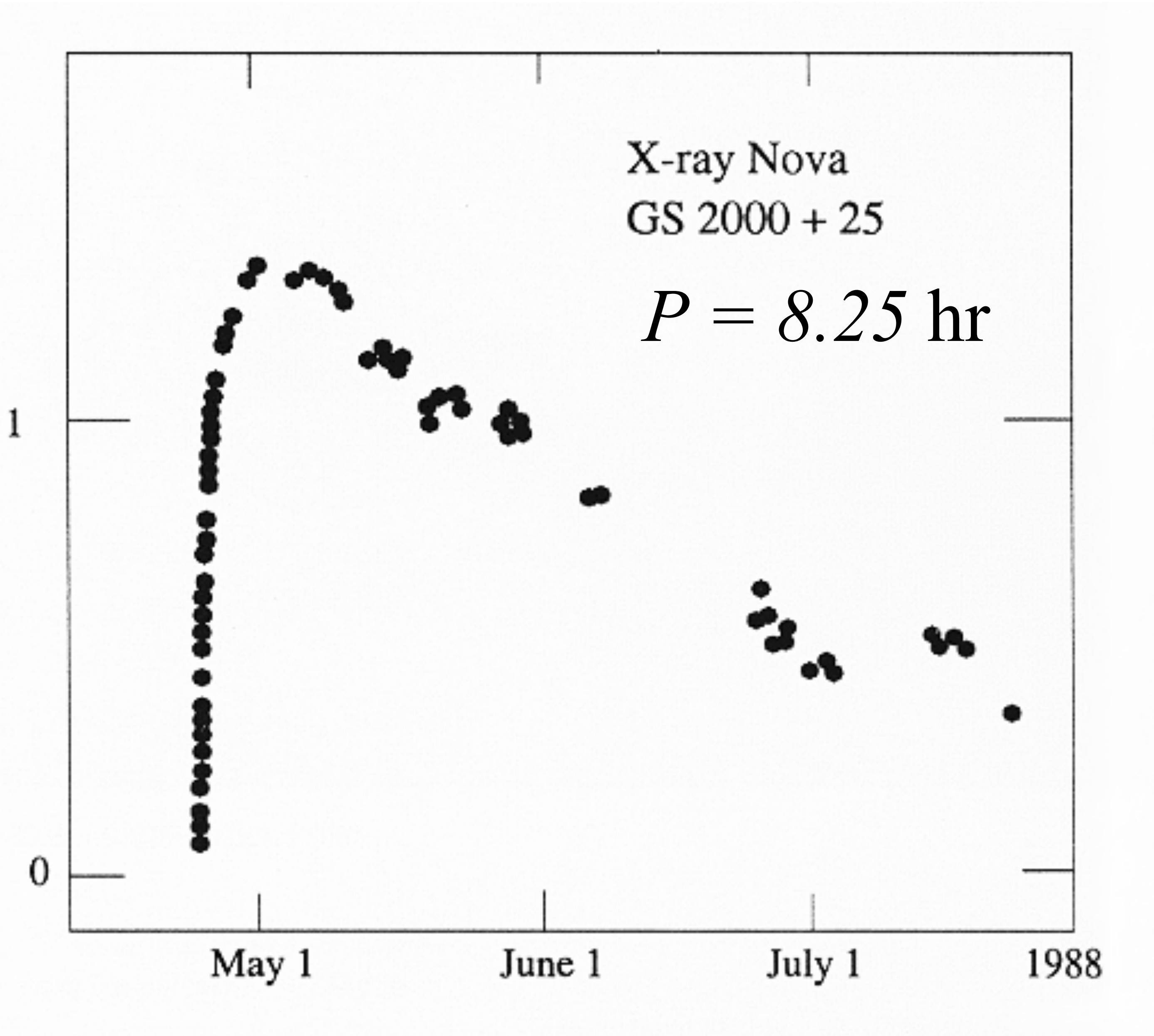
$$\text{thus} \quad F_X \propto T^4 \propto e^{-t/\tau}, \quad \text{so} \quad T \propto e^{-t/4\tau}$$

$$\text{optical} \quad \text{flux} \quad F_{\rm opt} \propto T^2 \propto e^{-t/2\tau}$$

