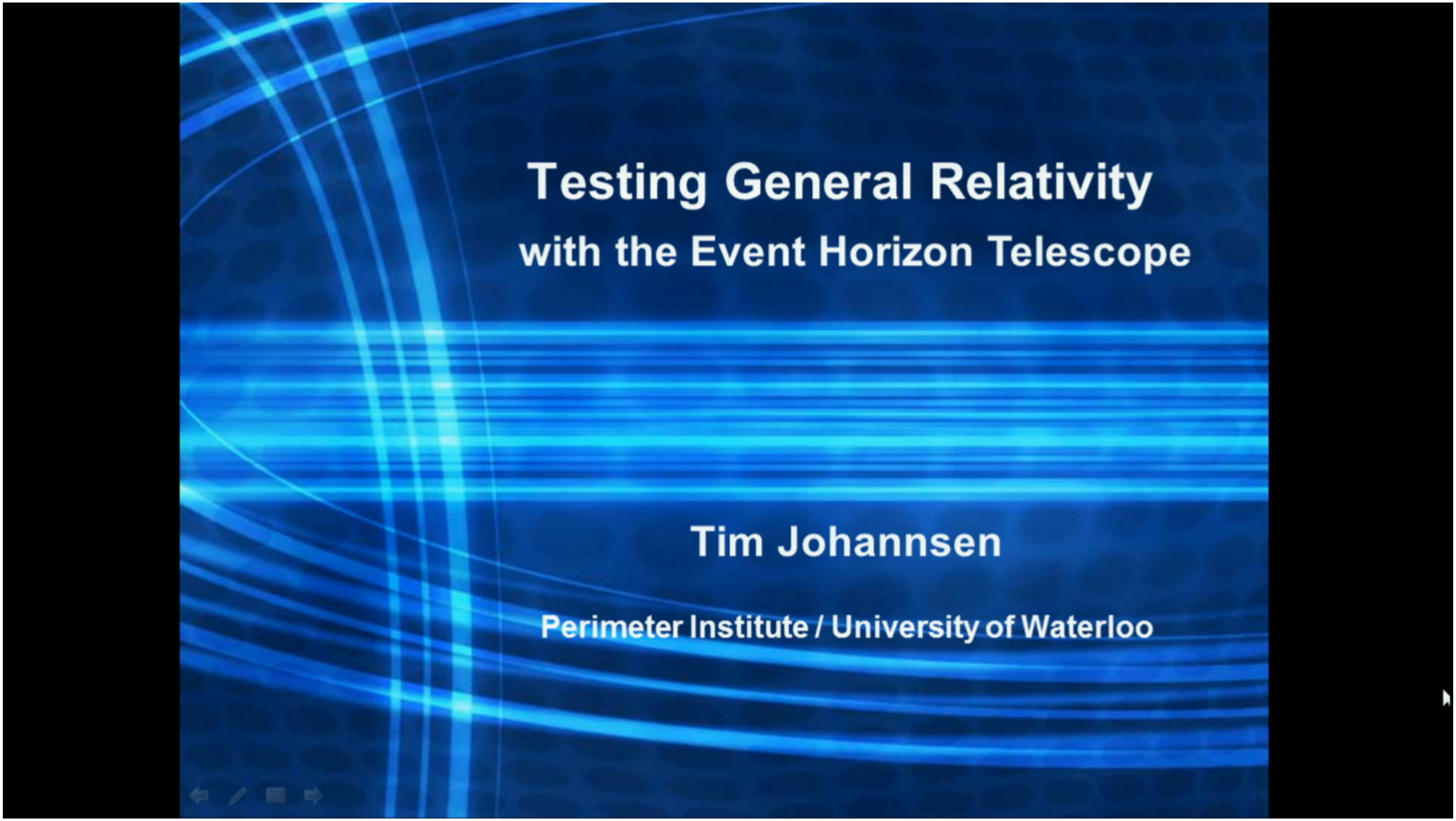
Title: Testing General Relativity with the EHT

Date: Nov 12, 2014 12:00 PM

URL: http://pirsa.org/14110093

Abstract: In general relativity, astrophysical black holes are characterized uniquely in terms of their masses and spins and are described by the Kerr metric. The high sensitivity and resolution of the EHT will allow for unprecedented tests of the Kerr nature of black holes and, hence, of general relativity. I will present current and future limits on deviations from the Kerr metric from Sgr A* in the context of radiatively-inefficient accretion flow models. I will also show how largely model-independent constraints on such deviations can be obtained from the angular diameter of the photon ring of Sgr A* in combination with existing mass and distance measurements. Finally, I will describe a new general framework for the parametrization of deviations from the Kerr metric.



Testing General Relativity
with the Event Horizon Telescope
Tim Johannsen
Perimeter Institute / University of Waterloo

The No-Hair Theorem

The Kerr solution is the only possible stationary axisymmetric metric in vacuum 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…

- Non-Kerr black holes in other gravity theories:
  Einstein-Dilaton-Gauss-Bonnet, Chern-Simons, Braneworld, Horava-Lifshitz,…
- Exotic objects, naked singularities?
- Kerr solution not unique to GR   Sotiriou & Faraoni 2012, PRL, 108, 081103

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 2010, 2011
Vigeland et al. 2011

Testing the No-Hair Theorem Observationally

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Vigeland et al. 2011

A New Metric for Rapidly Spinning Black Holes

$$
\begin{aligned}
ds^2 = &-\frac{\tilde{\Sigma}\left(\Delta - a^2 A_2(r)^2 \sin^2\theta\right)}{\left[\left(r^2+a^2\right)A_1(r) - a^2 A_2(r)\sin^2\theta\right]^2} dt^2 \\
&- \frac{a\left(\left(r^2+a^2\right)A_1(r)A_2(r) - \Delta\right)\tilde{\Sigma}\sin^2\theta}{\left[\left(r^2+a^2\right)A_1(r) - a^2 A_2(r)\sin^2\theta\right]^2} dt\,d\phi \\
&+ \frac{\tilde{\Sigma}}{\Delta A_5(r)} dr^2 + \tilde{\Sigma}\,d\theta^2 \\
&+ \frac{\tilde{\Sigma}\sin^2\theta\left(\left(r^2+a^2\right)^2 A_1(r)^2 - a^2\Delta\sin^2\theta\right)}{\left[\left(r^2+a^2\right)A_1(r) - a^2 A_2(r)\sin^2\theta\right]^2} d\phi^2
\end{aligned}
$$

