Some Uncomfortable Questions about Single and Double Black Holes

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How Reliable Are Single Black Hole Masses?

- We understand the dynamics of stellar kinematics, masers; is that true of BLR motions in AGN?

  Both g and $g_{rad} \sim r^{-2}$

  $\langle\kappa_{ion}\rangle \gg \kappa_T$ so even if $L \ll L_E$ can have $g_{rad} > g$

  Magnetized winds? Other forces?

- Cross-correlation lags are not maps, and statistical correlations of L_B with lags are even worse
- What about flattening/inclination angle?

  $M \sim (\sin i)^{-2}$

How Well Can We Measure Spin?

- Thermal continuum fitting

  Separating thermal spectrum from Comptonized?

  L, T give R, but need M, and what is $R(R_{ISCO})$?

  T_{color} vs. T_{eff} (depends on details of atmosphere)

- Kα profile fitting

  Why should emissivity be a cut-off power-law? Why should the cut-off fall exactly at the ISCO?

Does Spin Really Control Jet Strength?

- What about stellar mass black holes, whose jets change drastically on very short timescales?
- $L_{BZ} \sim c(B_{pol}^2/8\pi)r_g^2 f(a/M)$

Magnetic field as important as spin; what controls its intensity? (Simulations show it's **not** the poloidal field in the disk)

Topology of field in disk? Large-scale flux?

If Mergers Trigger AGN, Which Ones?

- What mass ratio is required?

  Could a burst of gas accretion be as effective as a true merger? What about quasi-steady accretion rather than individual events?

- What if mergers work, but only on galaxies with pre-existing conditions? Does this qualify as “merger-driven”?
- Do mergers preferentially lead to specific AGN types?
- If mergers are responsible for only a minority of AGN, why the community obsession?

Does Gadget = Truth?

Used for: black hole growth, galaxy merger dynamics, galaxy assembly,…..

- Parameterized prescriptions for: star-formation, stellar heating, interstellar cooling, black hole accretion, AGN heating,….
- Resolution: $r_{influence} \sim 4\ M_7\ v_{100}^{-2}$ pc, $r_{ISM} \sim 1 - 30$ pc
- Test: Can it predict accretion rates in nearby galaxies?

Can Circumbinary Disks Solve the "Final Parsec" Problem?

Hoped-for solution: binary torques on outer gas remove angular momentum

- Pro: Seems natural
- Con: Need interaction with $M_{disk} \sim M_{binary}$; can enough be gathered? Will self-gravity transform the disk into stars?
- Pro: Genuine MHD calculation (Shi, K., Lubow & Hawley in prep.) shows ~15x torque/M_{disk} than α-hydro
- Con: MHD also shows ~40x accretion/M_{disk} than α-hydro, enough to nearly cancel binary shrinkage **(details matter)**
- Pro(?): If there is substantial accretion, an AGN will illuminate the disk, perhaps driving off a wind (reducing accretion), but also perhaps accelerating inflow

Circumbinary Disks: Standard Theory

Binary exerts torque through disk resonances

- Break in axisymmetry required for net torque

When $q \sim 1$, torque stops accretion at $r \sim 2a$

Internal stresses described by α-model or self-gravity

Problems with Standard Theory

α-model dubious

Assumes steady-state inflow, not pile-up in inner disk

Applies deep within disk, but greatest torque occurs **inside** the edge; leakage takes place **across boundaries**, outside of disk

Fundamentally unphysical

Are disks smooth?

Parsec-scale gas in AGN likely clumpy; affects stresses?

Ordinary disk theory assumes vertical support, pressure due to local mechanisms

If one or both black holes accrete, irradiation important

Are disks aligned with the binary orbit?

What if they are oblique or retrograde?

