Testing the No-Hair Theorem with Quasi-Periodic Variability

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The No-Hair Theorem

The Kerr solution is the only possible stationary axisymmetric metric in vacuum that has no naked singularities and no closed time-like loops.

- Black holes have only 2 parameters: mass and spin
- Any other signature radiated away by gravitational waves
- Expectation: All astrophysical black holes are Kerr black holes

However…

- Non-spherical collapse: naked singularities possible

  Shapiro & Teukolsky 1992, PRD, 45, 44

- Kerr solution not unique to GR

  Psaltis et al. 2008, PRL, 100, 091101

Testing the No-Hair Theorem Observationally

Kerr black hole? | Something else?

- Expand spacetime in multipole moments (mass *M*, spin *a*, …)
- Parameterize quadrupole moment: $q = -(a^2 + \varepsilon)$
- Use observations to measure (at least) 3 moments
- Check whether: $q = -a^2$ i.e.: $\varepsilon = 0$

Ryan 1995, 1997a,b
Barack & Cutler 2004, 2007
Collins & Hughes 2004
Glampedakis & Babak 2006
Brink 2008, 2009
Gair et al. 2008
Li & Lovelace 2008
Will 2008
Vigeland & Hughes 2010
Johannsen & Psaltis 2010a, 2011b
Vigeland et al. 2011

A New Metric for Rapidly Spinning Black Holes

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right)\left(1 + h(r,\theta)\right)dt^2 - \frac{4aMr\sin\theta}{\Sigma}\left(1 + h(r,\theta)\right)dt\,d\phi$$

$$+ \frac{\Sigma\left(1 + h(r,\theta)\right)}{\Delta + a^2 h(r,\theta)\sin^2\theta}dr^2 + \Sigma d\theta^2$$

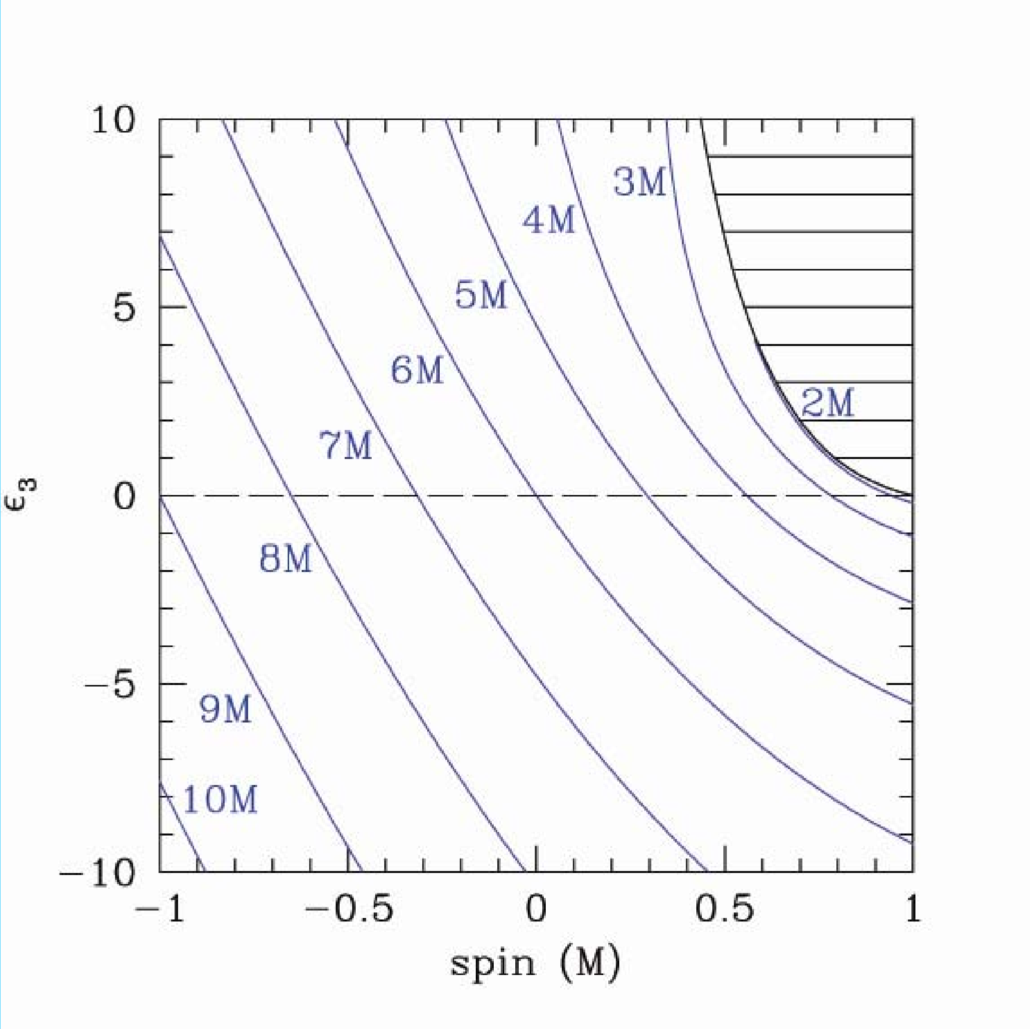
$$+ \left[\sin^2\theta\left(r^2 + a^2 + \frac{2a^2 Mr\sin^2\theta}{\Sigma}\right) + h(r,\theta)\frac{a^2(\Sigma + 2Mr)\sin^4\theta}{\Sigma}\right]d\phi^2$$

