Resolving the Space-Time Around Black Holes

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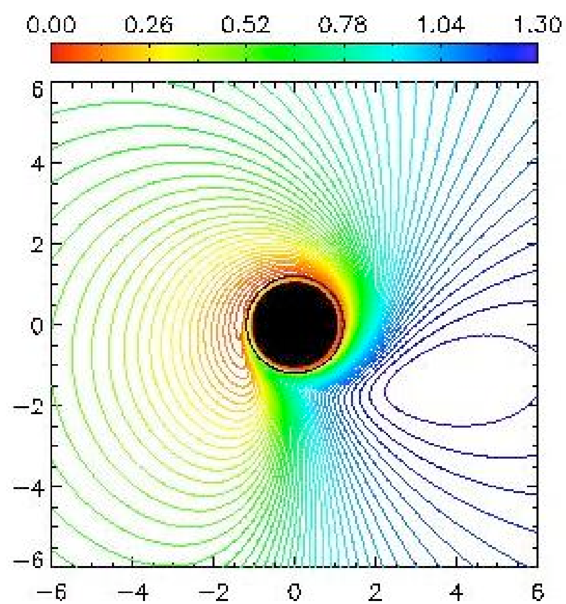


Image from Dovciak et al. (2004)

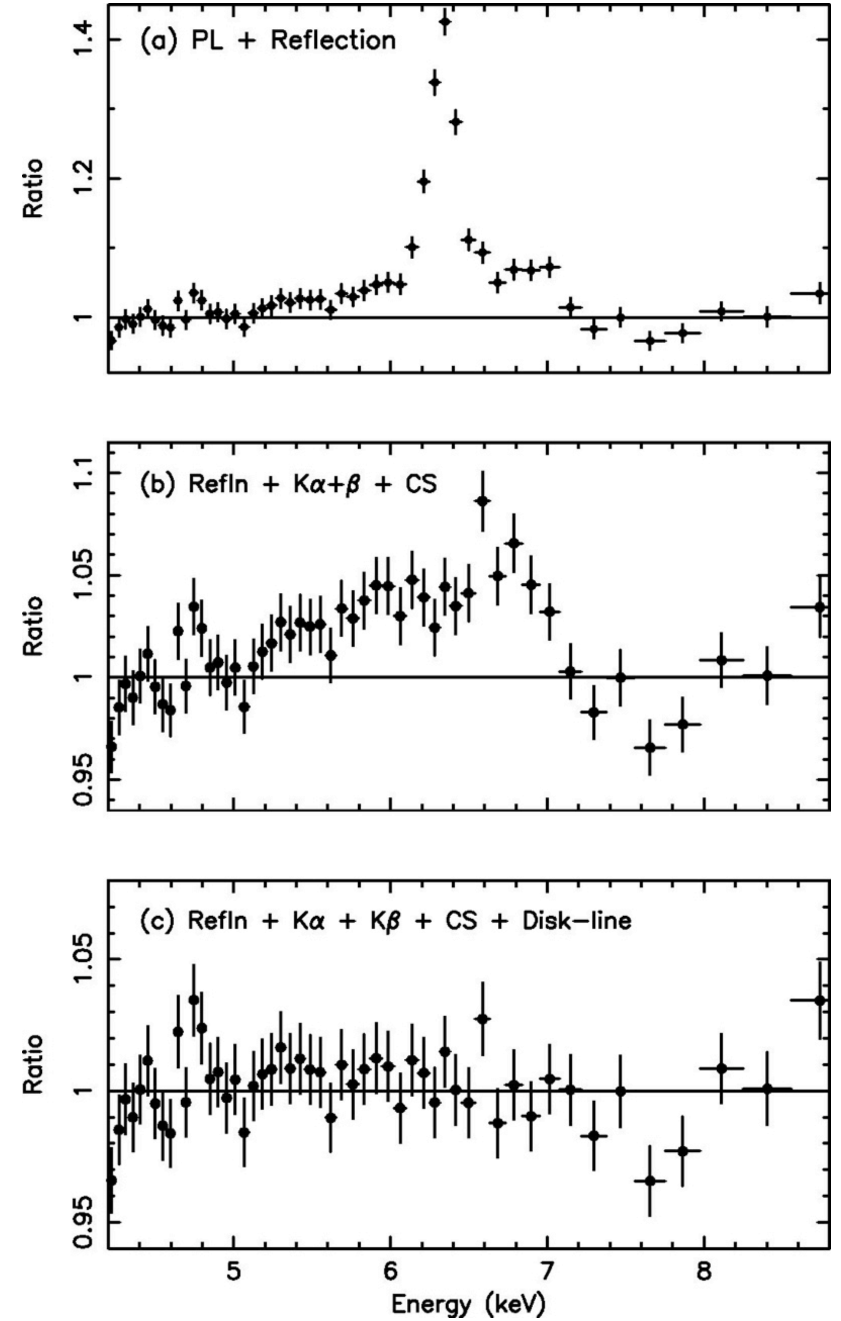
Introduction

- Black holes are defined by their mass, charge, and angular momentum (spin)
- Determining the spin is important for mapping the metric of the black hole
- Fe K emission line in the X-ray band is an important probe of the region near the black hole
- We investigate the capabilities of future missions to robustly measure spin independent of spatial emissivity of the disk (e.g. the effects of spatial emissivity are degenerate with spin)
- We discuss the accuracy of currently available spectral fitting routines to measure spin from future observations