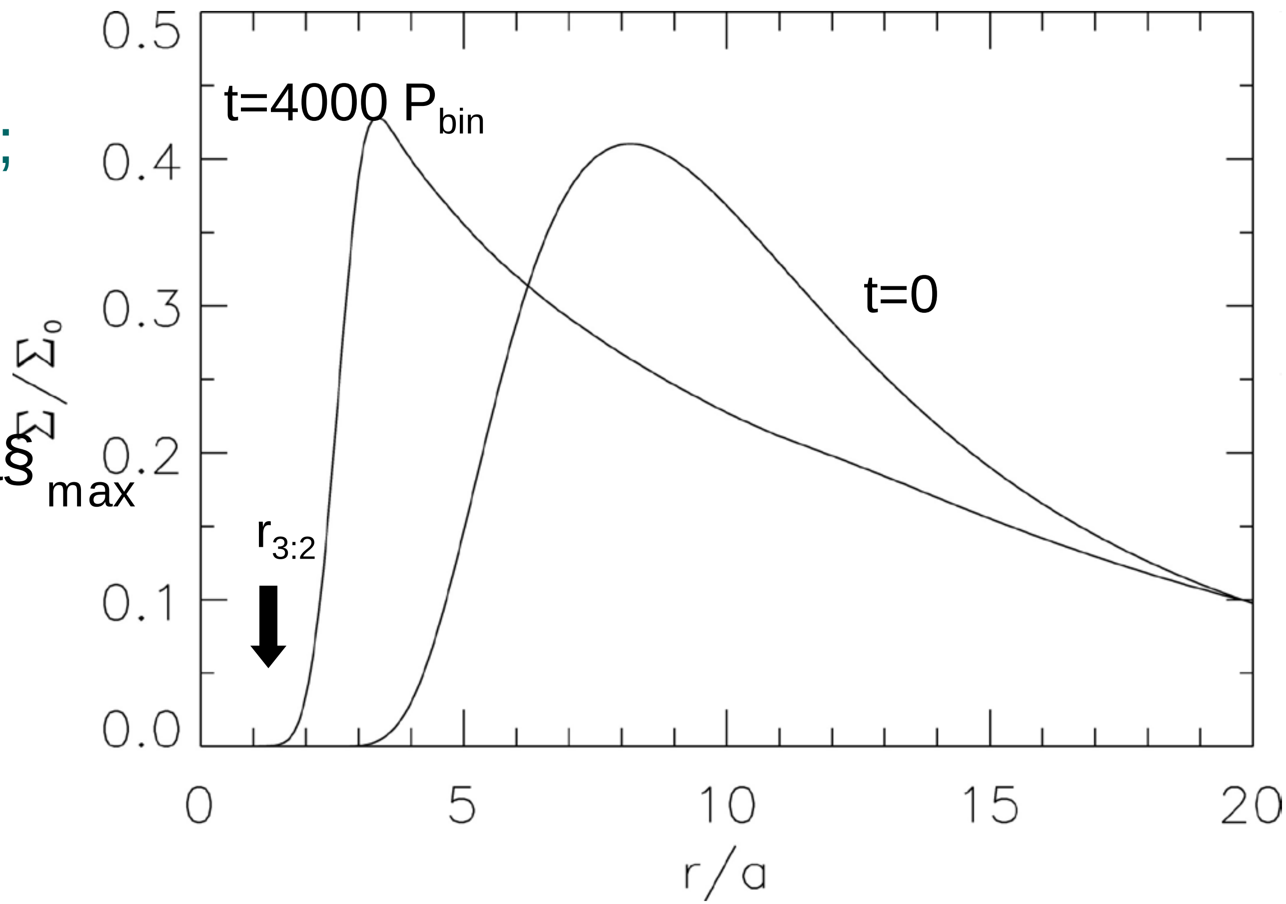
Azimuthally-Averaged Radial Structure from a Classical Disk Evolution Calculation

(MacFadyen & Milosavljevic 2008)