$$\text{IR} \quad \text{flux} \quad F_{\rm IR} \propto T \propto e^{-t/4\tau}$$

so optical, IR decay on timescale 2 -- 4 times X-rays: fundamental timescale is

$$\tau \sim 40 R_{11}^{5/4} \ \text{days}$$

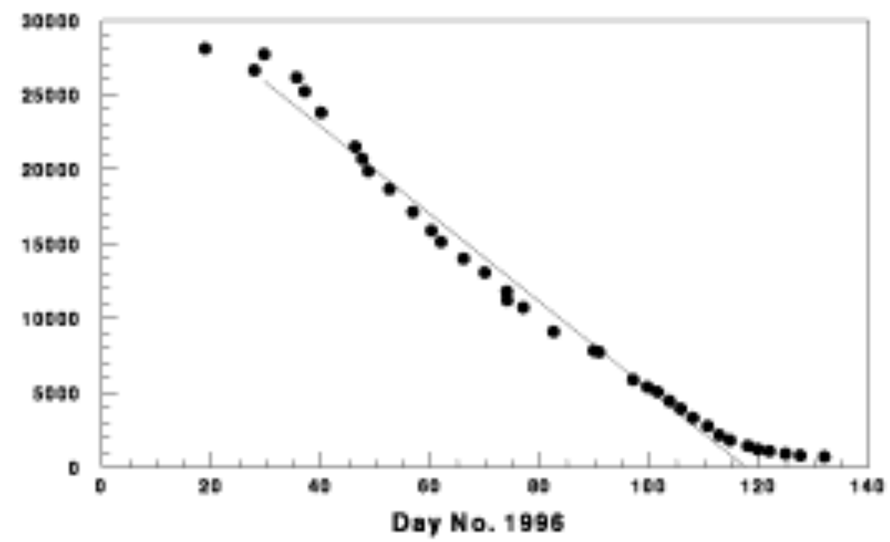


small discs (short-period systems) have exponential decays which eventually become linear

long-period systems should have linear decays if outer disc has reached steady state;

however hysteresis => outbursts have irregular light curves

GRO J1744-28 $P = 12$ d GILES ET



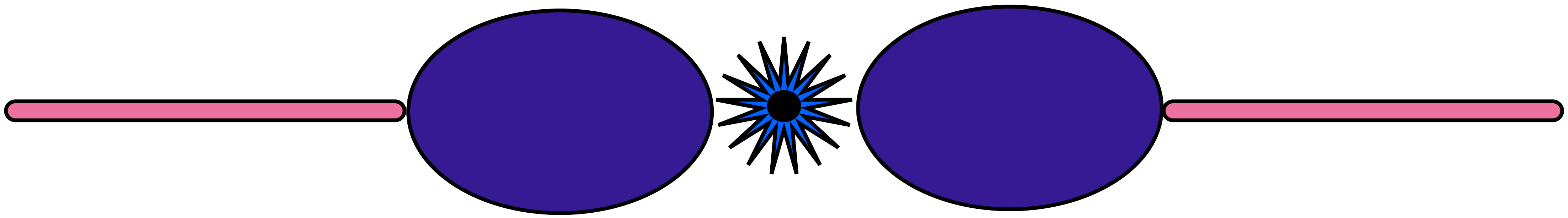
–The approximately linear decline of the nonbursting flux from 4–28 between 1996 January 18 and May 10. A few detectors were off observations, but all points have been normalized to counts per five detectors. The horizontal axis is the day number in 1996, with January 1. The straight-line fit is determined for data between days 7.

natter of judgment. We used the highest preburst level y the maximum mean level seen. Although for a time suggested a shallow exponential decline, the data January 29 and April 26 (days 029–117) can be nately fitted with the straight line flux(mcrab) = – $23.0D$, where D is the day number in 1996. Figure en corrected for dead time, pointing, and the number detectors in operation. The dead-time corrections are 6% for the persistent flux even in January. A cosmic rumental background estimate of 175 s^{-1} has also otracted.

& Strohmayer (1996) and Giles (1996) reported that grated burst flux also decreased with time in an nately linear fashion, but a full analysis requires ial dead-time corrections. The last burst detected by in the observation sequence presented here was on , when the persistent flux was ~110 mcrab. The d peak flux for this burst was 14.6×10^{-8} ergs cm^{-2} 0 keV).