where

$$h(r,\theta) \equiv \varepsilon_3 \frac{M^3}{r^3}$$

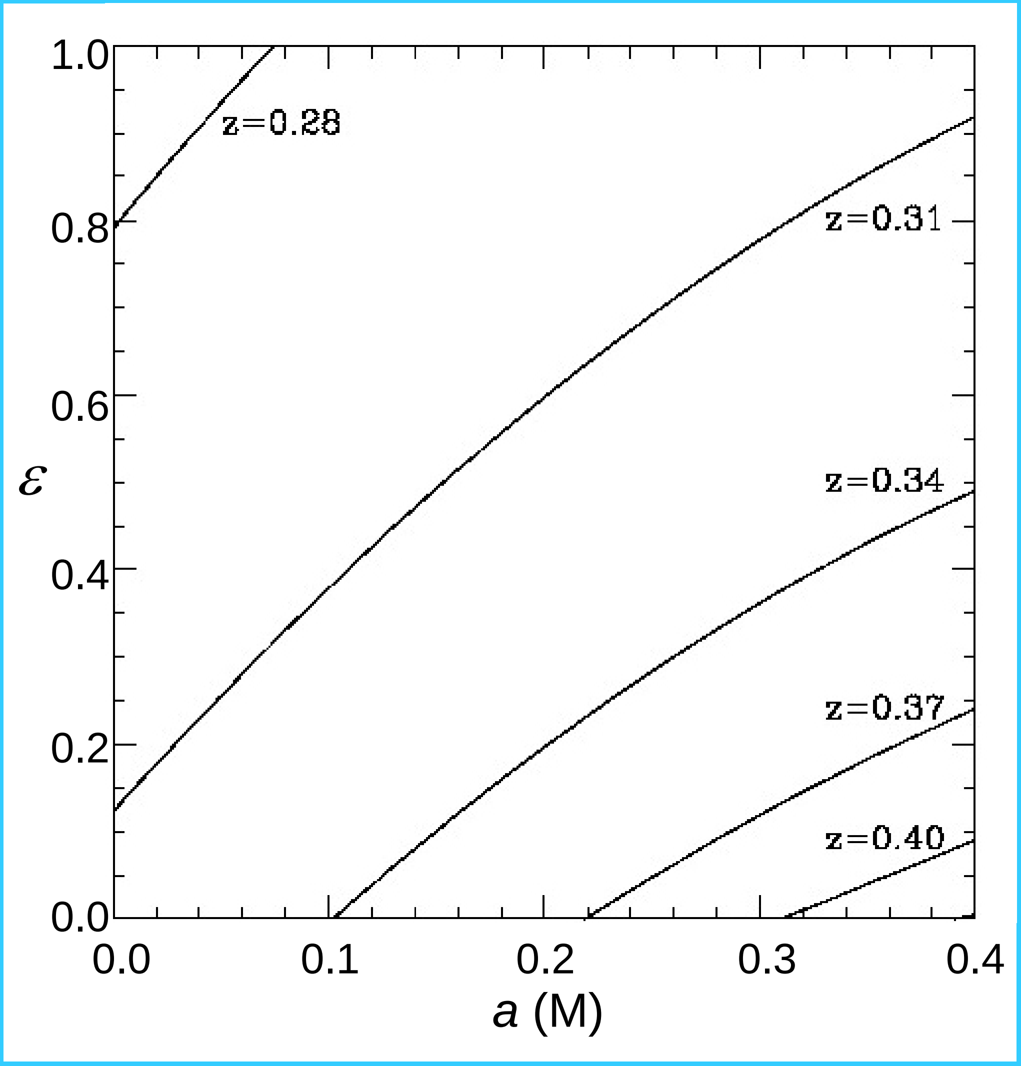
Johannsen & Psaltis 2011b, PRD, 83, 124015

Quadrupole Effects: (i) location of the ISCO



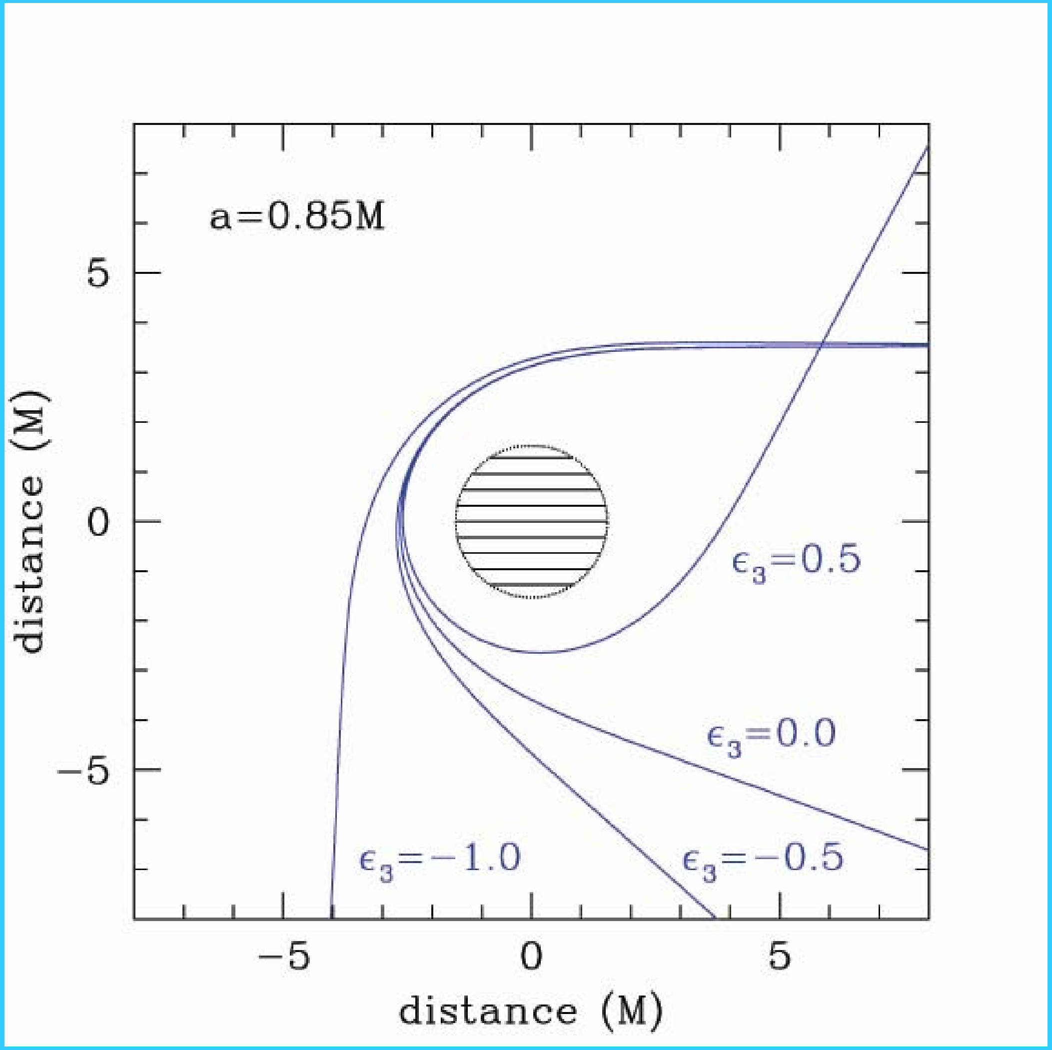
Johannsen & Psaltis 2011b, PRD, 83, 124015

