Title: Testing Strong-Field General Relativity with Black Holes

Date: Oct 04, 2012 01:00 PM

URL: http://pirsa.org/12100049

Abstract:

Collaborators

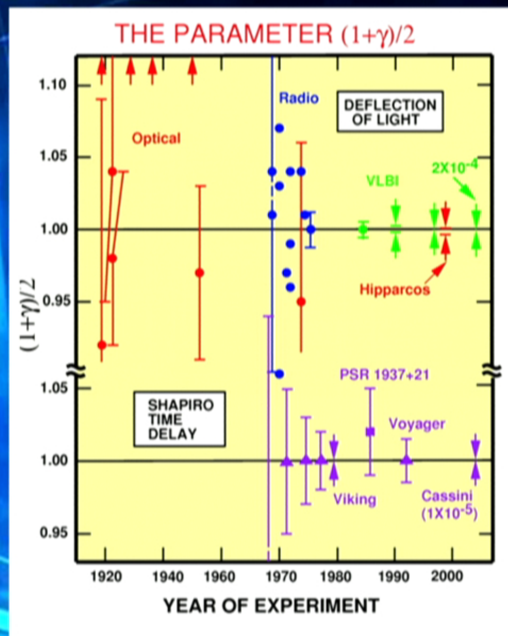
Dimitrios Psaltis (Arizona)

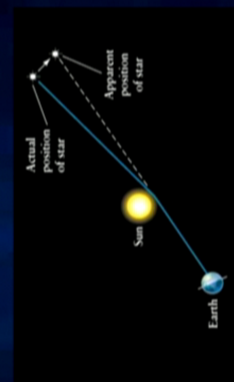
Avery Broderick (PI/UW), Shepherd Doeleman (MIT Haystack), Vincent Fish (MIT Haystack), Stefan Gillessen (MPE), Scott Hughes (MIT), Abraham Loeb (Harvard), Daniel Marrone (Arizona), Jeffrey McClintock (Harvard), Feryal Ozel (Arizona), James Steiner (Harvard), Sarah Vigeland (JPL), Nicolas Yunes (MSU)

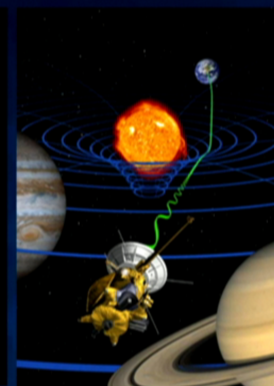
Outline

- Current Tests of General Relativity
- A Framework for Strong-Field Tests of GR
- Astrophysical Tests with Black Holes
- The Future: Upcoming Instruments

Current Tests of (Weak-Field) General Relativity







$$ds^2 = -A(r)dt^2 + B(r)dr^2 + r^2 d\Omega$$

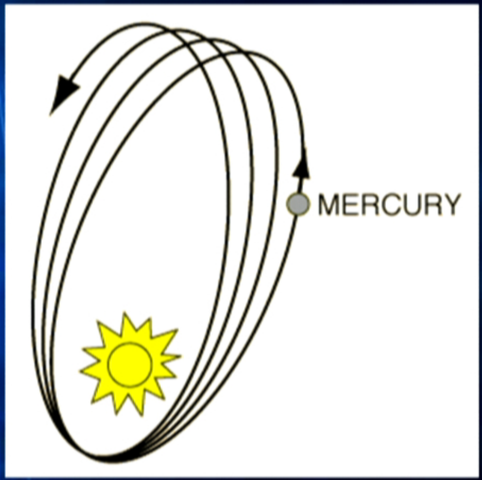
$$A(r) \equiv 1 - \frac{2M}{r} + 2(\beta - \gamma)\left(\frac{M}{r}\right)^2$$

$$B(r) \equiv 1 + 2\gamma \frac{M}{r}$$

PPN Formalism

Will 2006, LRR, 9, 3

Current Tests of (Weak-Field) General Relativity



Other planets: 531.63 (arcsec/century)

GR: 42.98

Total: 574.61

Observed: 574.10 ± 0.65

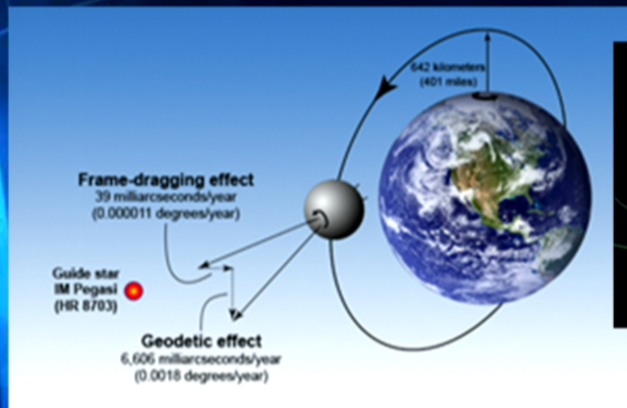
$$|2\gamma - \beta - 1| < 3\times10^{-3}$$

With Lunar Laser Ranging:

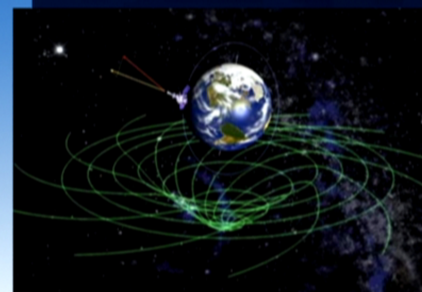
$$\beta - 1 = (1.2 \pm 1.1)\times10^{-4}$$