$$\Delta \equiv r^2 - 2Mr + a^2$$

$$\tilde{\Sigma} \equiv r^2 + a^2\cos^2\theta + \sum_{n=3}^{\infty} \varepsilon_n \frac{M^n}{r^{n-2}}$$

$$A_1(r) \equiv 1 + \sum_{n=3}^{\infty} \alpha_{1n}\left(\frac{M}{r}\right)^n$$

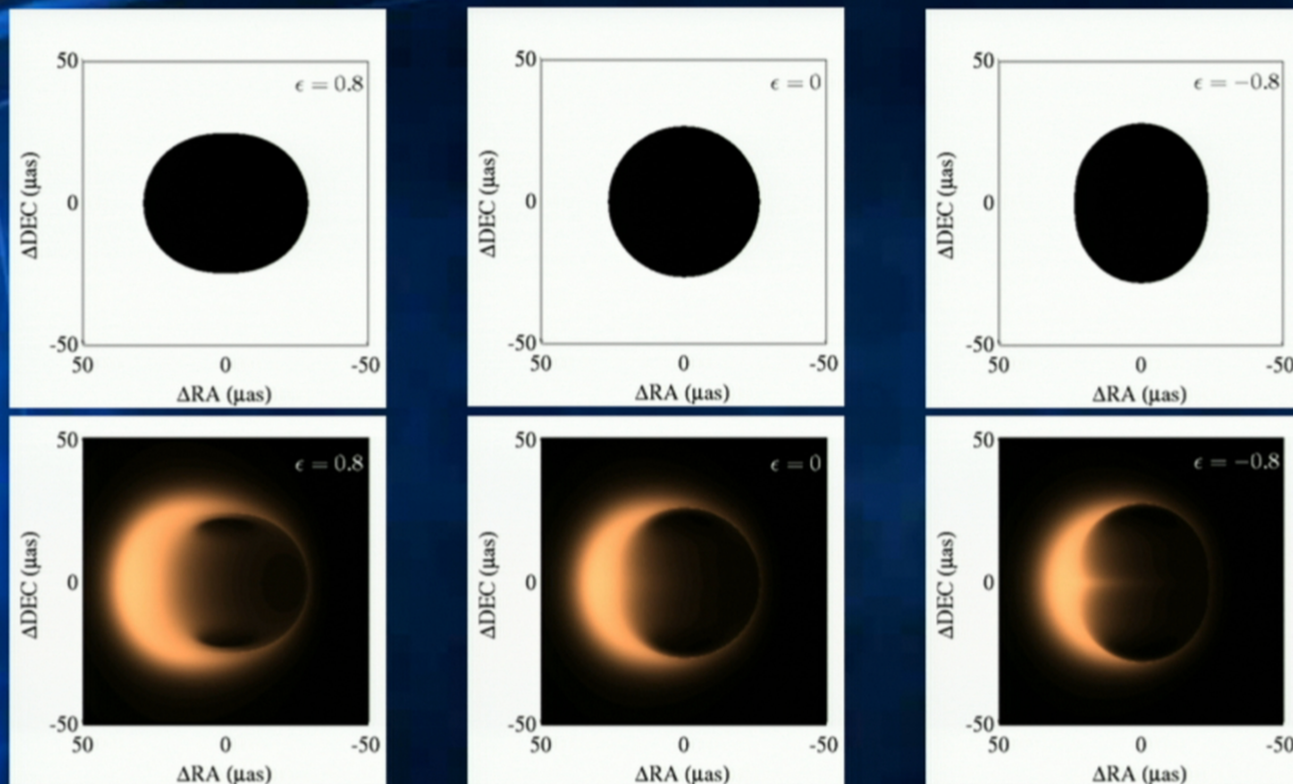
$$A_2(r) \equiv 1 + \sum_{n=2}^{\infty} \alpha_{2n}\left(\frac{M}{r}\right)^n$$

$$A_5(r) \equiv 1 + \sum_{n=2}^{\infty} \alpha_{5n}\left(\frac{M}{r}\right)^n$$

- Black hole, can be mapped to known non-GR black holes
- Spacetime symmetries: 4 deviation functions
- Suitable for GRMHD-type simulations