Quadrupole Effects: (ii) photon redshift



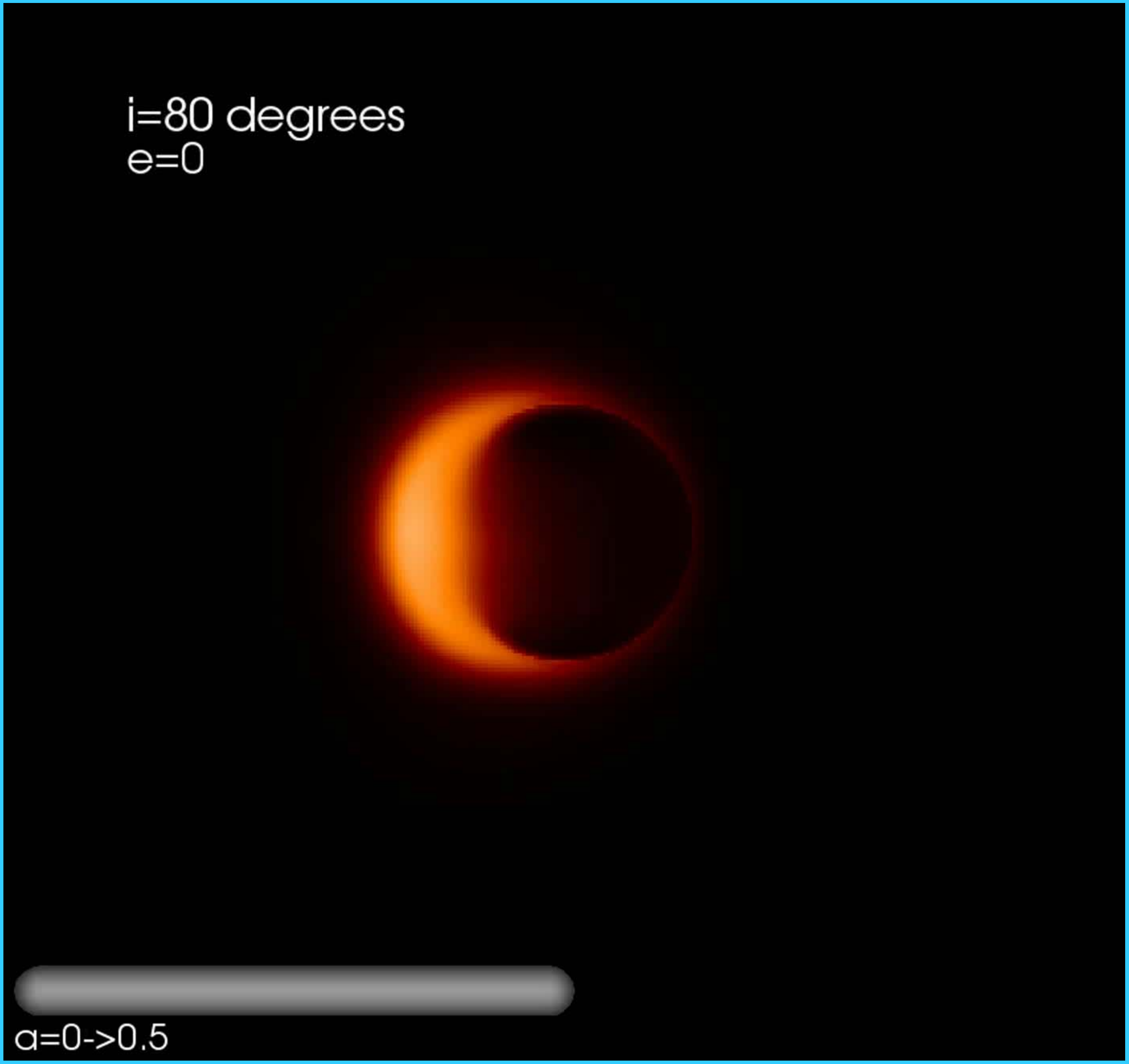
Johannsen & Psaltis 2010a, ApJ, 716, 187