Will 2006, LRR, 9, 3

Current Tests of (Weak-Field) General Relativity



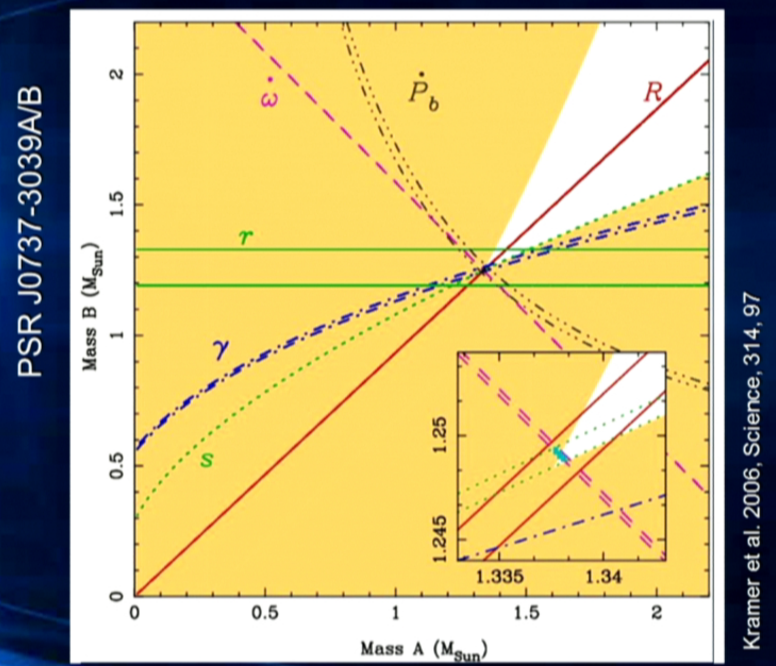
(per year)	Measured	Predicted
Geodetic precession (mas)	6602 ± 18	6606
Frame-dragging (mas)	37.2 ± 7.2	39.2