Johannsen 2013, PRD, 88, 044002

Imaging the Shadow of Sgr A*



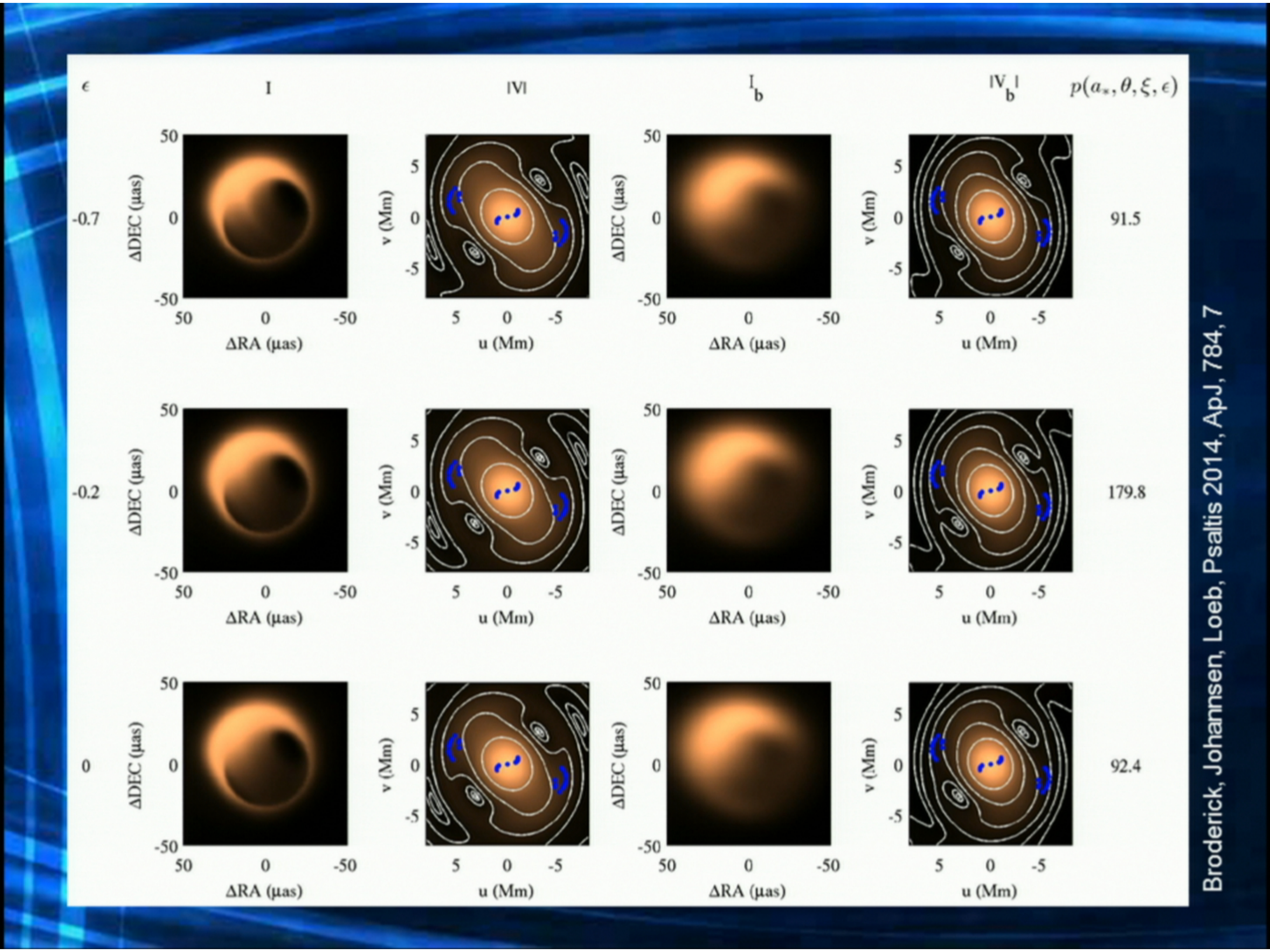
Broderick, Johannsen, Loeb, Psaltis 2014, ApJ, 784, 7

Shape of shadow depends uniquely on mass, spin, inclination

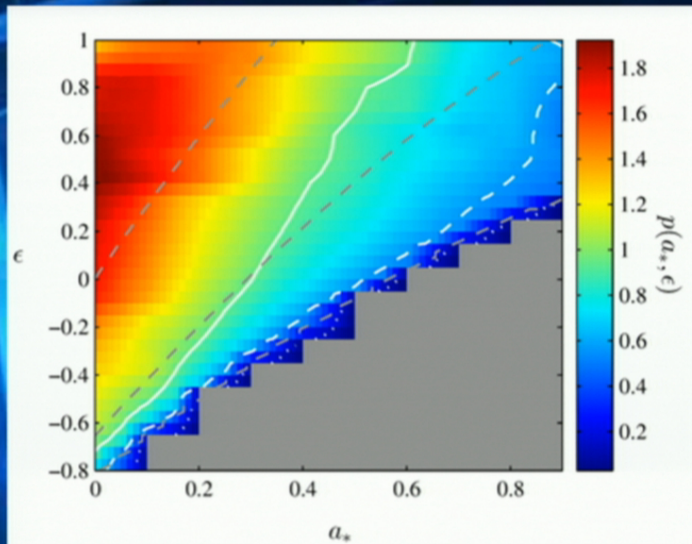
e.g., Falcke et al. 2000, ApJ, 528, L13

...as well as on quadrupole moment

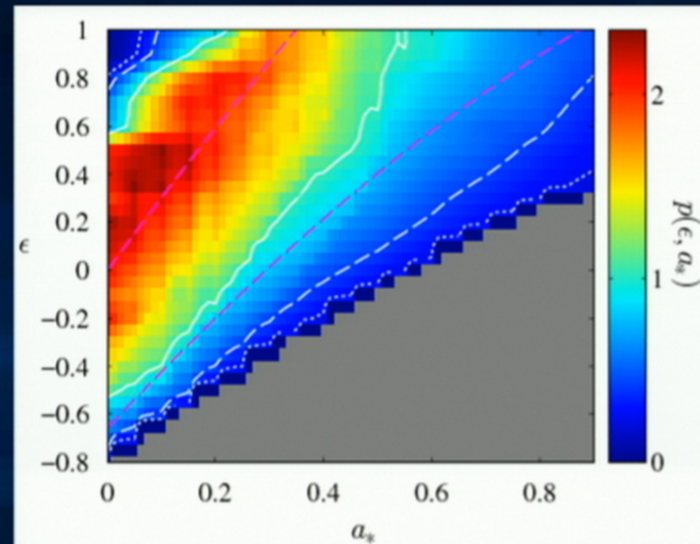
Johannsen & Psaltis 2010, ApJ, 718, 446


ϵ
I
|V|
I_b
$|V_b|$
$p(a_*, \theta, \xi, \epsilon)$
-0.7
91.5
-0.2
179.8
0
92.4
ΔDEC (μas)
ΔRA (μas)
v (Mm)
u (Mm)
Broderick, Johannsen, Loeb, Psaltis 2014, ApJ, 784, 7

Results – Current Data



Broderick, Johannsen, Loeb, Psaltis 2014, ApJ, 784, 7



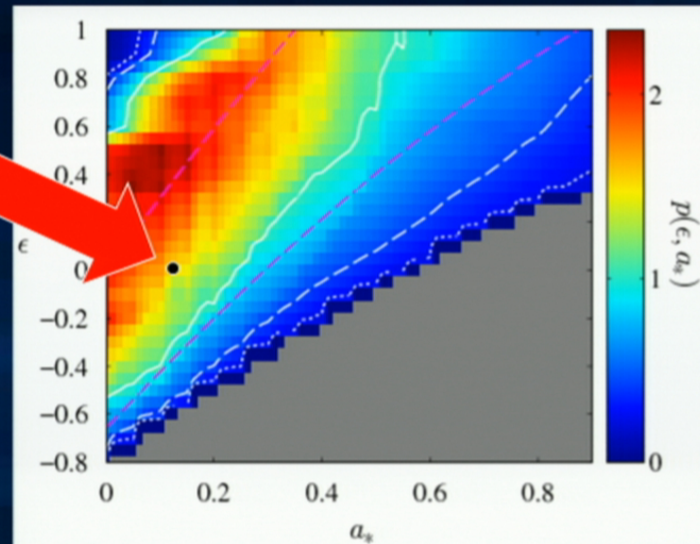
Johannsen, Wang, Broderick, et al. (in prep.)