Quadrupole Effects: (iii) gravitational lensing

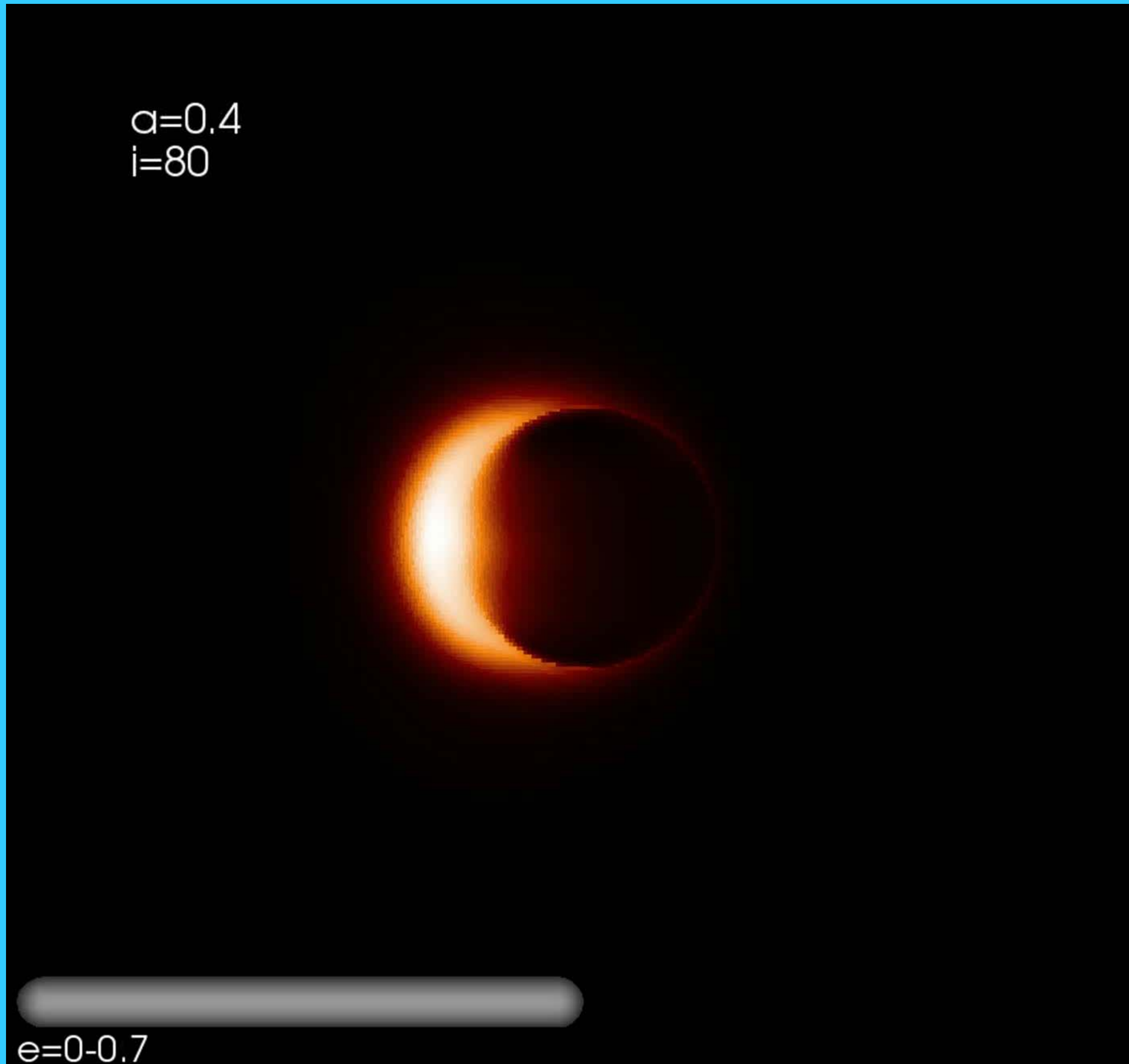


Johannsen, arXiv:1105.5645

I. Imaging the Shadow of Sgr A*

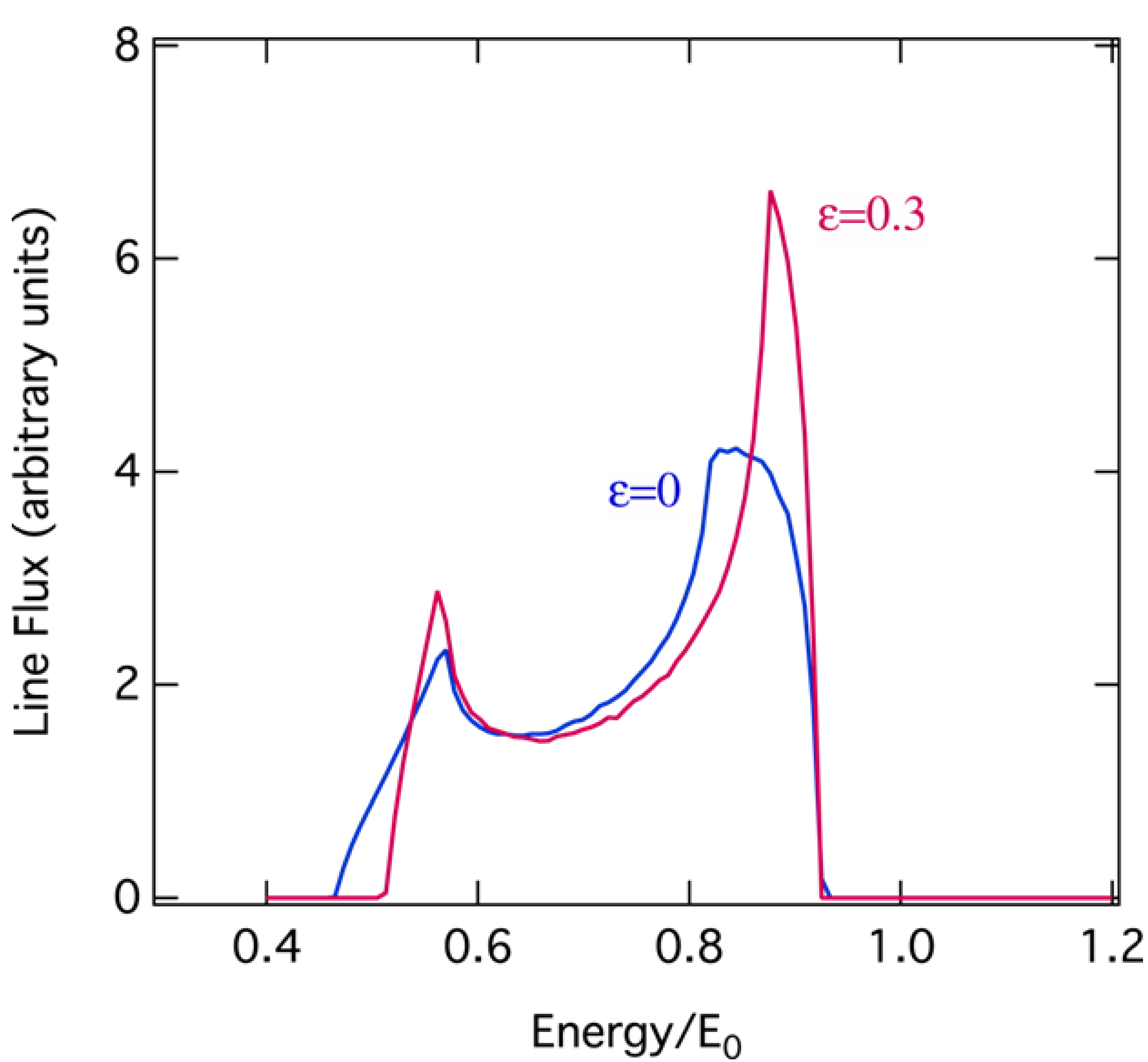


with A. Broderick, A. Loeb
Johannsen & Psaltis 2010a, ApJ, 716, 187



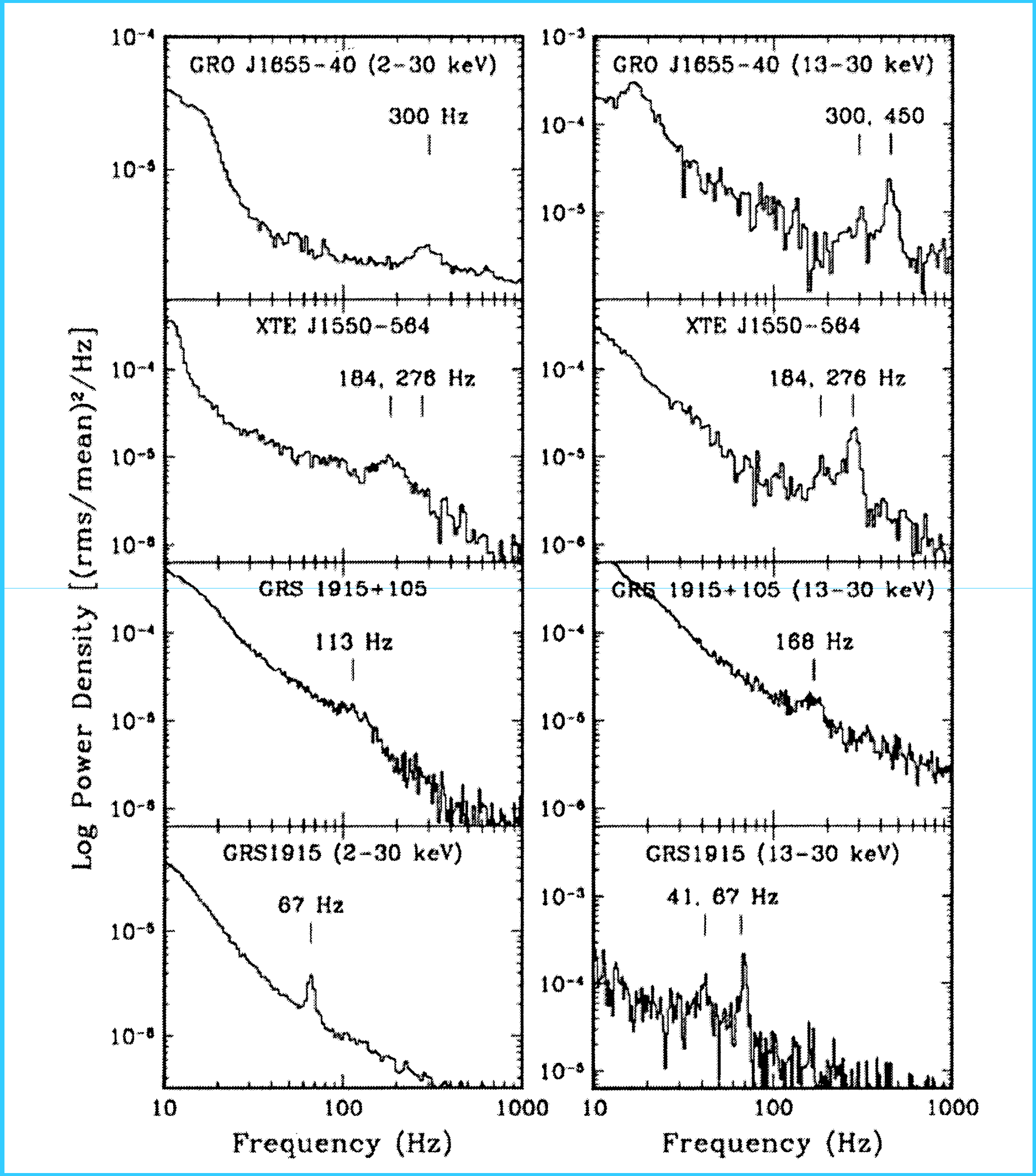
with A. Broderick, A. Loeb
Johannsen & Psaltis 2010a, ApJ, 716, 187