Gravity Probe B

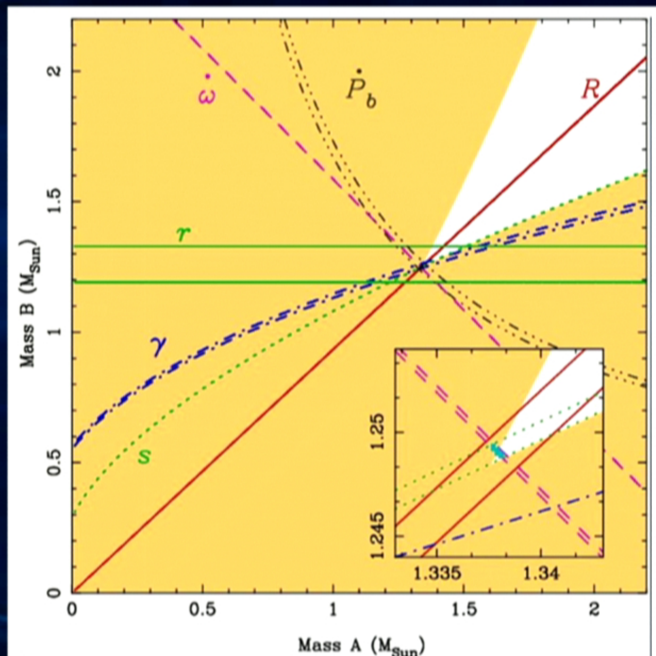
Everitt, et al. 2011,
PRL, 106, 221101

Current Tests of (Weak-Field) General Relativity



Current Tests of (Weak-Field) General Relativity

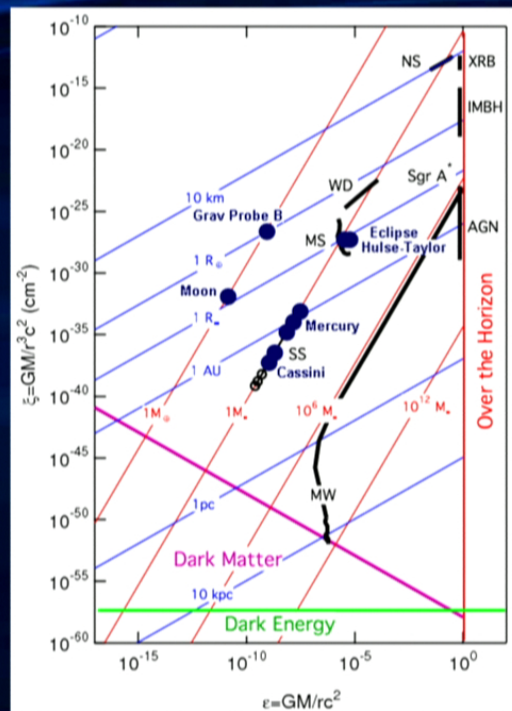
PSR J0737-3039A/B



Kramer et al. 2006, Science, 314, 97

The Need for Strong-Field Tests of GR

$$\frac{GM}{rc^2} \sim 1$$



After Psaltis 2008, LRR, 11, 9

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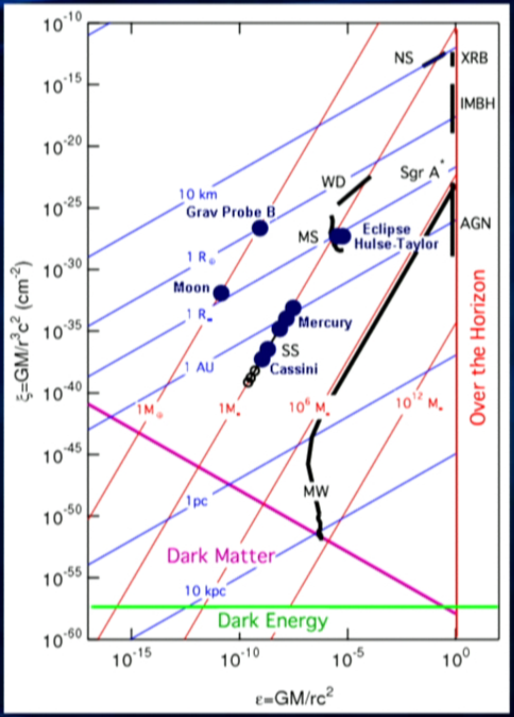

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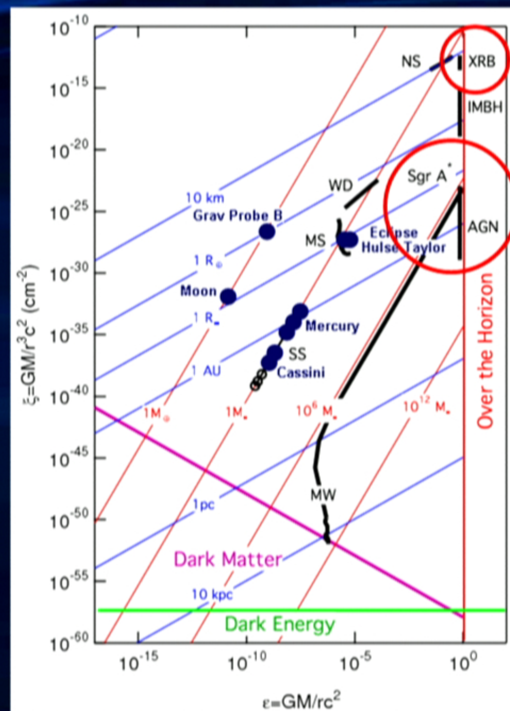

After Psaltis 2008, LRR, 11, 9

The Breakdown of GR

- Classical theory
- Not renormalizable
- Singularities
- Cosmological constant problem
- Vacuum fluctuations
- …

GR, an effective theory of quantum gravity?

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Ways to Modify GR

$$S = \frac{c^4}{16\pi G}\int d^4x\sqrt{-g}\,(R - 2\Lambda)$$

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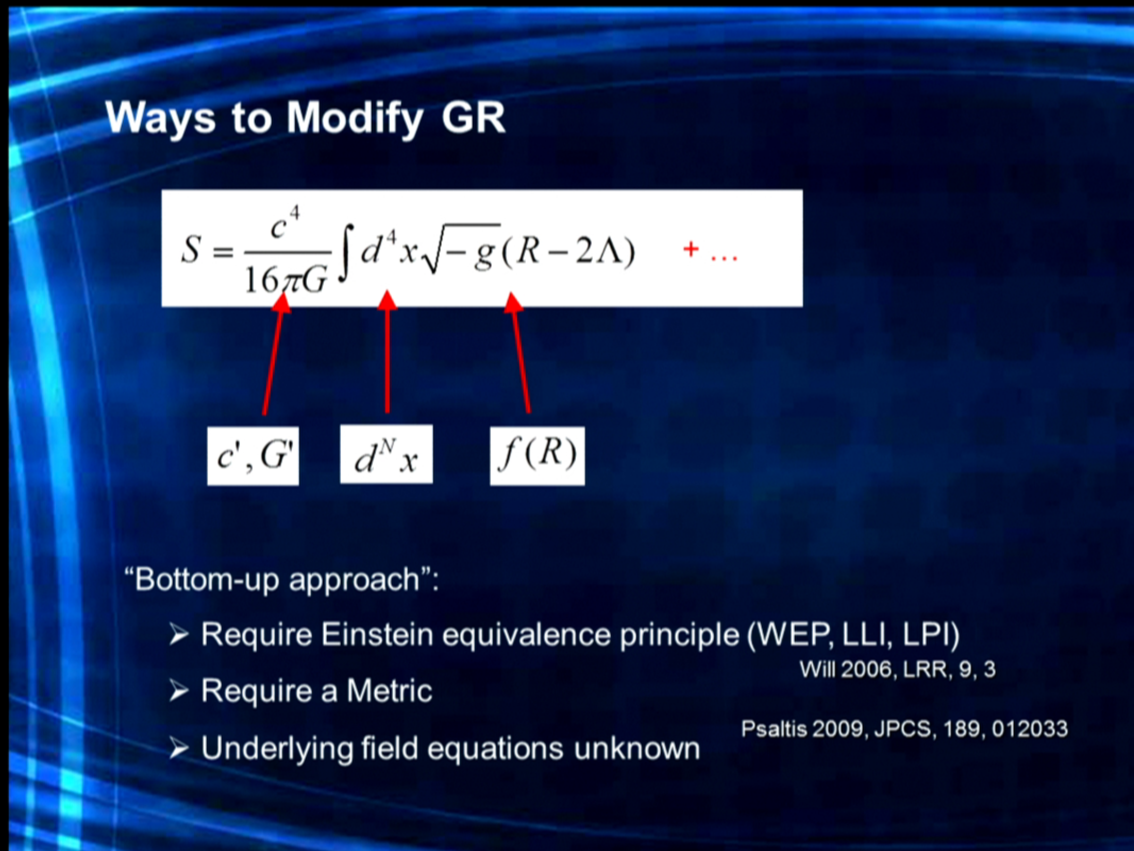
c', G' $\quad$ $d^N x$ $\quad$ $f(R)$