Spin:	$a_* = 0.05^{+0.27}_{-0.15}$
Deviation:	**too weak**
Inclination:	$\theta = 65^{\circ}{}^{+21^{\circ}}_{-11^{\circ}}$
Position Angle:	$\xi = 127^{\circ}{}^{+17^{\circ}}_{-14^{\circ}}$

Spin:	$a_* = 0.05^{+0.30}_{-0.05}$
Deviation:	$\varepsilon = 0.50^{+0.45}_{-0.25}$ **(formally!)**
Inclination:	$\theta = 70.0^{\circ}{}^{+12.5^{\circ}}_{-2.5^{\circ}}$
Position Angle:	$\xi = 123^{\circ} \pm 7^{\circ} / 139^{\circ}{}^{+18^{\circ}}_{-1^{\circ}}$

Results – Current Data

FULL EHT !!!



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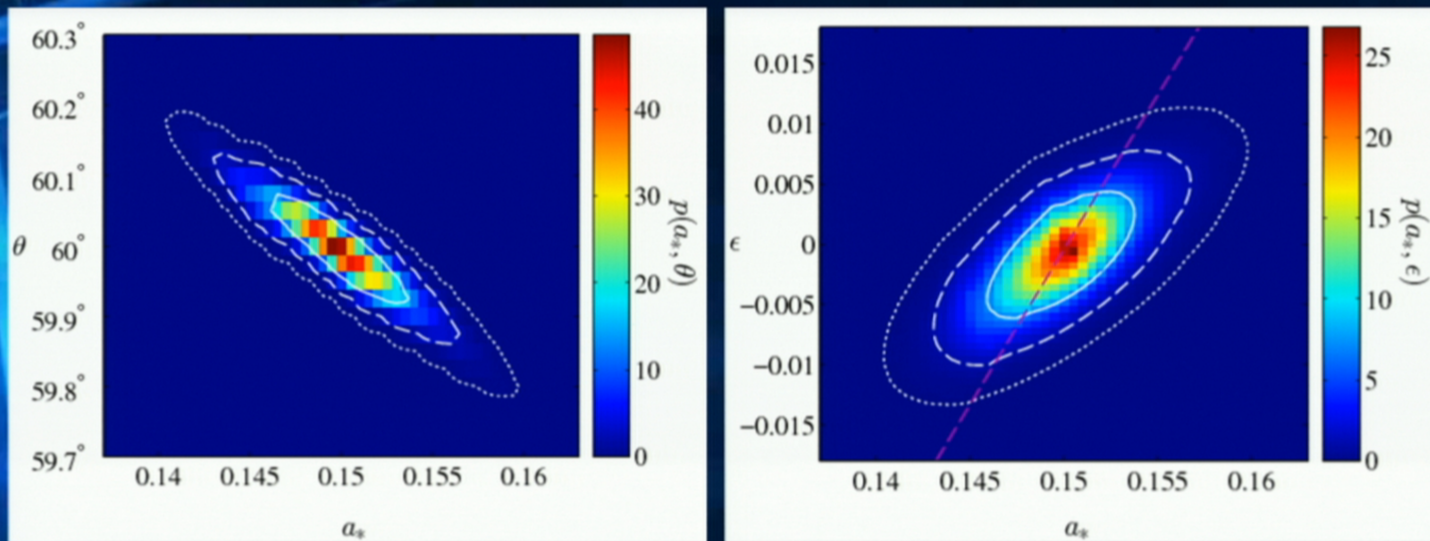
Results – Future Data



Johannsen, Wang, Broderick, et al. (in prep.)