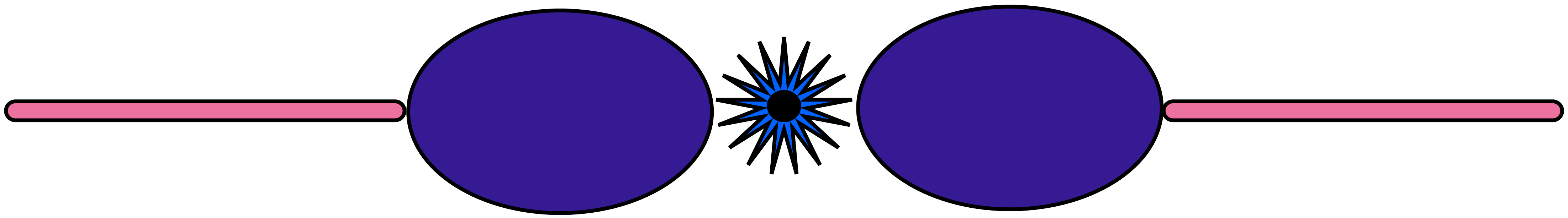
6. DISCUSSION AND CONCLUSIONS

theoretical problems



theoretical problems

1. usual viscosity problem: limited predictive power



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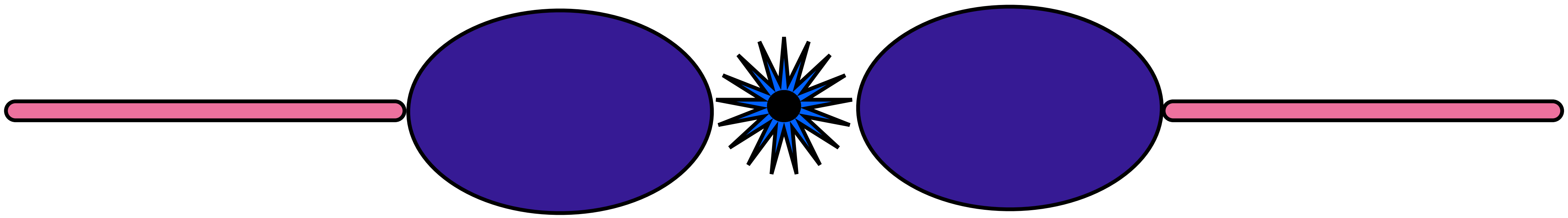
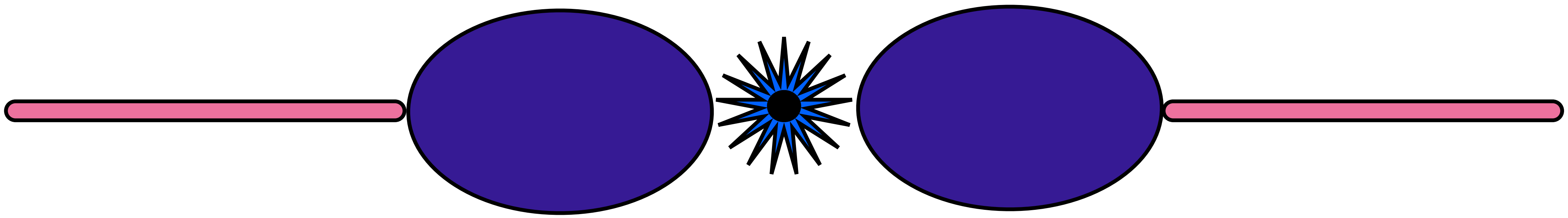


2. calculations show inner disc becomes *convex*: shields most of disc from irradiation

(Cannizzo, 1994; Dubus et al., 1999)

theoretical problems?



but observation says it *is* irradiated: the model must be too simple

what’s wrong?

evidently point-source approximation is incorrect - why?

1. perhaps disc is warped by self-irradiation - Pringle 1996, 1997

1997MNRAS.292..136P

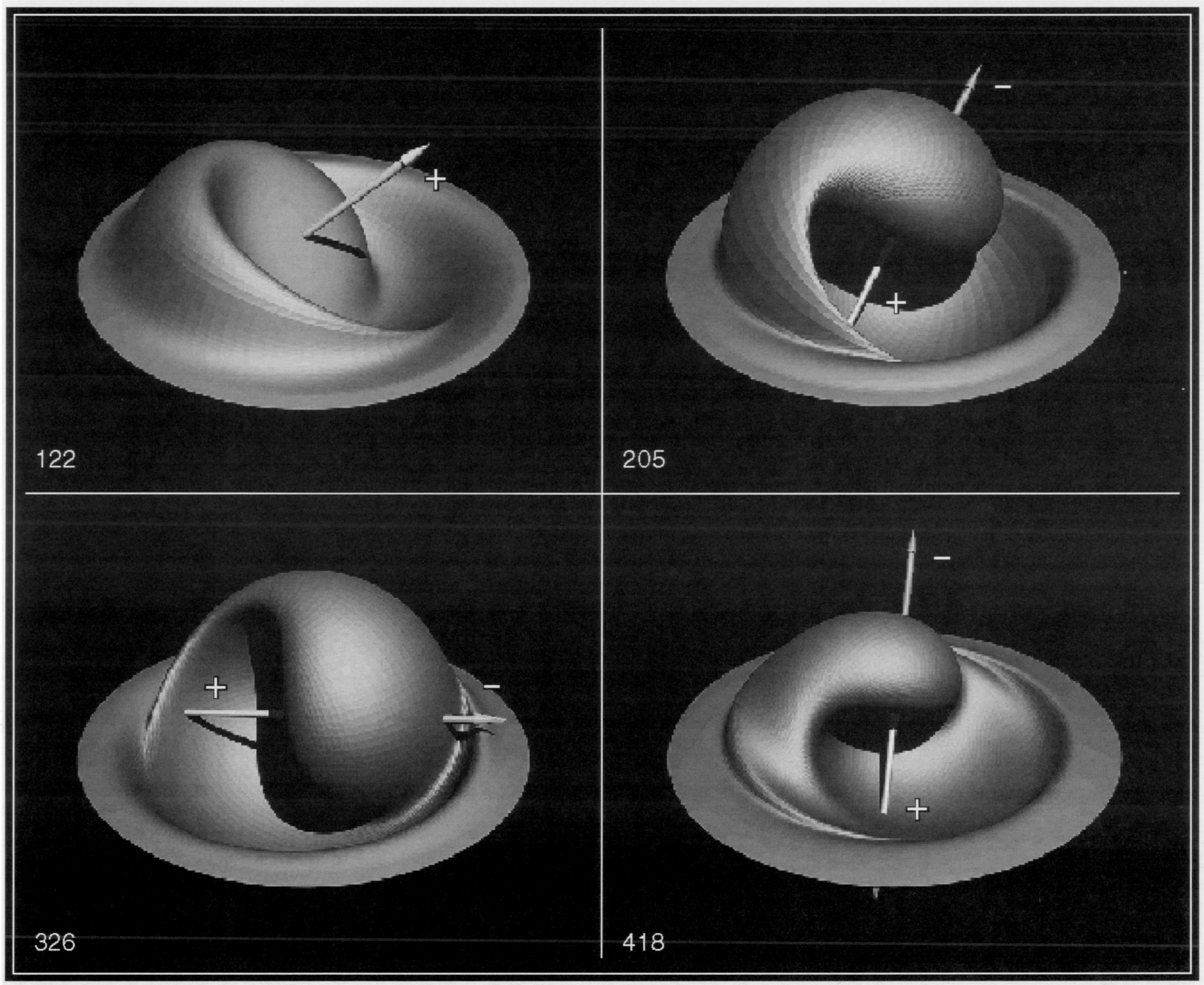


Figure 6. The shape of the disc for case B1 is shown at various dimensionless times τ. For illustrative purposes the disc is illuminated externally and the radii of the annuli have been plotted logarithmically. Thus the innermost radius $r=1$ is at the origin ($\log r=0$). The outermost radius corresponds to $\log r=4$. The warping instability is allowed to occur only at radii less than $r=10^3$, i.e., at $\log r=3$. The disc is shown at times $\tau=122$, 205, 326 and 418.