Ways to Modify GR
$S = \frac{c^4}{16\pi G}\int d^4x\sqrt{-g}(R-2\Lambda)$ + …
c', G'
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$f(R)$
"Bottom-up approach":
Require Einstein equivalence principle (WEP, LLI, LPI)
Will 2006, LRR, 9, 3
Require a Metric
Underlying field equations unknown
Psaltis 2009, JPCS, 189, 012033

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Will 2006, LRR, 9, 3

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The No-Hair Theorem

The Kerr solution is the only possible stationary, axisymmetric, asymptotically flat, vacuum metric in GR 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…

- Other types of black holes
  Johannsen & Psaltis 2011, PRD, 83, 124015
- 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
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The No-Hair Theorem

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- ✓ Stationary
- ✓ Axisymmetric
- ✓ Asymptotically flat, correct Newtonian limit

- Vacuum in GR?
- Pathologies?

Strong-field gravity: Cannot use PPN, need to model spacetime.

Parametric Deviations from the Kerr Metric

- Gravitational waves: (approximately) integrable
- Accretion flows: regular outside event horizon

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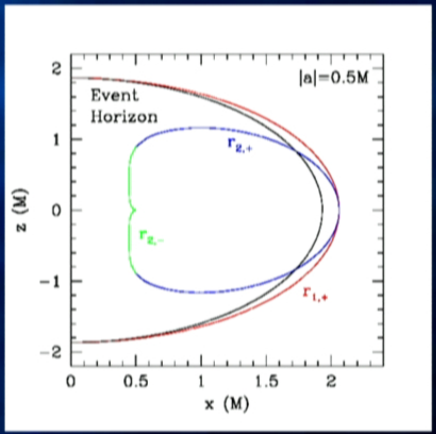

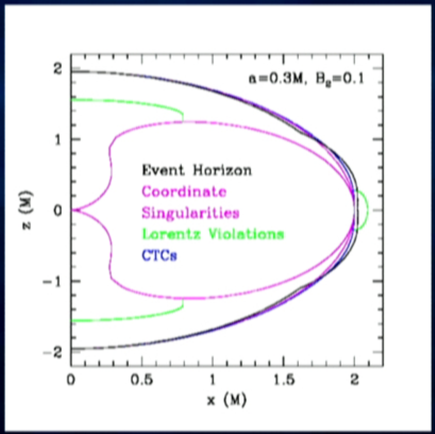

Metric: Bumpy Kerr metric (Vigeland & Hughes 2010)

Johannsen, Vigeland, Yunes, Hughes, Psaltis 2012

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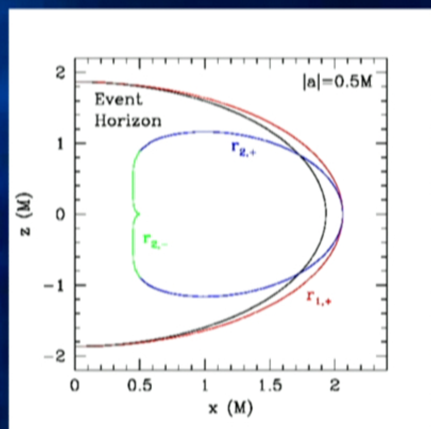

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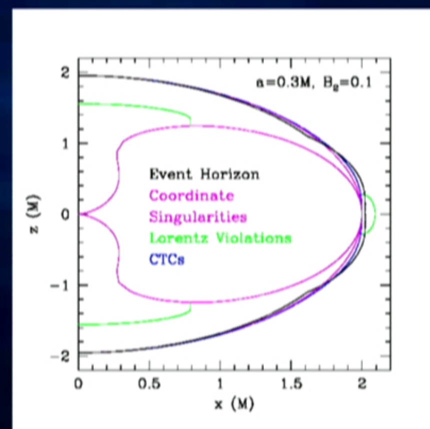

Johannsen, Vigeland, Yunes, Hughes, Psaltis 2012

A New Metric for Rapidly Spinning Black Holes

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

where

$$\Delta \equiv r^2 - 2Mr + a^2 \qquad \Sigma \equiv r^2 + a^2\cos^2\theta \qquad h(r,\theta) \equiv \varepsilon_3 \frac{rM^3}{\Sigma^2}$$