2-d hydro: $\alpha=0.01$;
q=1, e=0

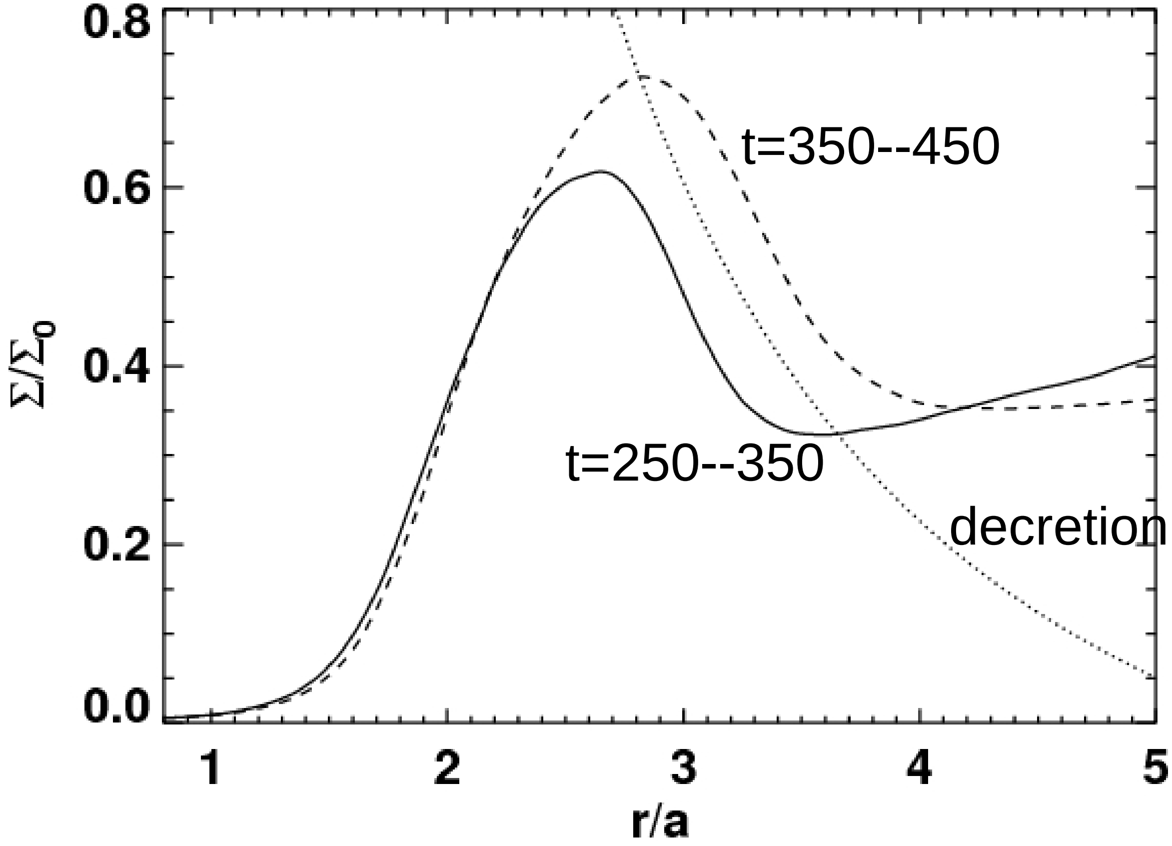
$T_{tot} \simeq 0.0014 G M a \Sigma_{max}$