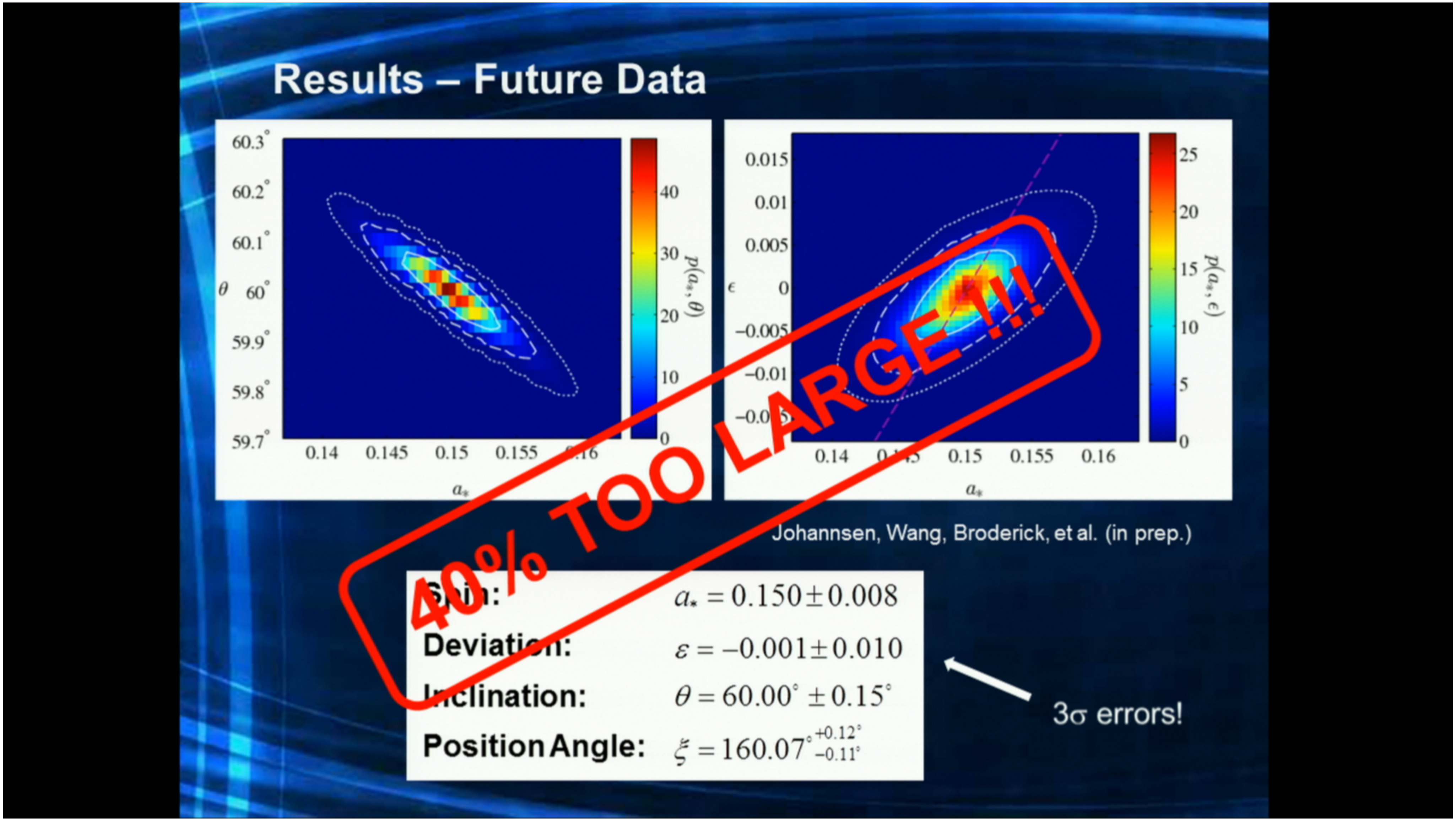
Spin: $a_* = 0.150 \pm 0.008$

Deviation: $\varepsilon = -0.001 \pm 0.010$

Inclination: $\theta = 60.00^\circ \pm 0.15^\circ$

Position Angle: $\xi = 160.07^{\circ}{}^{+0.12^\circ}_{-0.11^\circ}$

3σ errors!



Results – Future Data
60.3°
60.2°
60.1°
θ 60°
59.9°
59.8°
59.7°
0.14 0.145 0.15 0.155 0.16
a*
40
30
20
10
0
p(a*, θ)
0.015
0.01
0.005
ϵ 0
−0.005
−0.01
0.14 0.145 0.15 0.155 0.16
a*
25
20
15
10
5
0
p(a*, ϵ)
40% TOO LARGE!!!
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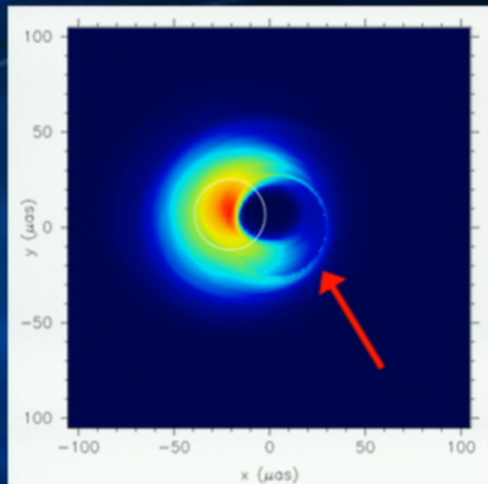
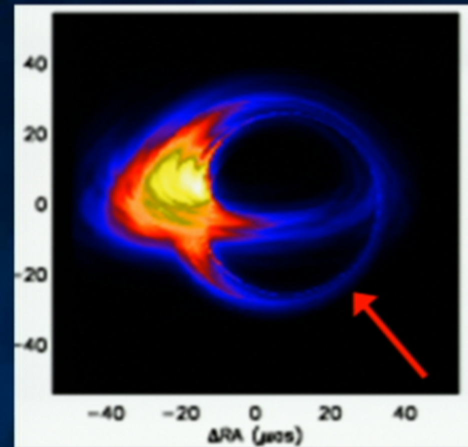
3σ errors!