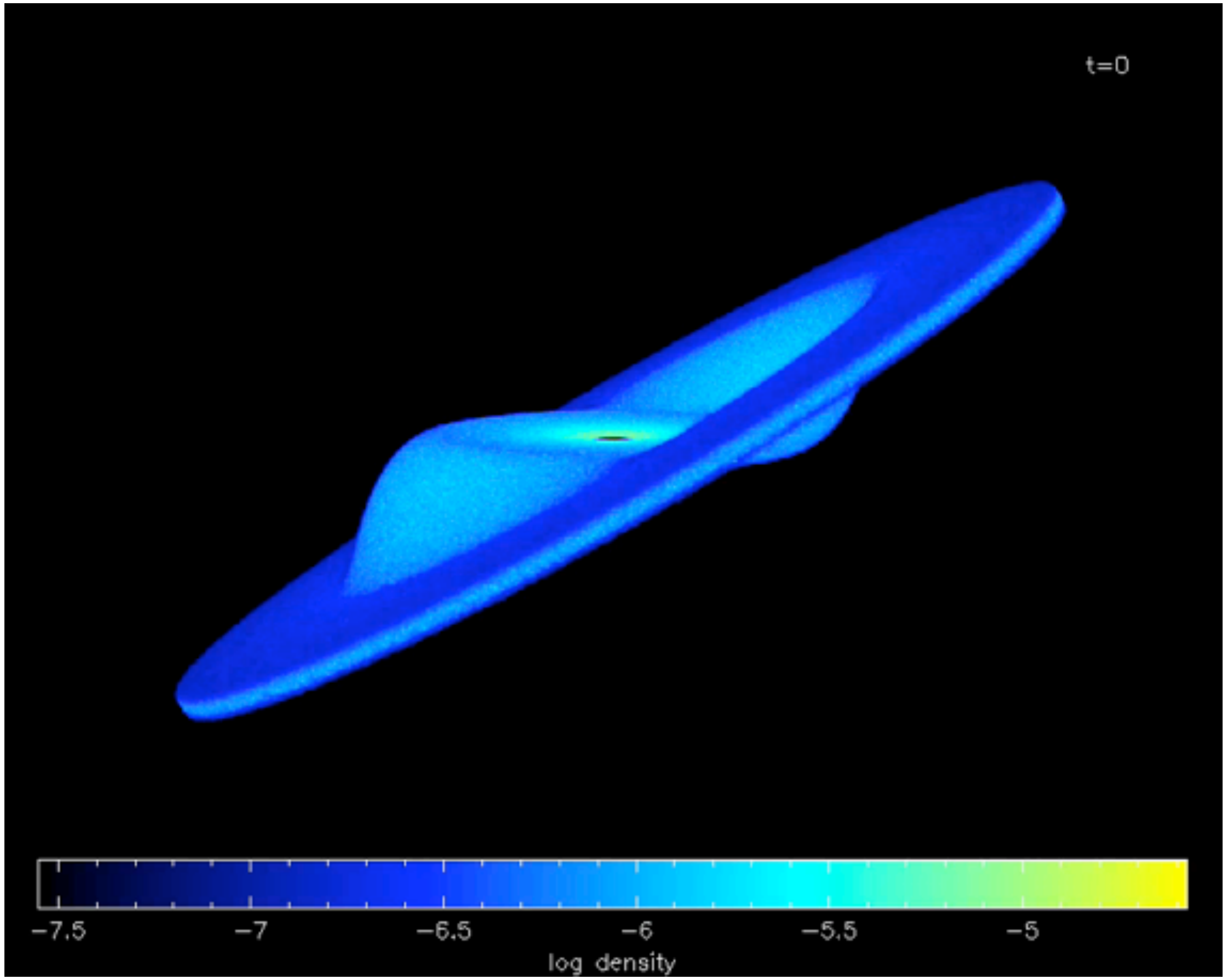
no fully self-consistent calculation relating central accretion rate to conditions in disc so far

what's wrong?

evidently point-source approximation is incorrect - why?