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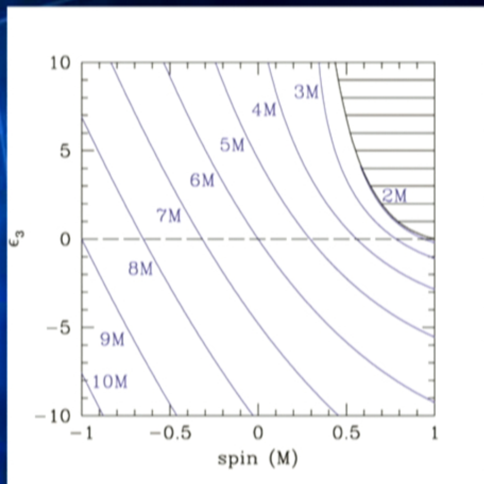
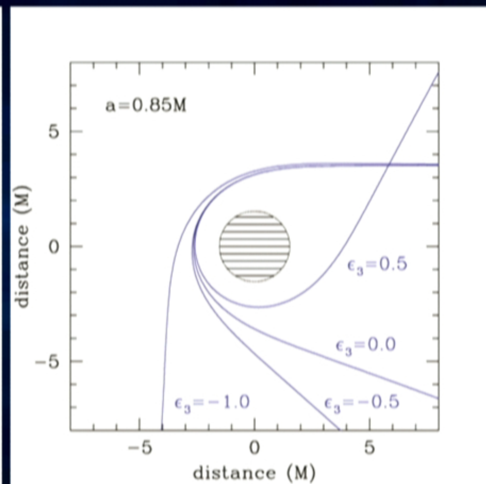
New Metric Properties



2. Location of the ISCO

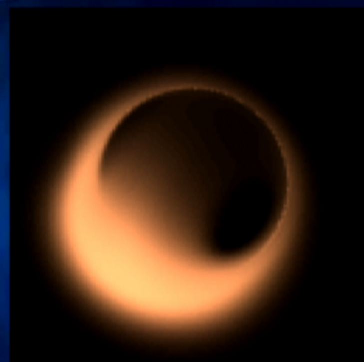
Johannsen & Psaltis 2011, PRD, 83, 124015



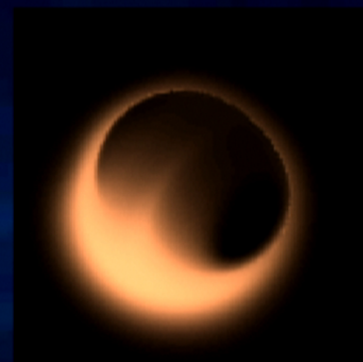
3. Lightbending

Johannsen 2012, Adv. Astron., 2012, 1

1. Testing the No-Hair Theorem with Sgr A*



$\varepsilon = 0.4$



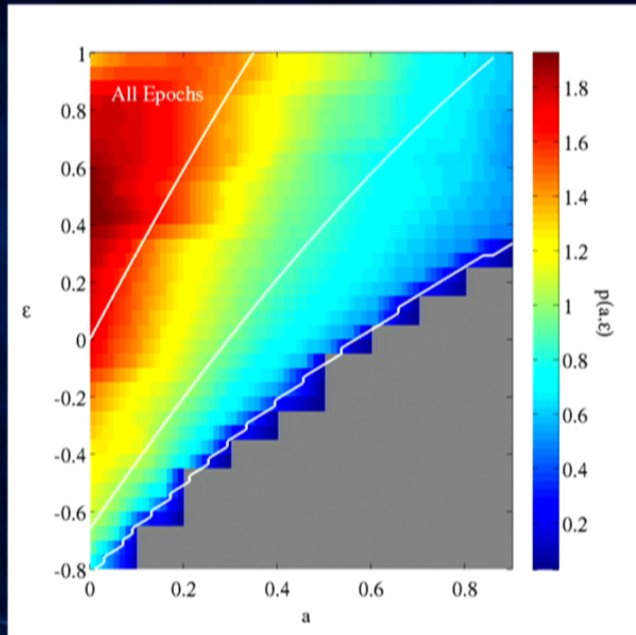
$\varepsilon = -0.8$

Broderick, Johannsen, Loeb, Psaltis 2012

Shape of shadow depends uniquely on mass, spin, disk inclination
e.g., Falcke et al. 2000, ApJ, 528, L13

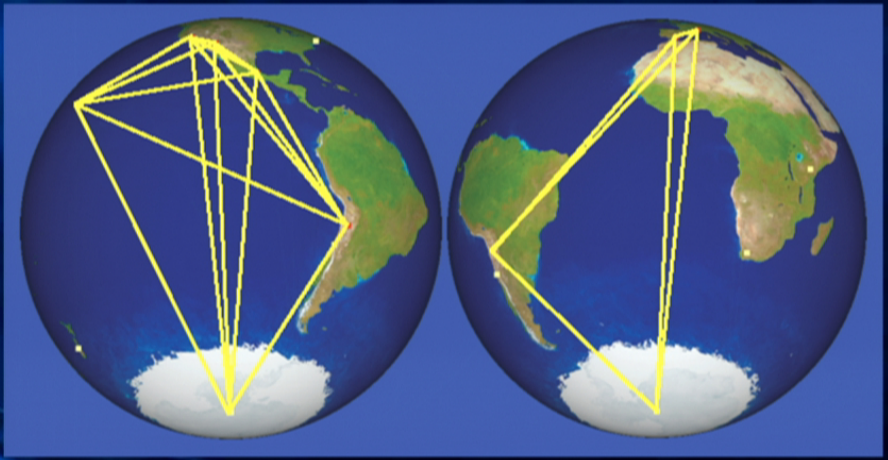
...as well as on quadrupole moment
Johannsen & Psaltis 2010, ApJ, 718, 446