$\dot{M}_{in} \simeq 0.2 \dot{M}_{out}$

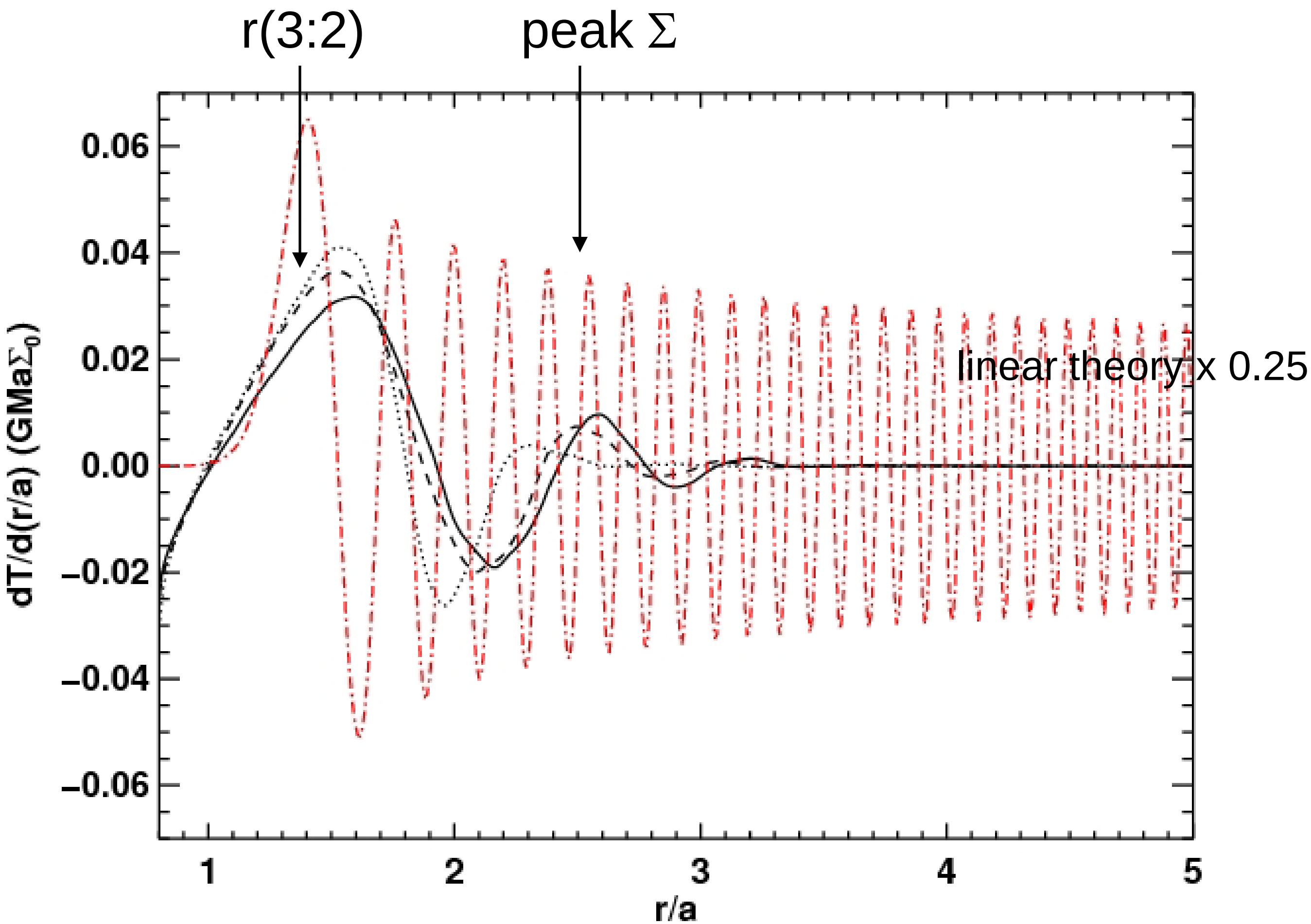


Azimuthally-Averaged Radial Structure from 3-d MHD

(Jiming Shi, K., Lubow & Hawley 2011)



Radial Profile of Torque



Total torque exquisitely sensitive to edge profile

Results

Because $\Sigma_{\beta,2}/\Sigma_{max}$ ~ 20x greater than MM08,

$$\bar{T}_{tot} \simeq 0.02 G m a \Sigma_{max} \approx 14 \times \bar{T}_{tot,MM}$$

$$\dot{M}_{in} \approx O(0.1) \dot{M}_{out}$$

similar to MM08

But

$$\dot{M}_{in} / \Sigma_{max} \approx 40 \times \mathrm{MM08}$$

Effect on Binary Orbit

Binary separation depends on J, but also the total mass and the mass ratio

$$\frac{\dot a}{a} = 2\frac{\dot J}{J} + \frac{\dot M_{tot}}{M_{tot}} - 2\left(\frac{\dot M_1}{M_1} + \frac{\dot M_2}{M_2}\right)$$

For equal masses

$$\frac{\dot a}{a} = 2\frac{\dot J}{J} - 3\frac{\dot M_{tot}}{M_{tot}}$$

$$\frac{\dot a}{a} = -2\frac{T}{J} + 2\frac{\dot M_{tot}}{M_{tot}}\left(j_{acc}/j_{bin} - 3/2\right)$$