The Photon Ring

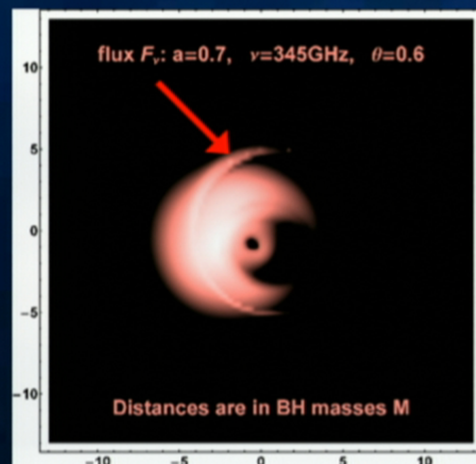


Moscibrodzka et al. 2009, ApJ, 706, 497



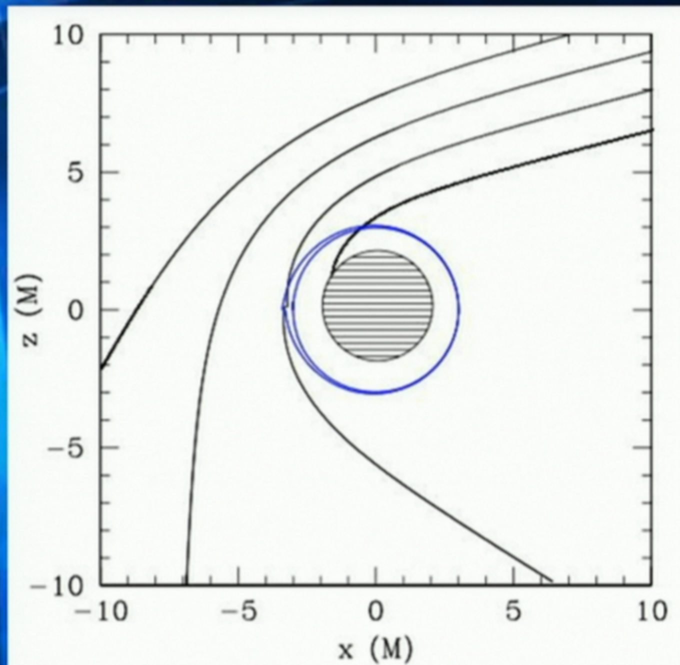
Dexter et al. 2009, ApJ, 703, L142

A ubiquitous signal, independent of the details of the accretion flow

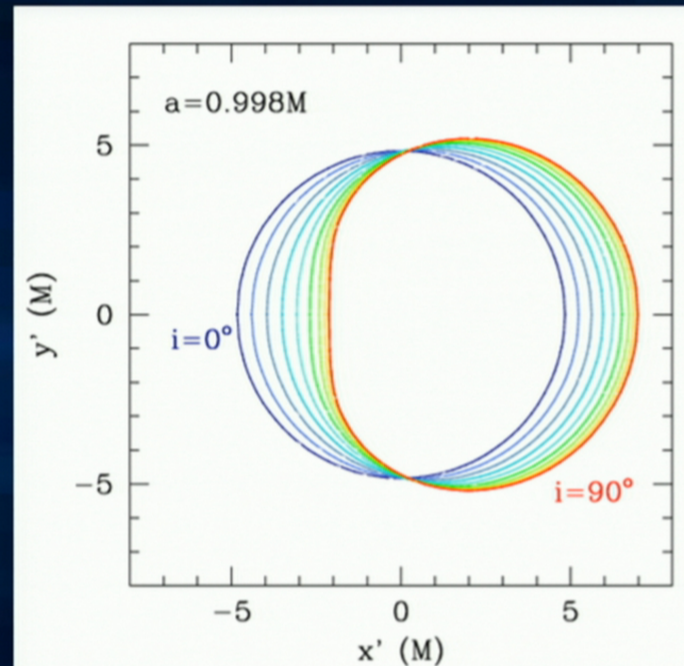


Shcherbakov & Penna 2011, ASP Conf. Ser., 439, 372

The Photon Ring



Johannsen & Psaltis 2010, ApJ, 718, 446

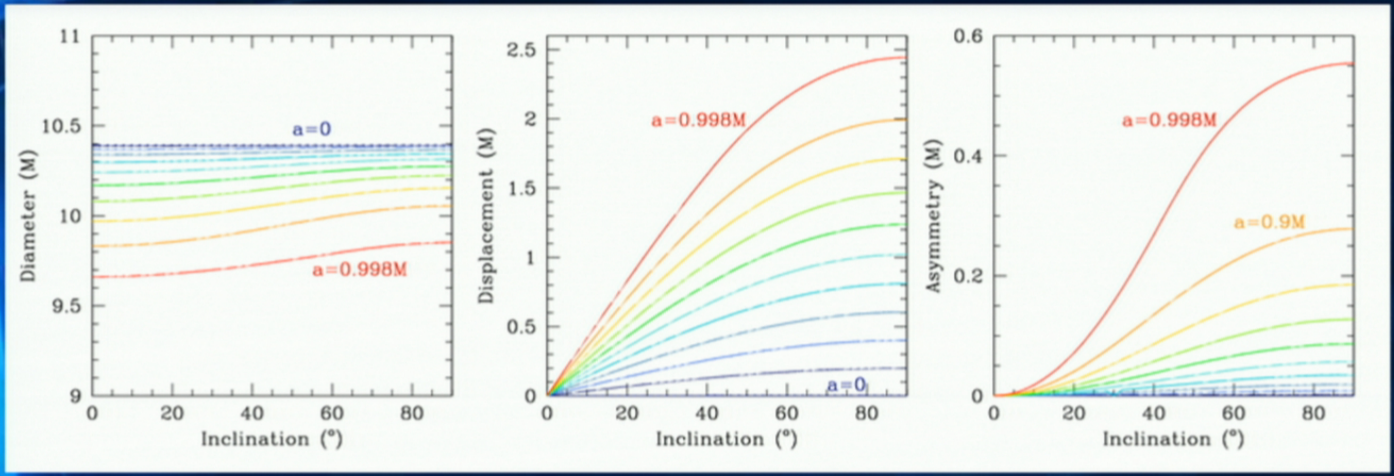


Chan, Psaltis & Özel 2013, ApJ, 777, 13
Johannsen 2013, ApJ, 777, 170

✓ clearly distinguishable from underlying accretion flow

✓ largely independent of flow turbulence and properties

Shape of Photon Ring (Kerr)



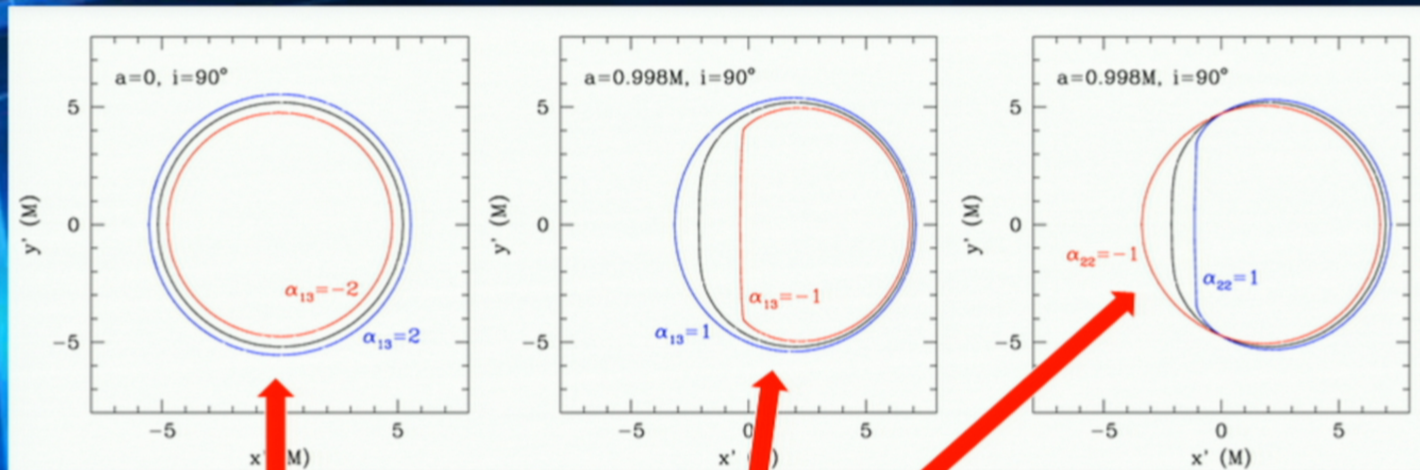
Johannsen 2013, ApJ, 777, 170
Chan, Psaltis & Özel 2013, ApJ, 777, 13
Johannsen & Psaltis 2010, ApJ, 716, 187