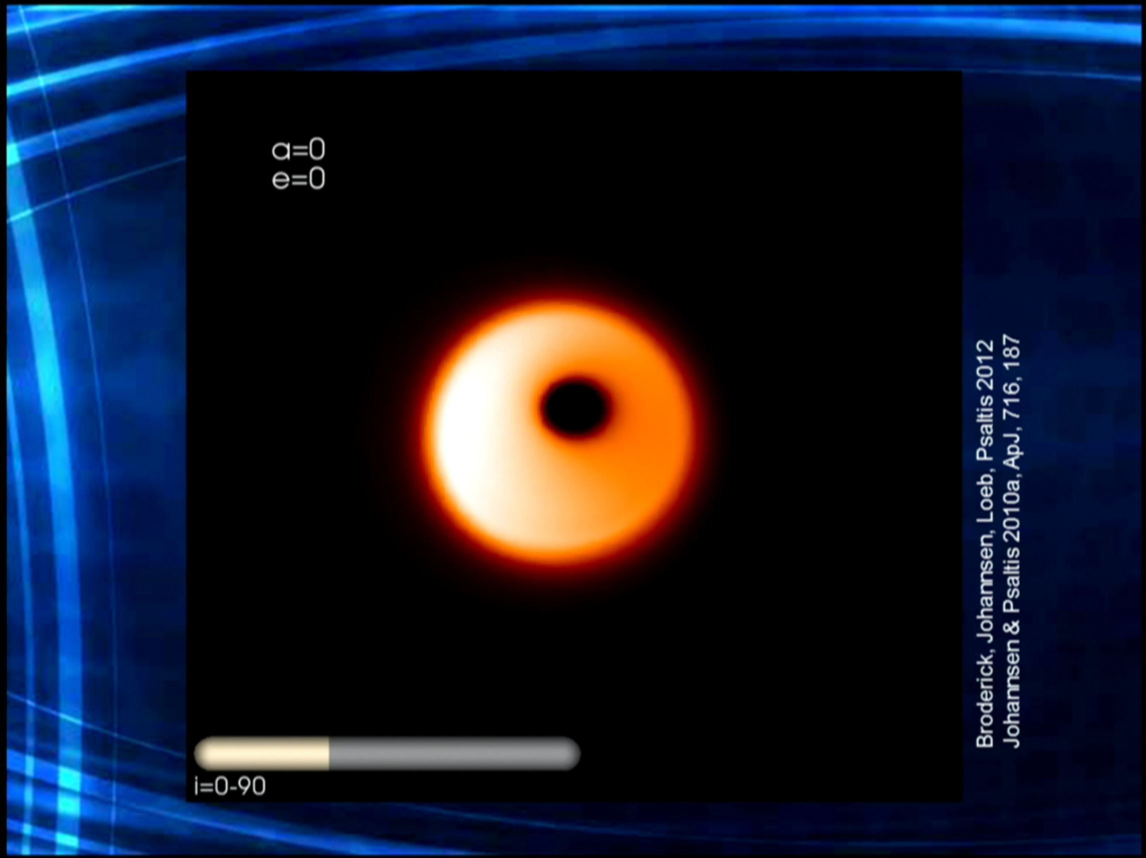
Spin and Quadrupole Deviation



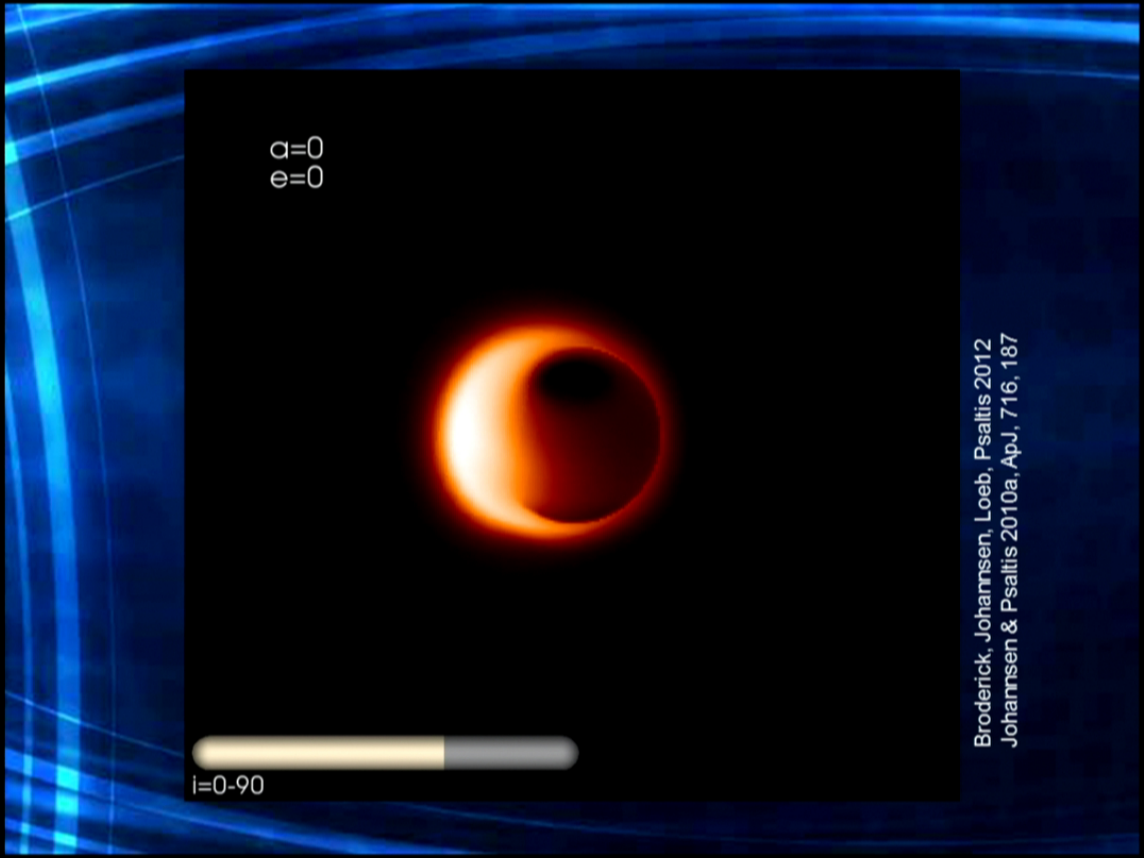
Broderick, Johannsen, Loeb, Psaltis 2012