II. Flourescent Iron Lines



Psaltis & Johannsen, arXiv:1011.4078

III. Quasi-Periodic Variability



McClintock & Remillard 2006, in *Compact Stellar X-Ray Sources*

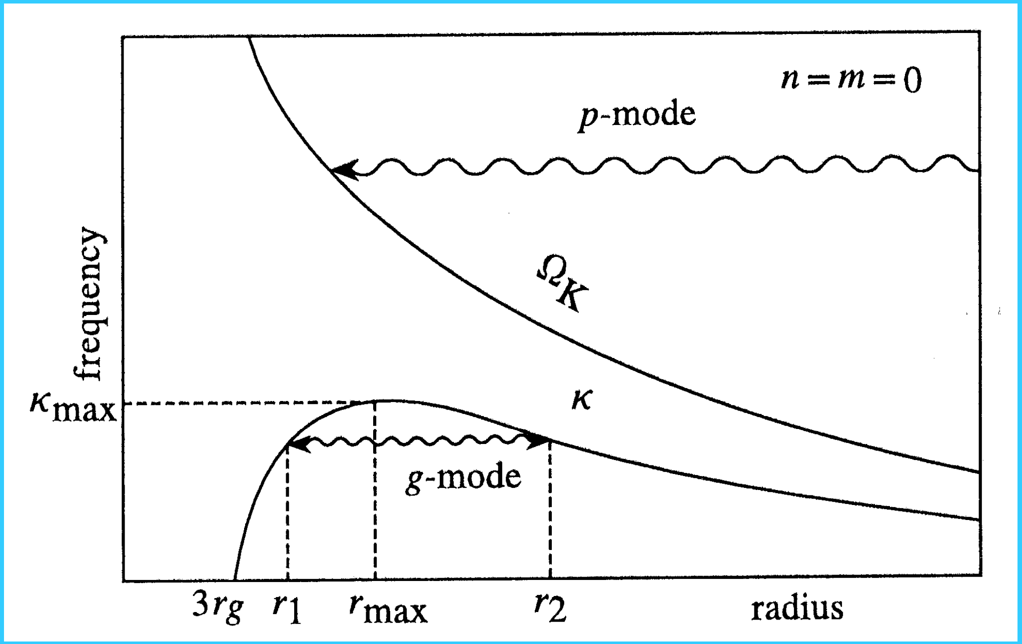
1. Diskoseismology Model

Perez et al. 1997, ApJ, 476, 589
Silbergleit et al. 2001, ApJ, 548, 335

Consider perturbations on thin accretion disk:

Continuity eq.
Energy eq.
Eqs. of motion

} dispersion relation ⇒ g-modes, c-modes



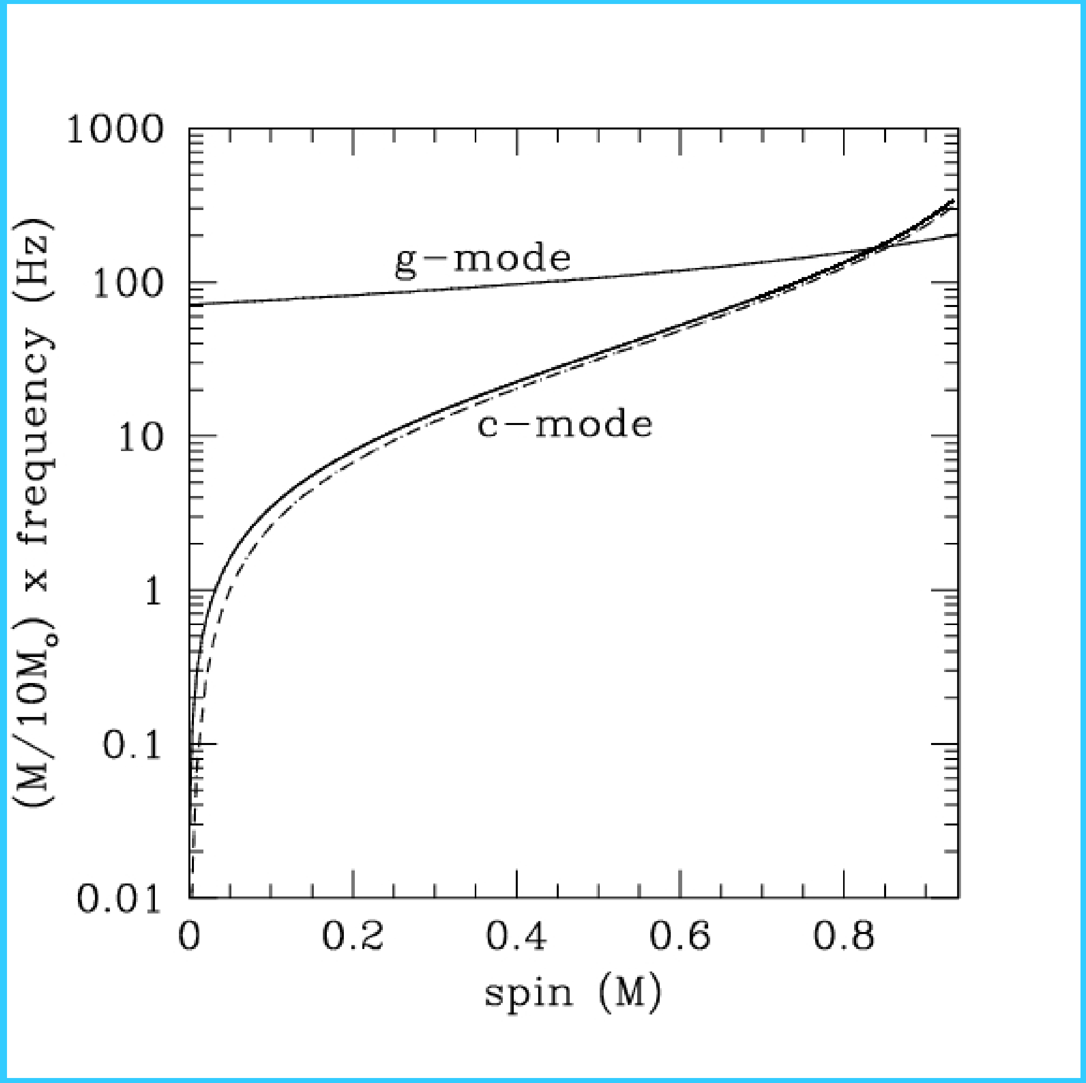
Kato 2001

fundamental g-mode:

$$\frac{\kappa_{max}}{2\pi}$$

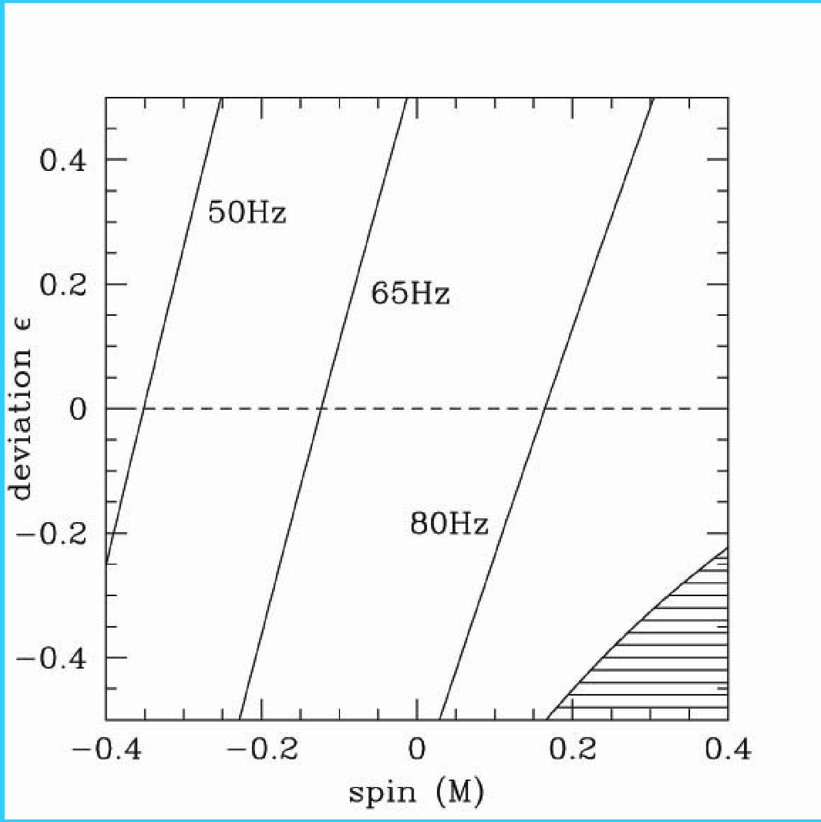
fundamental c-mode:

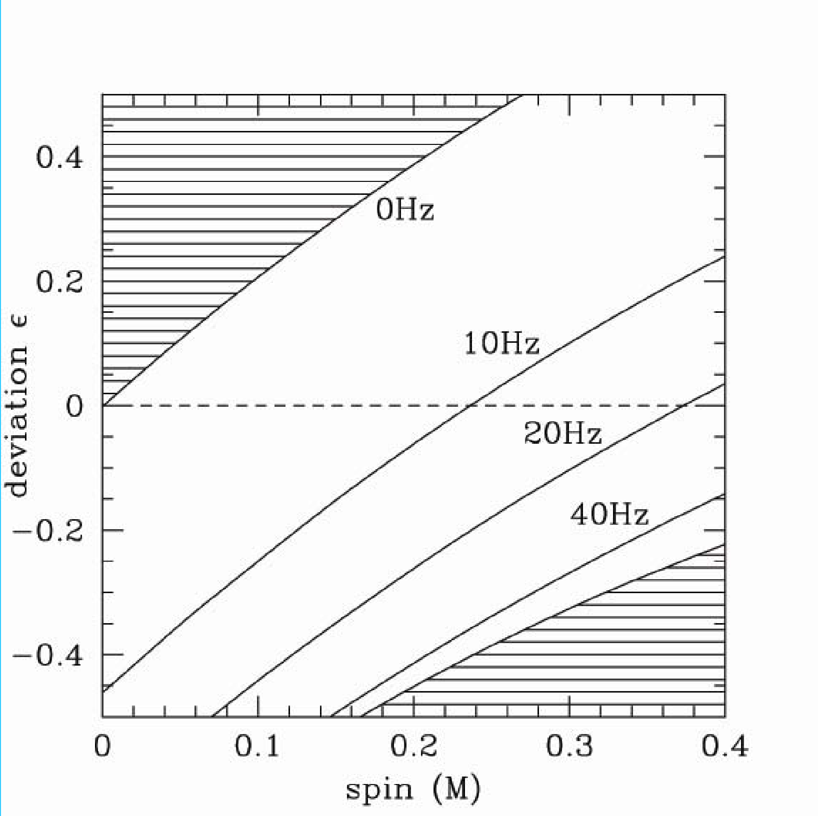
$$\frac{\Omega_{LT}(ISCO)}{2\pi}$$



Wagoner et al. 2001, ApJ, 559, L25
Johannsen & Psaltis 2011a, ApJ, 726, 11

Kerr black hole





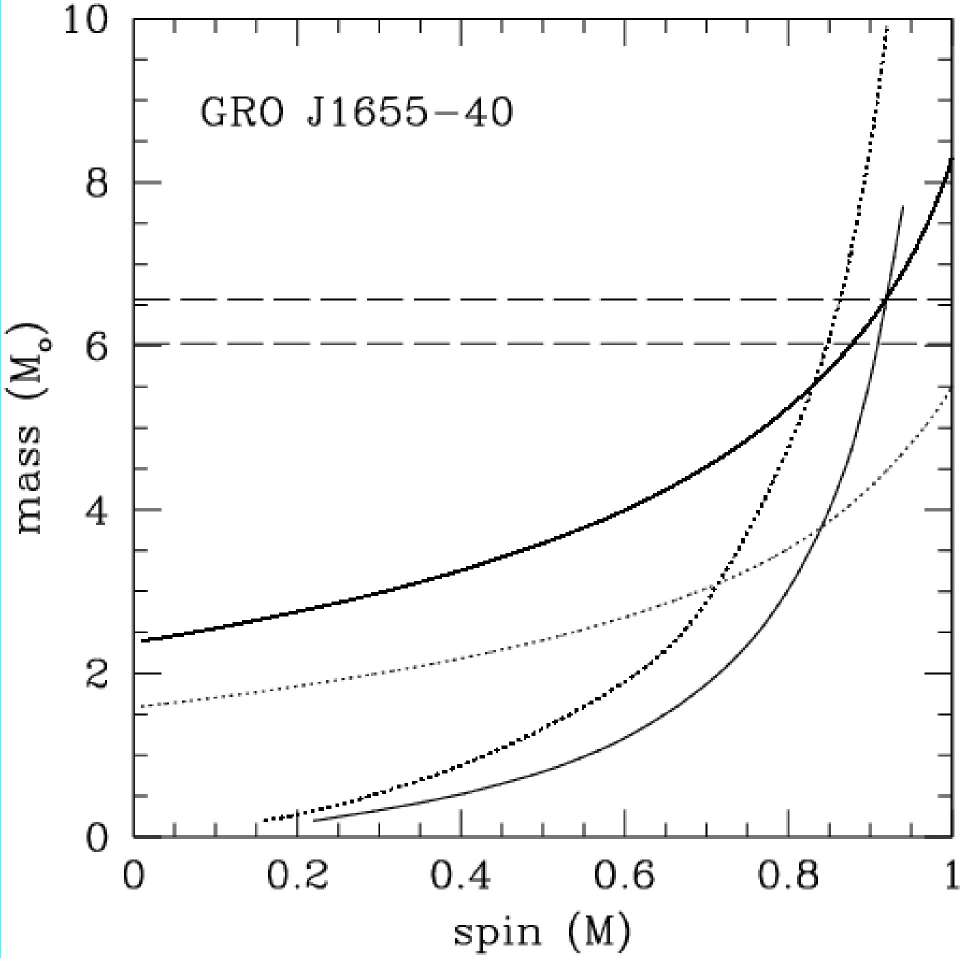
fundamental g-mode

fundamental c-mode

(in units of 10 solar mass BH)