Fe K Line Profiles

Radially Integrated Disk Emission

- What can be measured?
  - Disk Inclination Angle: mainly from blue wing
  - BH Spin: mainly from red wing
- BUT the measurements also depend on:
  - Radially emissivity of the disk
  - Ionization state of Fe
  - Complex continuum modeling
  - Inclusion of possible emission from inside marginally stable orbit



MCG -5-23-16, Reeves et al (2007)

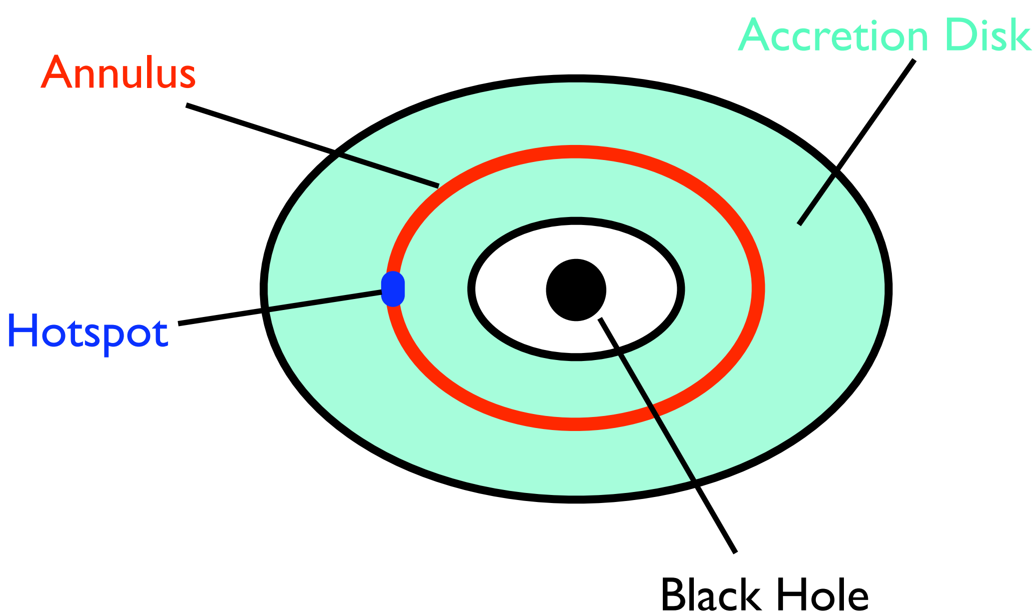
Measuring Black Hole Spin

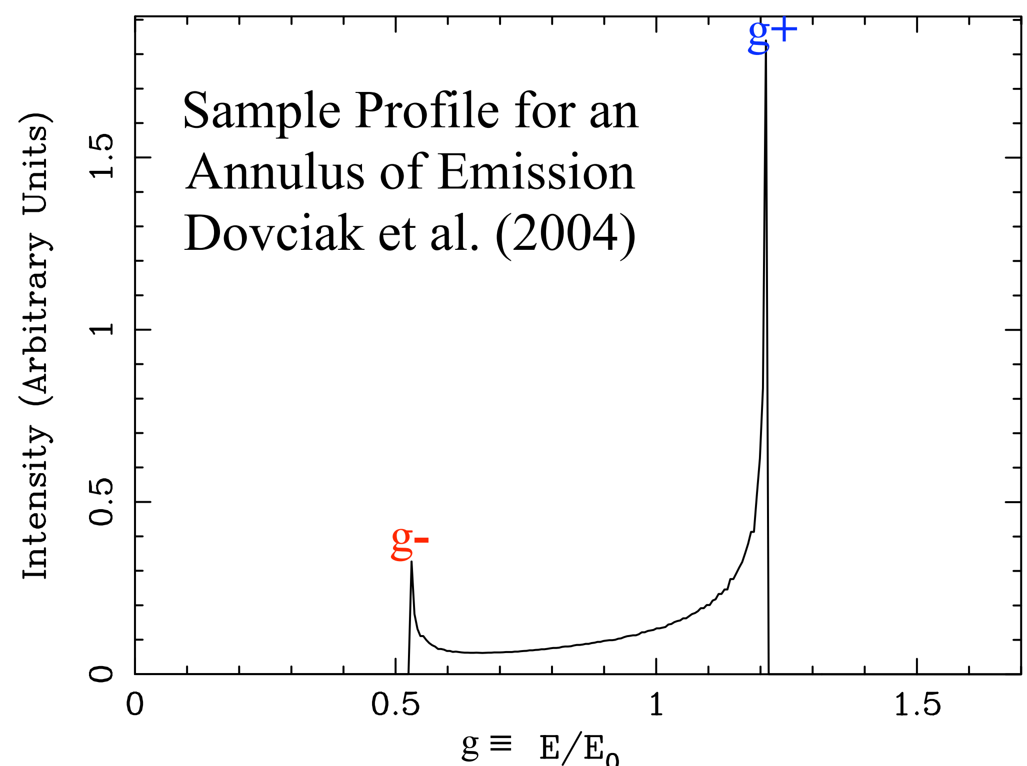
- Suppose there is a local magnetic flare ("hot spot") within tens of gravitational radii or less from the black hole.