2. disc tearing - Nixon, King, Price & Frank, ApJ Lett 2012

suppose BH or neutron-star spin is not aligned with binary: then disc must warp under Lense-Thirring



Lodato & Price, 2010

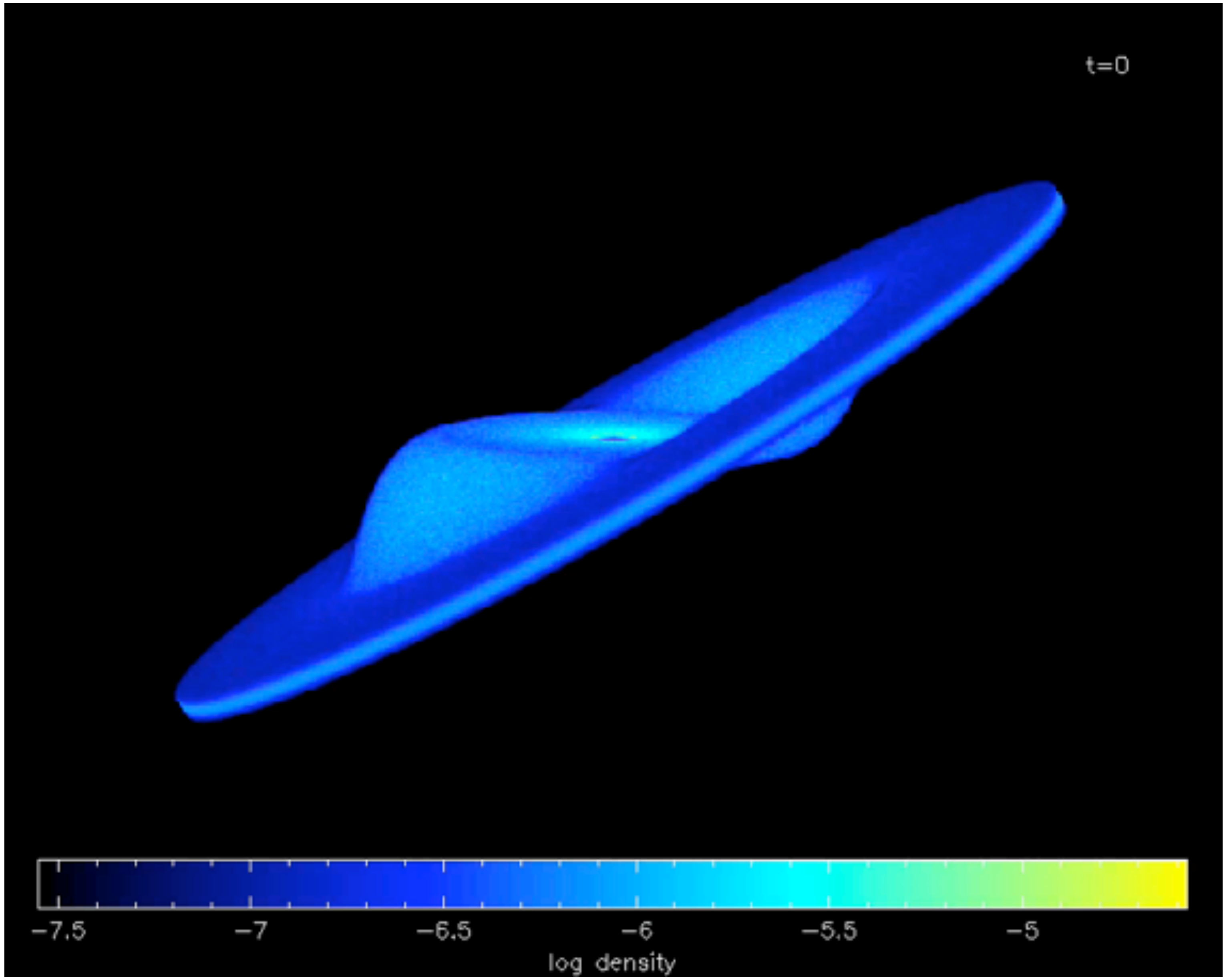
if inclination is moderate disc develops regular warped shape

what's wrong?

evidently point-source approximation is incorrect - why?

2. disc tearing - Nixon, King, Price & Frank, ApJ Lett 2012

suppose BH or neutron-star spin not aligned with binary: then disc warps under Lense-Thirring effect



Lodato & Price, 2010

but if inclination is large, or viscosity weaker, disc breaks!

disc tearing

disc warps usually described by `horizontal' and `vertical' viscosity coefficients α_1, α_2

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but in a warp, vertical viscosity weakens (Ogilvie, 1999)

disc tearing

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for strong warp (or weak viscosity), disc `breaks' - disc plane effectively discontinuous

disc tearing

Nixon et al. show that the disc breaks at radius

$$R_{\rm break} \lesssim \left(\frac{4}{3}|\sin\theta|\frac{a}{\alpha}\frac{R}{H}\right)^{2/3} R_g$$

or a typical radius

$$R_{\rm break} \lesssim 350 R_g |\sin\theta|^{2/3}\left(\frac{a}{0.5}\right)^{2/3}\left(\frac{\alpha}{0.1}\right)^{-2/3}\left(\frac{H/R}{10^{-3}}\right)^{-2/3}$$

numerical simulations agree very well with this estimate

disc tearing

Lense-Thirring precession has a strong radial dependence $(\omega \propto r^{-3})$