Event Horizon Telescope





a=0
e=0
i=0-90
Broderick, Johannsen, Loeb, Psaltis 2012
Johannsen & Psaltis 2010a, ApJ, 716, 187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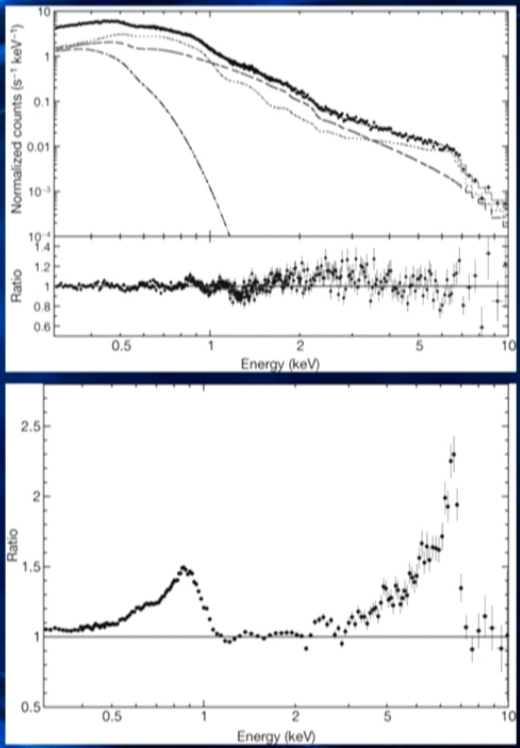
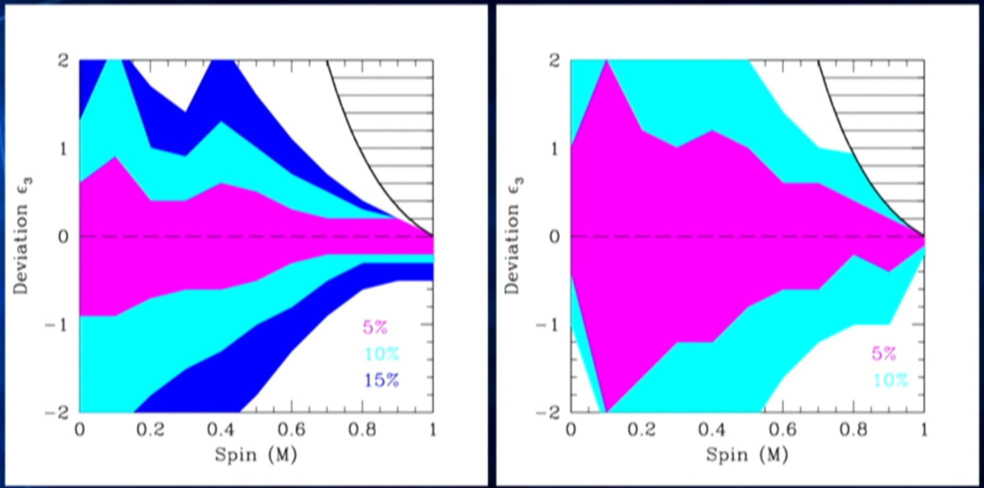