Diameter: measures mass/distance

Displacement: measures spin (in principle)

Asymmetry: negligible unless spin and inclination very large

Shape of Photon Ring (non-Kerr)

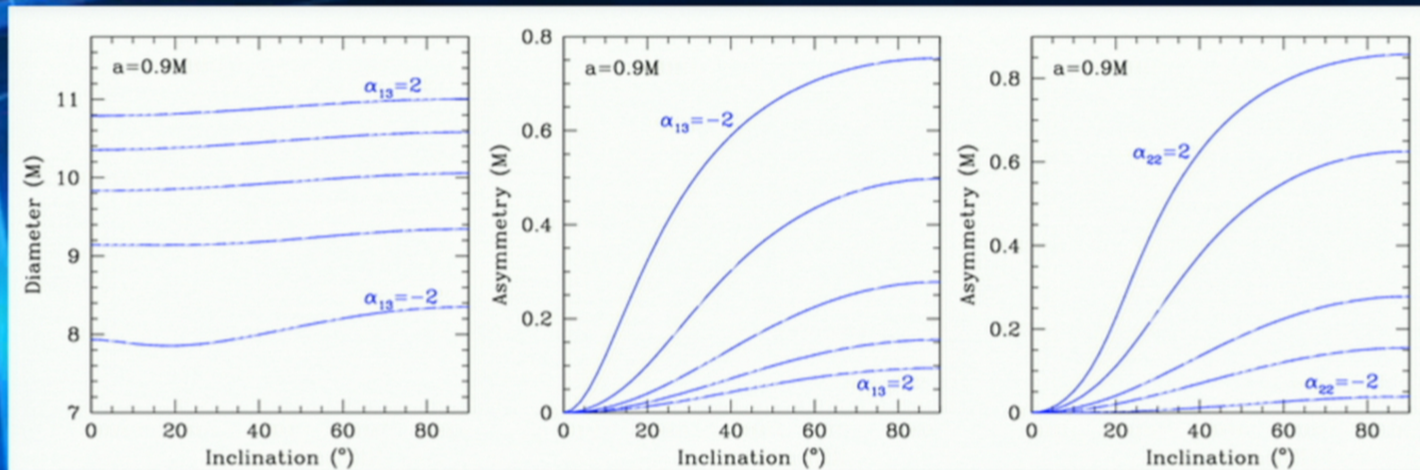


Johannsen 2013, ApJ, 777, 170
Johannsen & Psaltis 2010, ApJ, 716, 187

Ring Diameter varies!

Ring Shape becomes asymmetric!

Shape of Photon Ring (non-Kerr)



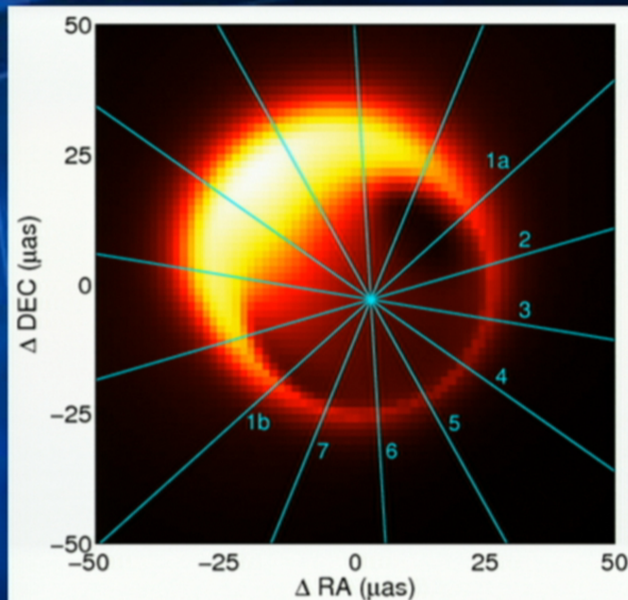
Johannsen 2013, ApJ, 777, 170
Johannsen & Psaltis 2010, ApJ, 716, 187

Diameter: measures mass/distance and deviation α_{13}

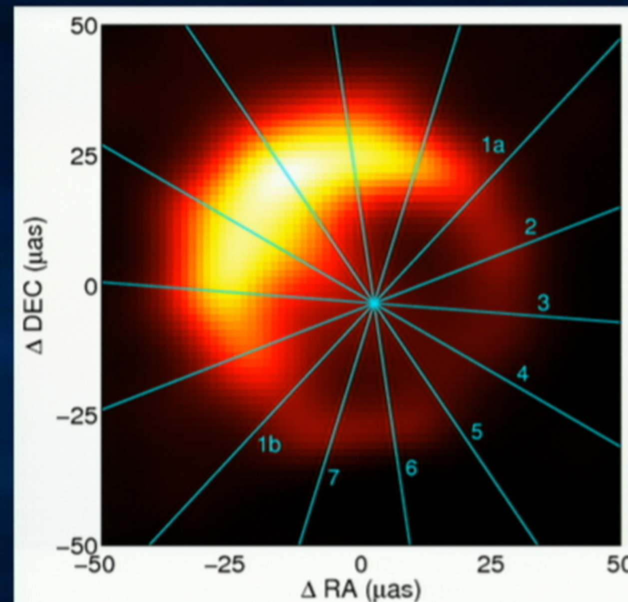
Asymmetry: measures deviations α_{13} and α_{22}

Ring asymmetry and disproportionate ring size are direct measures of a violation of the no-hair theorem!