inner and outer discs precess independently

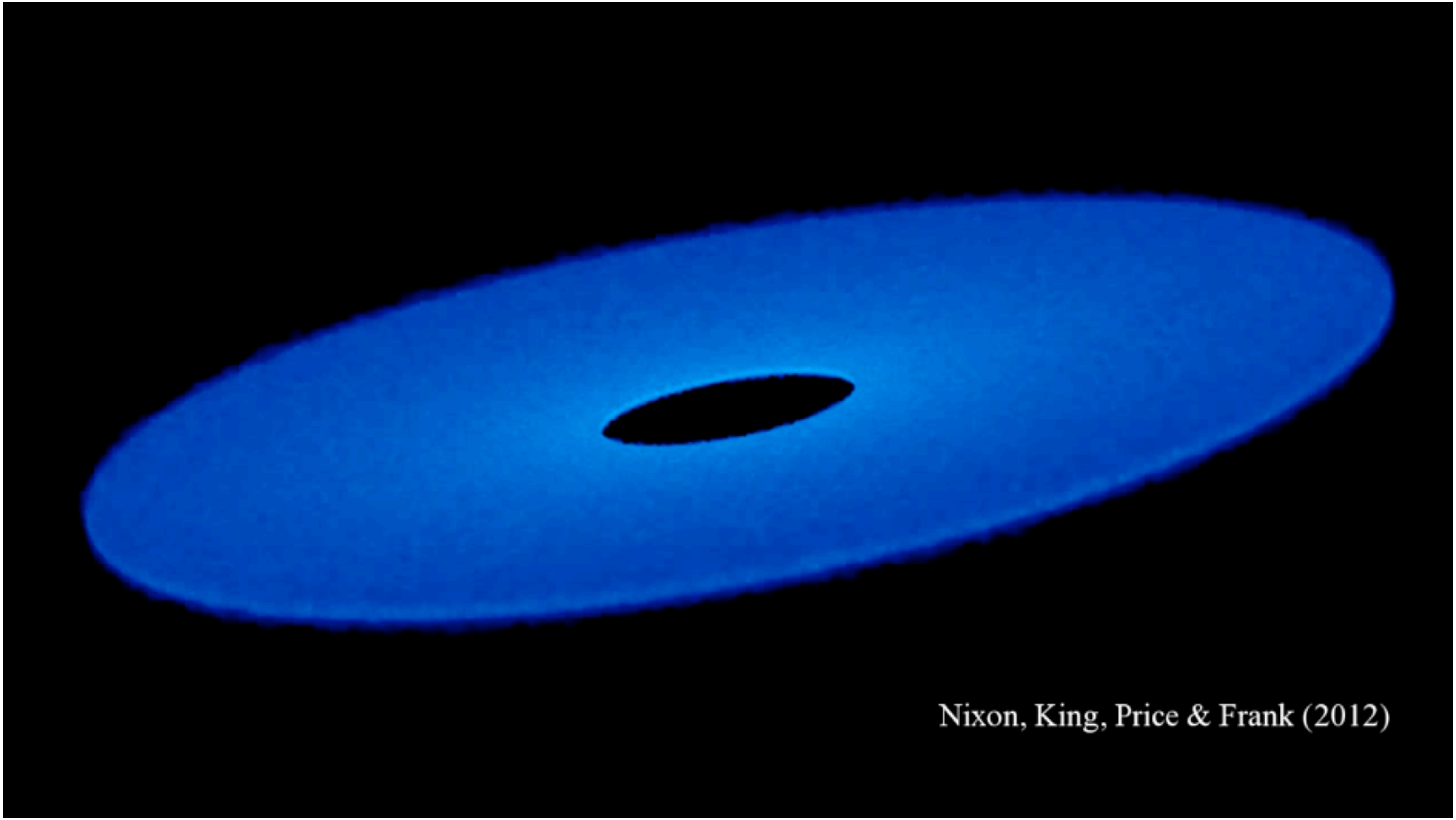
but if inclination $> 45^\circ$ these discs eventually have *partially opposed angular momenta*