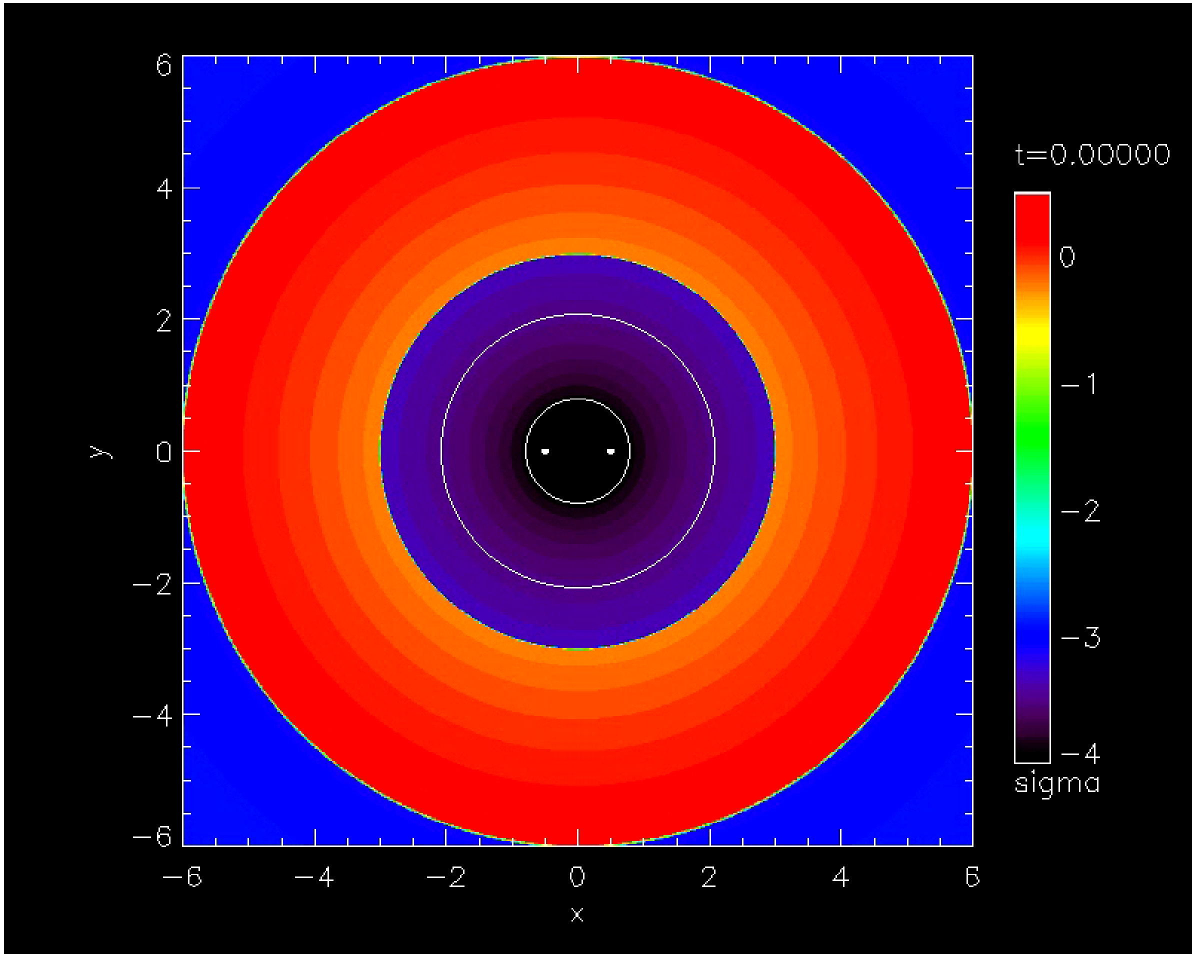
The ratio of accretion rate to torque matters; **increased** by MHD

We find

$$\text{net } \frac{\dot a}{a} \simeq -1.2\frac{T}{J}$$

About 70% faster than MM08 for equal M_d

Surprise: Strongly Asymmetric, Eccentric



Bottom Line: MHD Effects in Circumbinary Disks

- Internal stresses are stronger in disk body, even more so in the gap
- That leads to more matter in the gap, therefore greater torque
- And also leads to more matter accreted
- Near cancellation in binary shrinkage rate means details matter!

What if LISA (or something similar) Doesn't Fly Until 2040+? Can We Find **Reliable** EM Signatures of Black Hole Mergers?

How to recognize a **binary** black hole system?

- When should one or both black holes be an AGN?
- BLRs merge for all separations when $q \sim 1$, larger separations for all q; what distinguishes such a binary?

  Separated BLRs appear only for small separations, small q; implies large M_1
- Does every genuine binary merge?

Relativistic signals depend crucially on gas mass; how well can we predict $\Sigma(r)$?

- To what extent do binary torques retard inflow?
- How well can matter follow a rapidly compressing binary? (α-model does **not** apply)
- Energy deposited ~ gas mass by the Equivalence Principle
- Large energy deposition → large gass mass → optically thick → spectral reprocessing, variability suppression

Recap of Questions

- Can we trust AGN black hole masses?
- How can we measure AGN spin?
- Which parameters control jet strength?
- What part of nuclear activity is merger-driven?
- How reliable are galaxy evolution simulations?
- How do external disks interact with black hole binaries?
- Can we predict EM features associated with black hole binaries, mergers, and merger remnants well enough to search for them efficiently?