Measuring the Ring Diameter



Theoretical Image



Reconstructed Image

(preliminary)

Angular Diameter: ±0.94 μas

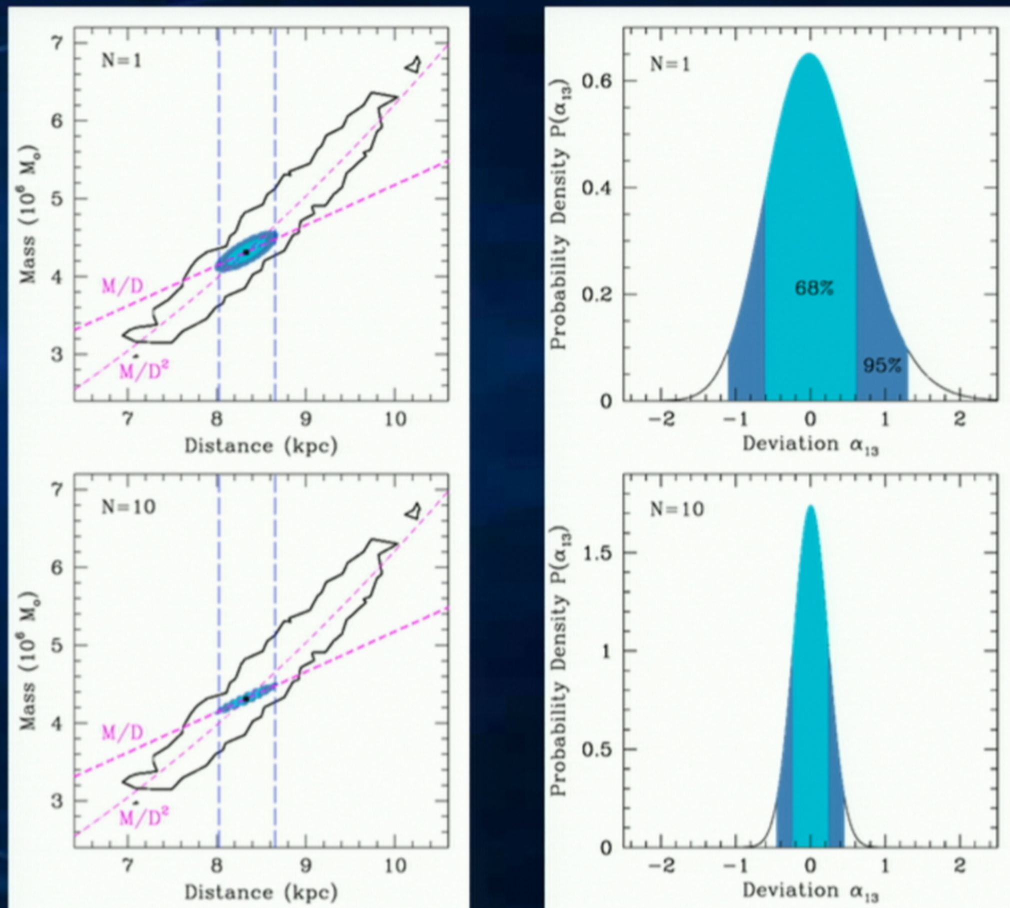
Johannsen, Broderick, Gillessen, et al. (in prep.)

Images from Fish, Johnson, Lu, et al. 2014, ApJ, 795, 134; see M. Johnson's talk on Friday!

Also: Pattern Matching Technique

Psaltis, Özel, Chan & Marrone, arXiv:1411.1454; see D. Psaltis' talk this afternoon!

Ring Diameter + Mass, Distance Measurements



(preliminary)

Johannsen, Broderick, Gillessen, et al. (in prep.)
Psaltis, Özel, Chan & Marrone, arXiv:1411.1454
Johannsen, Psaltis, Gillessen, et al. 2012, ApJ, 758, 30

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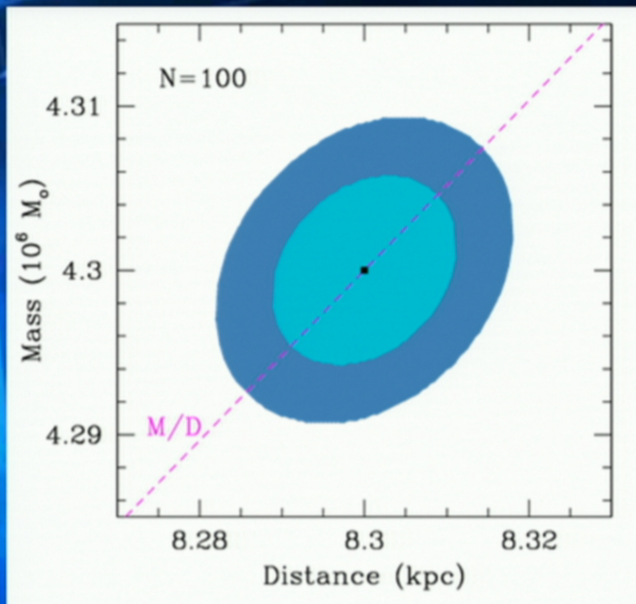

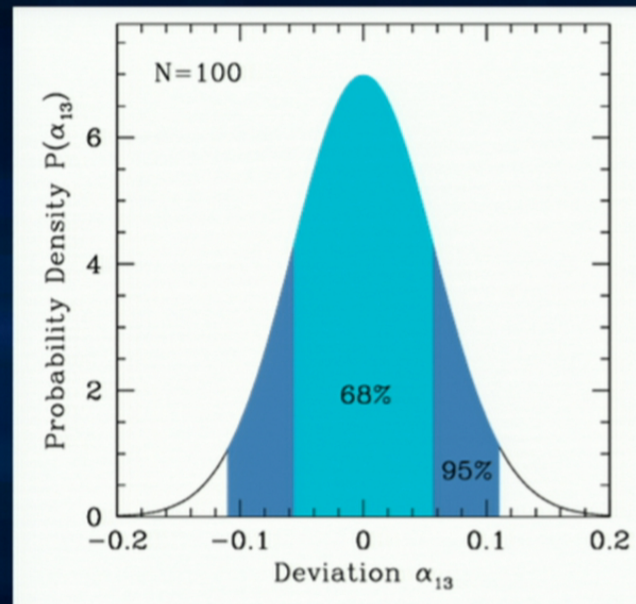

(preliminary)

Johannsen, Broderick, Gillessen, et al. (in prep.)

30m-class telescope: ΔM, ΔD ~0.1%

Weinberg, Milosavljević & Ghez 2005, ApJ, 622, 878

Testing General Relativity with the EHT

- With the EHT we are entering an era of high-precision strong gravity measurements!
- New Kerr-like black hole metric
- 2 scenarios: RIAF images and the photon ring
- Current and future constraints on potential deviations from GR
- Photon ring: asymmetric shape and disproportionate size = smoking guns of GR violation