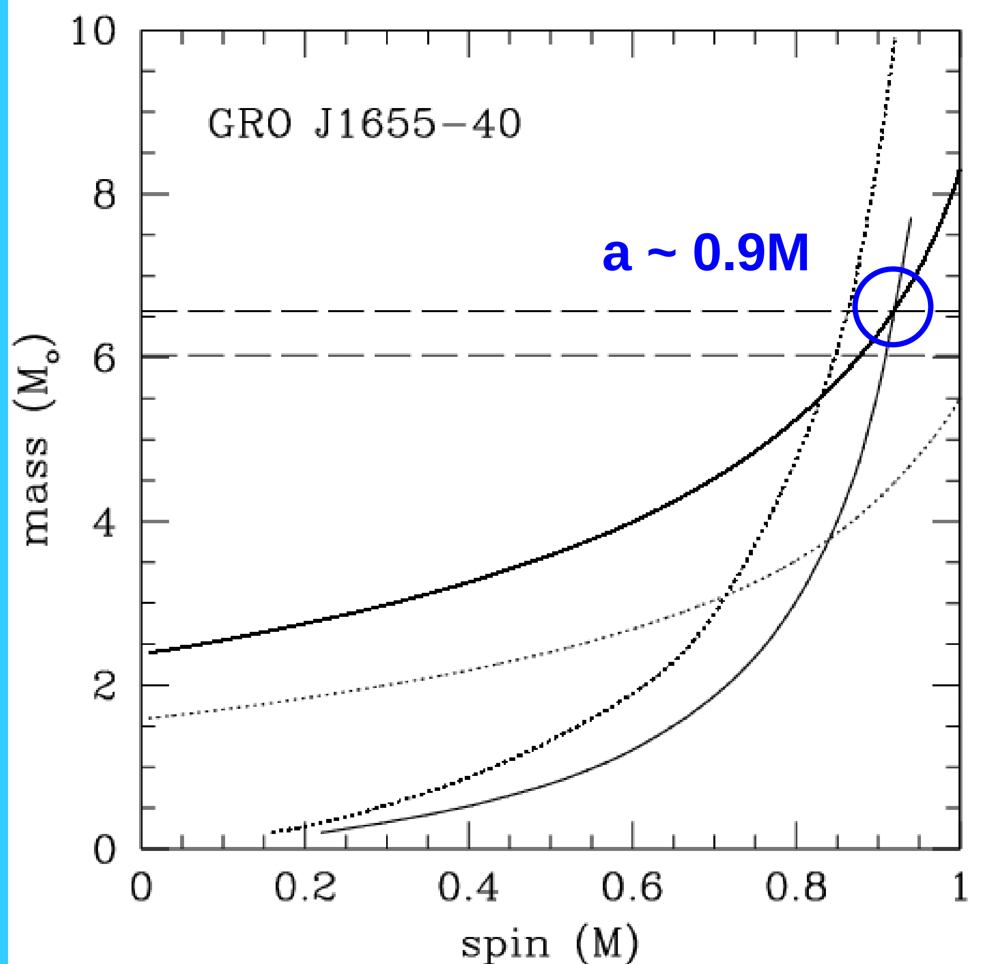
Johannsen & Psaltis 2011a, ApJ, 726, 11

Kerr black hole



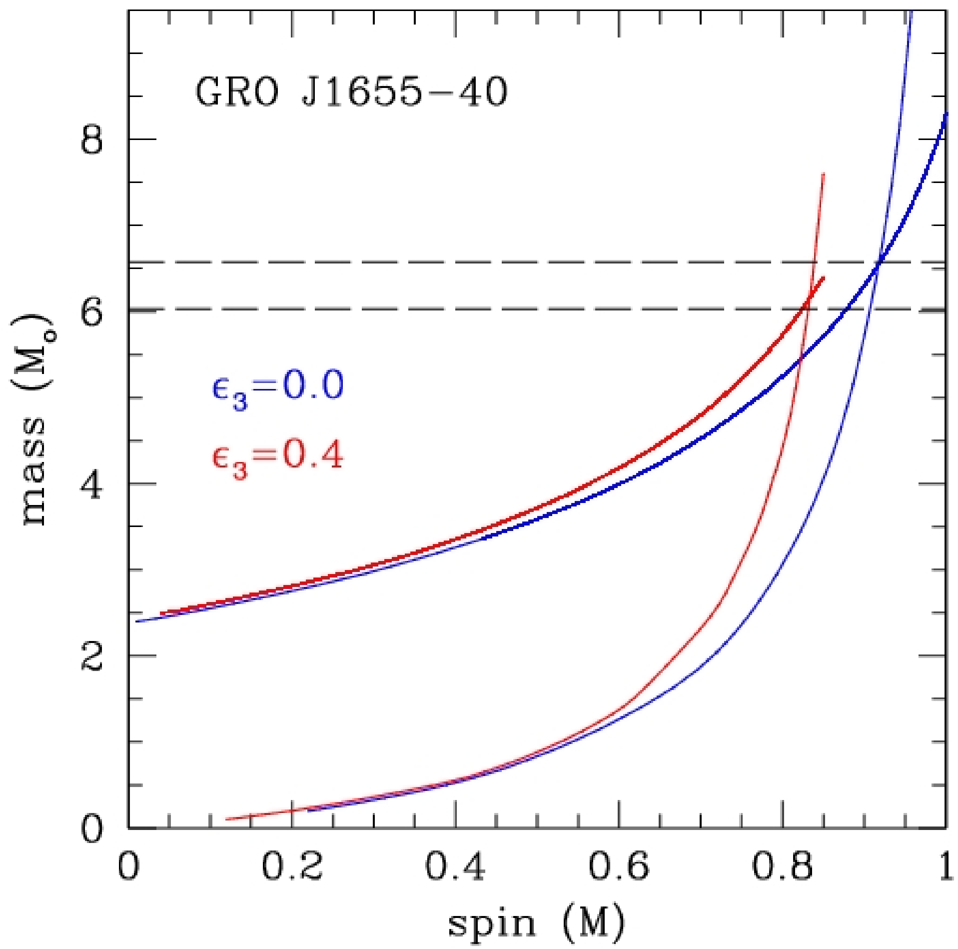
After Wagoner et al. 2001, ApJ, 559, L25
also Psaltis in *X-Ray Timing 2003: Rossi and Beyond*