viscous spreading => angular momentum cancellation => infall

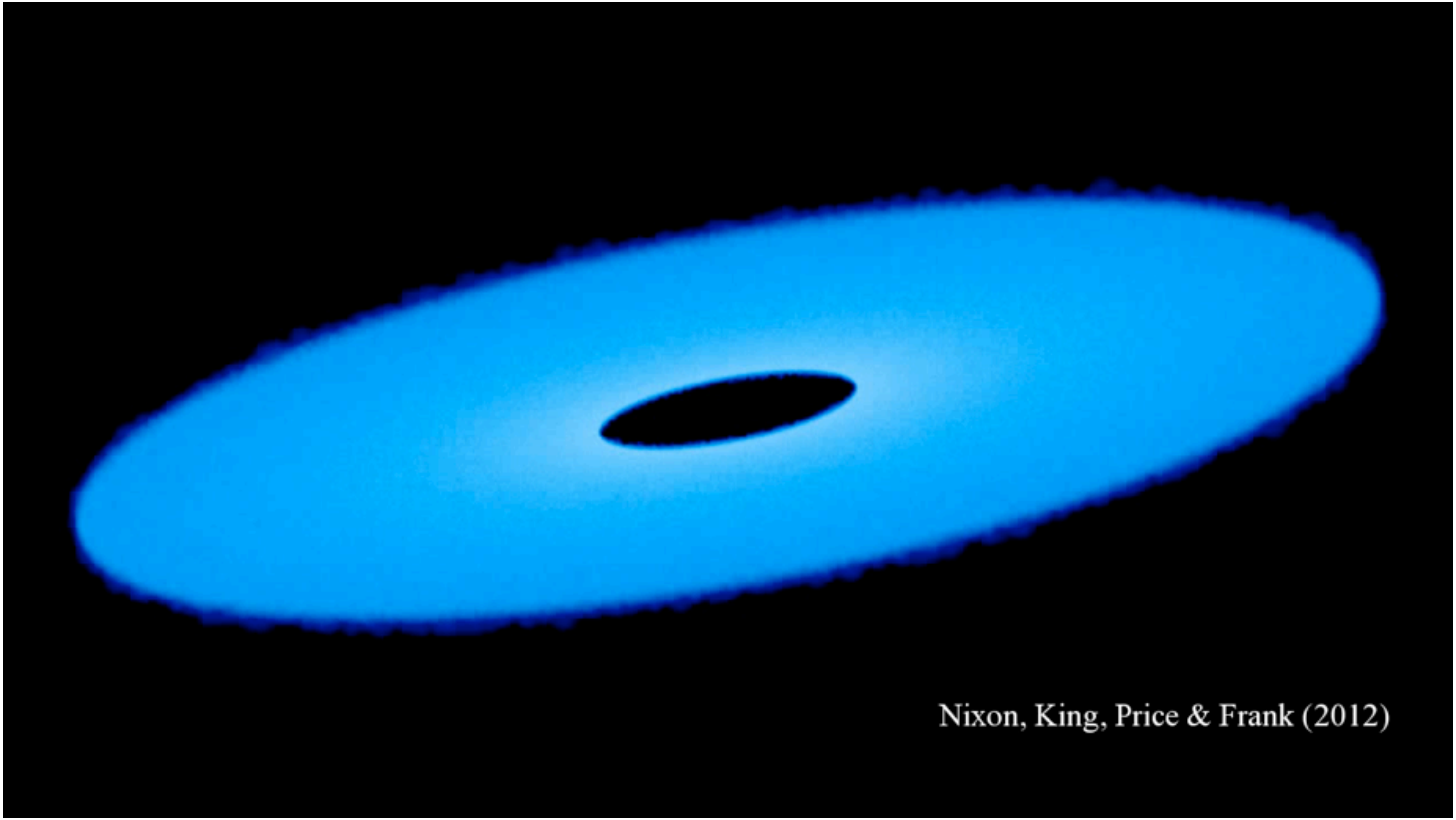
process repeats at smaller radii

inner accretion disc is torn up - no longer a point source

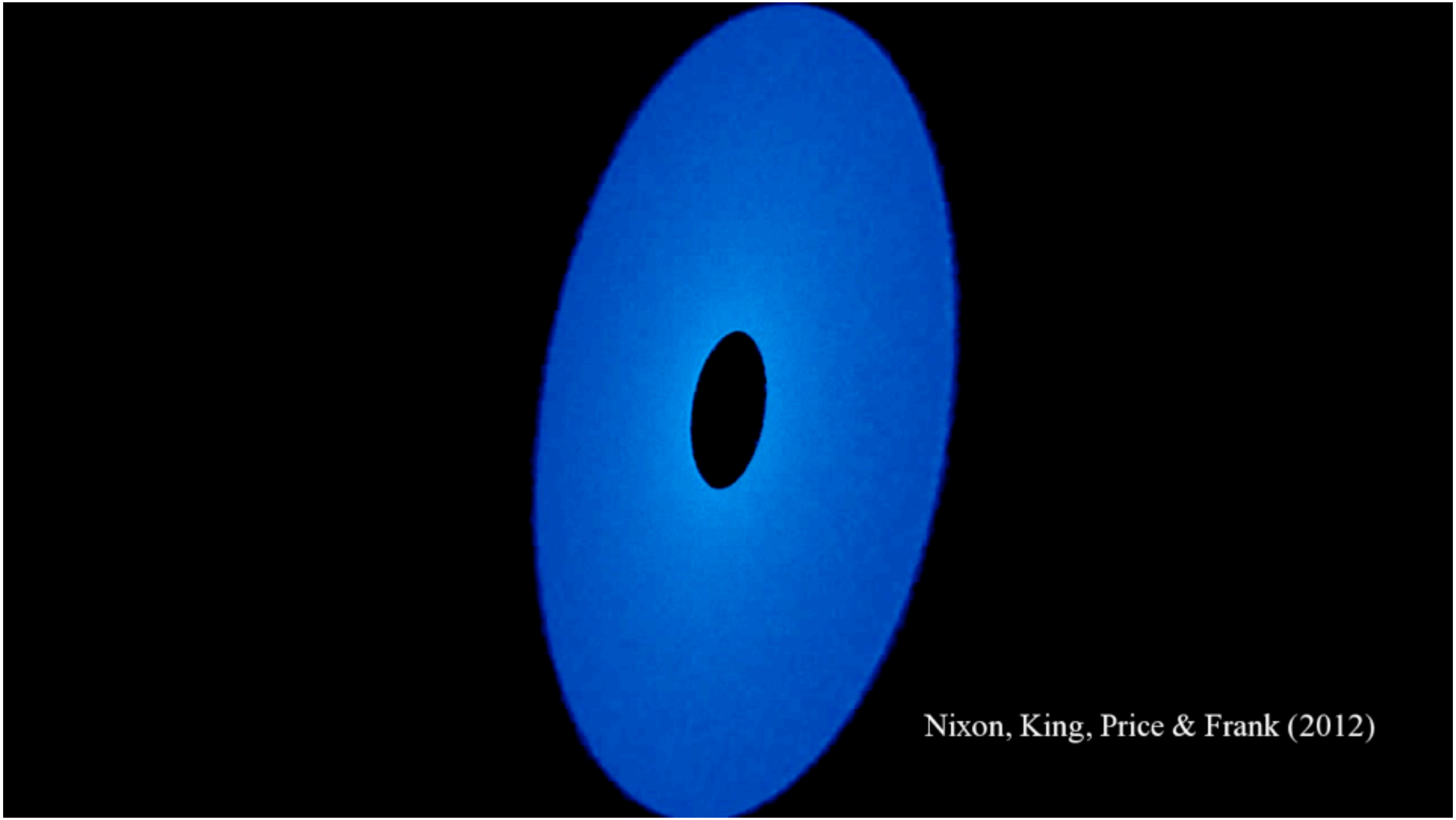
10 degrees 3D movie



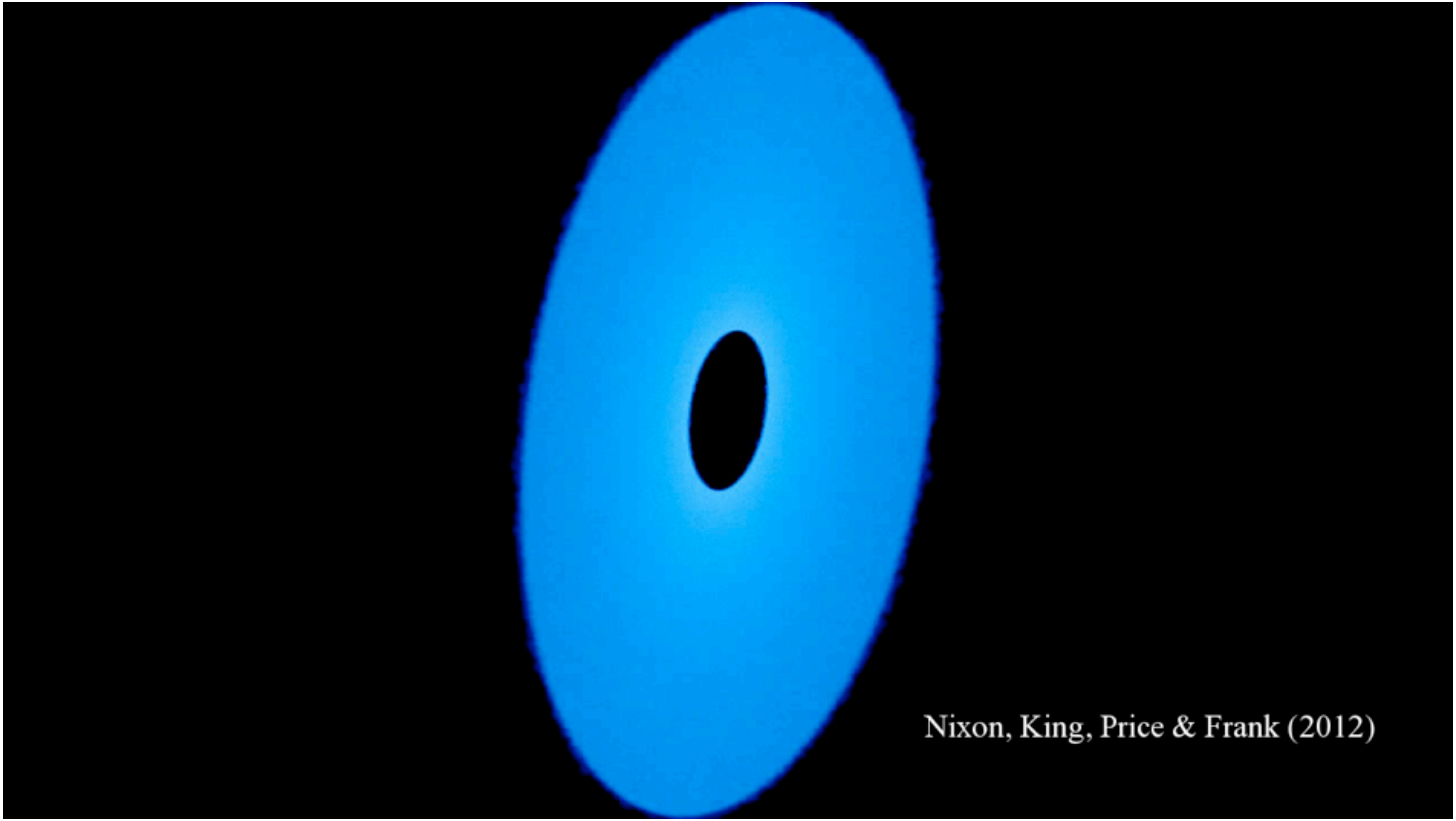
10 degree column density



60 degree 3D



60 degrees column density



disc tearing

to avoid tearing, a BH or neutron star disc must satisfy

$$|\sin\theta| \lesssim \frac{3\alpha}{4a}\frac{H}{R}$$

hard to avoid: e.g. moderately thick disc with $H/R = 0.1, \quad \alpha = 0.1$ and $a = 0.1$ must be inclined by less than 4° to avoid tearing

disc tearing

tearing can produce several effects (e.g. rapid accretion in AGN)

in binaries, it may produce QPOs, and make the X-ray source extended