Iron K- and L- Lines in 1H0707-495

Fabian et al. 2009, Nature, 459, 540

Required Precision for Future Instruments

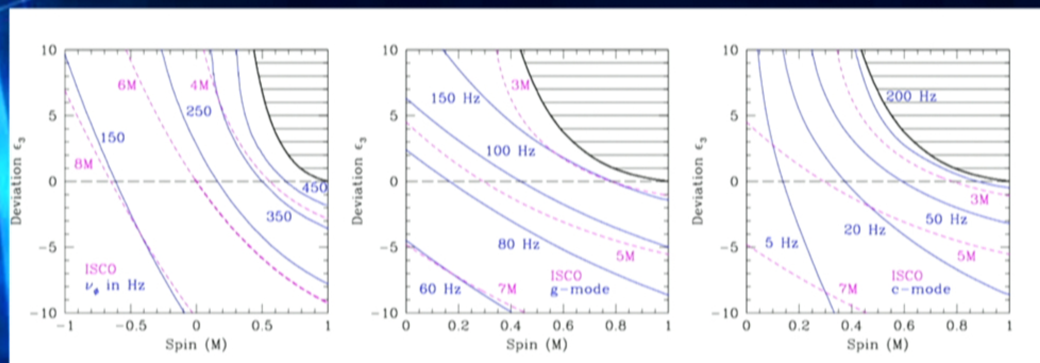


Inclination 30°   Inclination 60°

Johannsen & Psaltis, arXiv:1202.6069

3. Quasi-Periodic Variability

Johannsen & Psaltis, arXiv:1202.6069



Keplerian frequency

g-mode

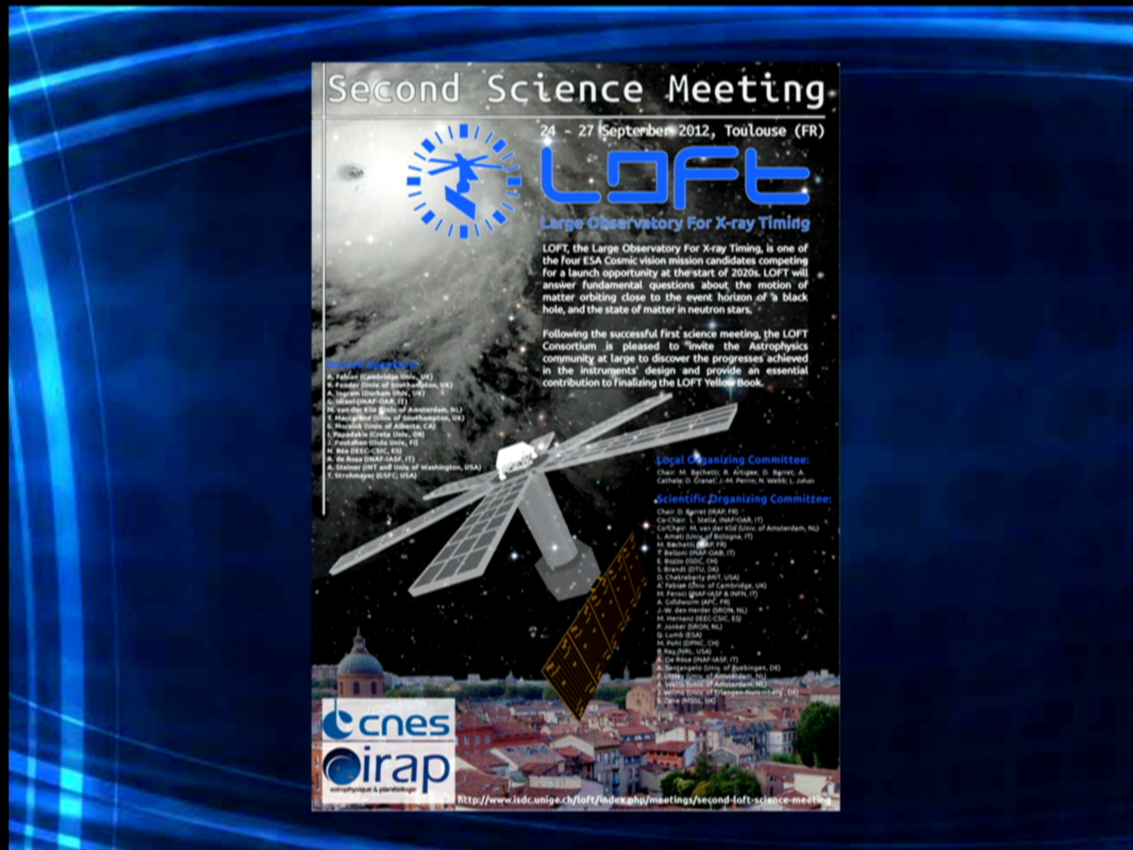
c-mode

Diskoseismology model:

Wagoner 2008,
New Astron. Rev., 51, 828

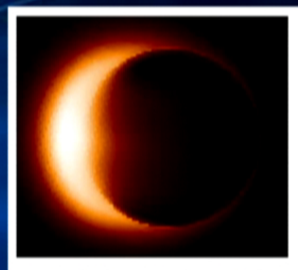
$$\frac{\kappa_{\max}}{2\pi}$$

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

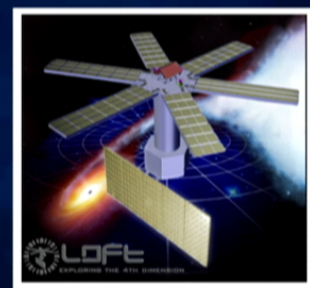


Second Science Meeting
24 - 27 September 2012, Toulouse (FR)
LOFT
Large Observatory For X-ray Timing
LOFT, the Large Observatory For X-ray Timing, is one of the four ESA Cosmic vision mission candidates competing for a launch opportunity at the start of 2020s. LOFT will answer fundamental questions about the motion of matter orbiting close to the event horizon of a black hole, and the state of matter in neutron stars.
Following the successful first science meeting, the LOFT Consortium is pleased to invite the Astrophysics community at large to discover the progresses achieved in the instruments' design and provide an essential contribution to finalizing the LOFT Yellow Book.
Local Organizing Committee:
Scientific Organizing Committee:
cnes
irap
http://www.isdc.unige.ch/loft/index.php/meetings/second-loft-science-meeting

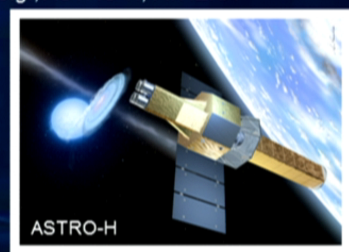
Observational Tests of the No-Hair Theorem



1. VLBI-Imaging of Sgr A*
   Event Horizon Telescope



2. Fluorescent Iron Lines
   e.g., ASTRO-H, ATHENA



3. Quasi-Periodic Variability
   e.g., LOFT