Kerr black hole

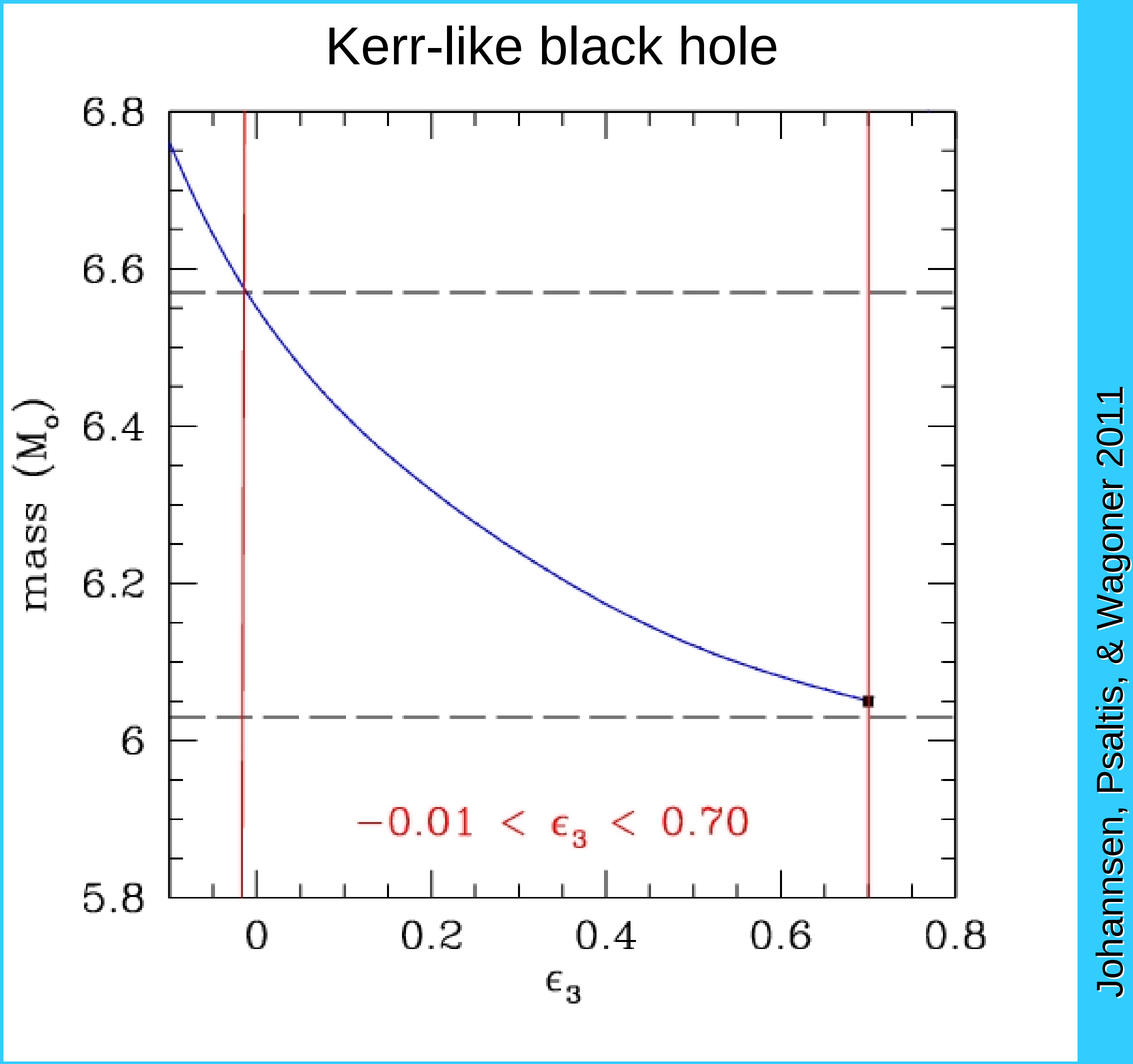


After Wagoner et al. 2001, ApJ, 559, L25
also Psaltis in *X-Ray Timing 2003: Rossi and Beyond*

Kerr-like black hole



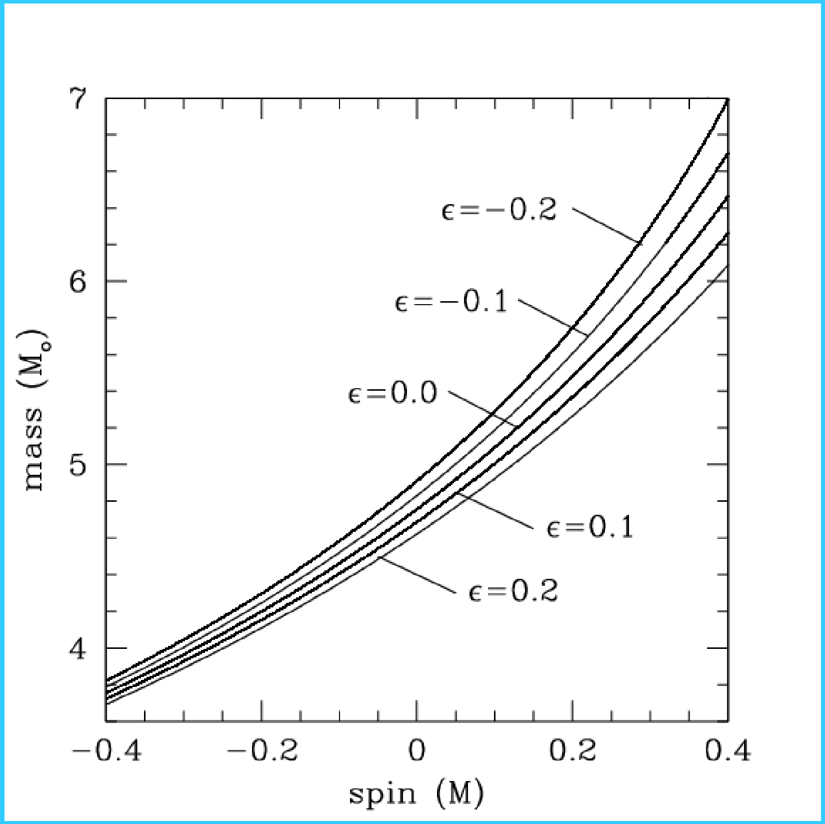
Johannsen, Psaltis, & Wagoner 2011

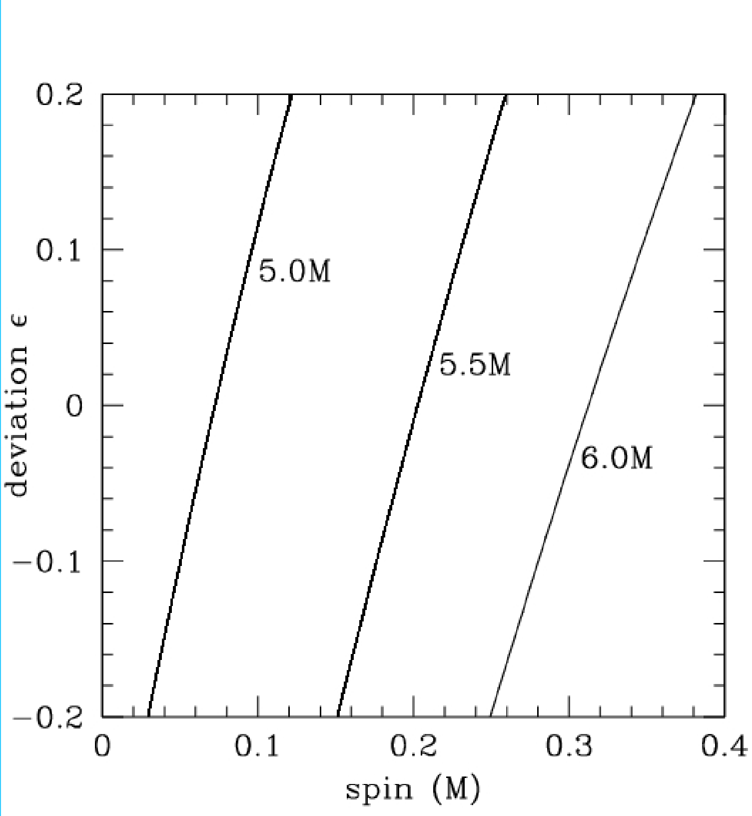


Test no-hair theorem with 2 QPOs + mass measurement !!

2. Resonance Model

Abramowicz & Kluzniak 2001, A&A, L19





Johannsen & Psaltis 2011a, ApJ, 726, 11

1:2 resonance between Keplerian and radial epicyclic frequencies

Test no-hair theorem with 2 QPOs + mass + spin measurement

Summary and Outlook

- ✓ No-hair theorem characterizes nature of black holes
- ✓ Can be tested by measuring 3 multipole moments
- ✓ Observational tests: Imaging, Iron Lines, QPOs
- ✓ Diskoseismology model: 2 QPOs + mass measurement
- ✓ Resonance model: 2 QPOs + mass + spin measurement

Need Timing Mission to detect higher order harmonics and resolve model degeneracy

e.g., LOFT, arXiv:1107.0436