- If the hot spot co-rotates with the disk for at least one orbit forming a thin annulus ⇒ two sharp spikes from enhanced region over the time-averaged line profile (corresponding to extreme red- and blue-shifts of hot spot)

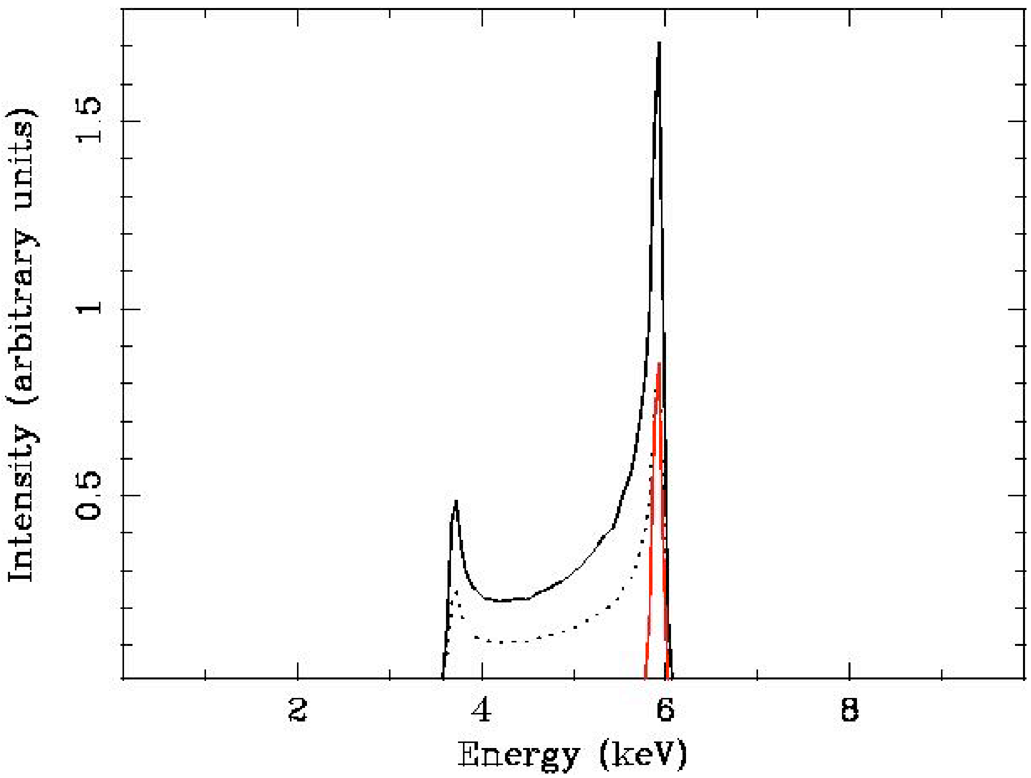
    - Each peak is a function of radius, spin, and disk inclination angle

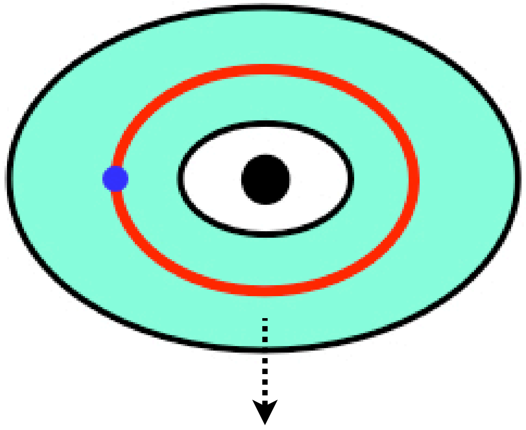
    - Independently measure inclination ⇒ constrain radius and spin





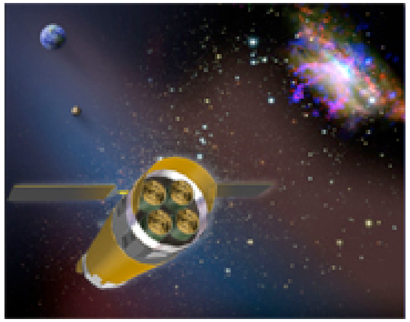
Hot Spot Emission



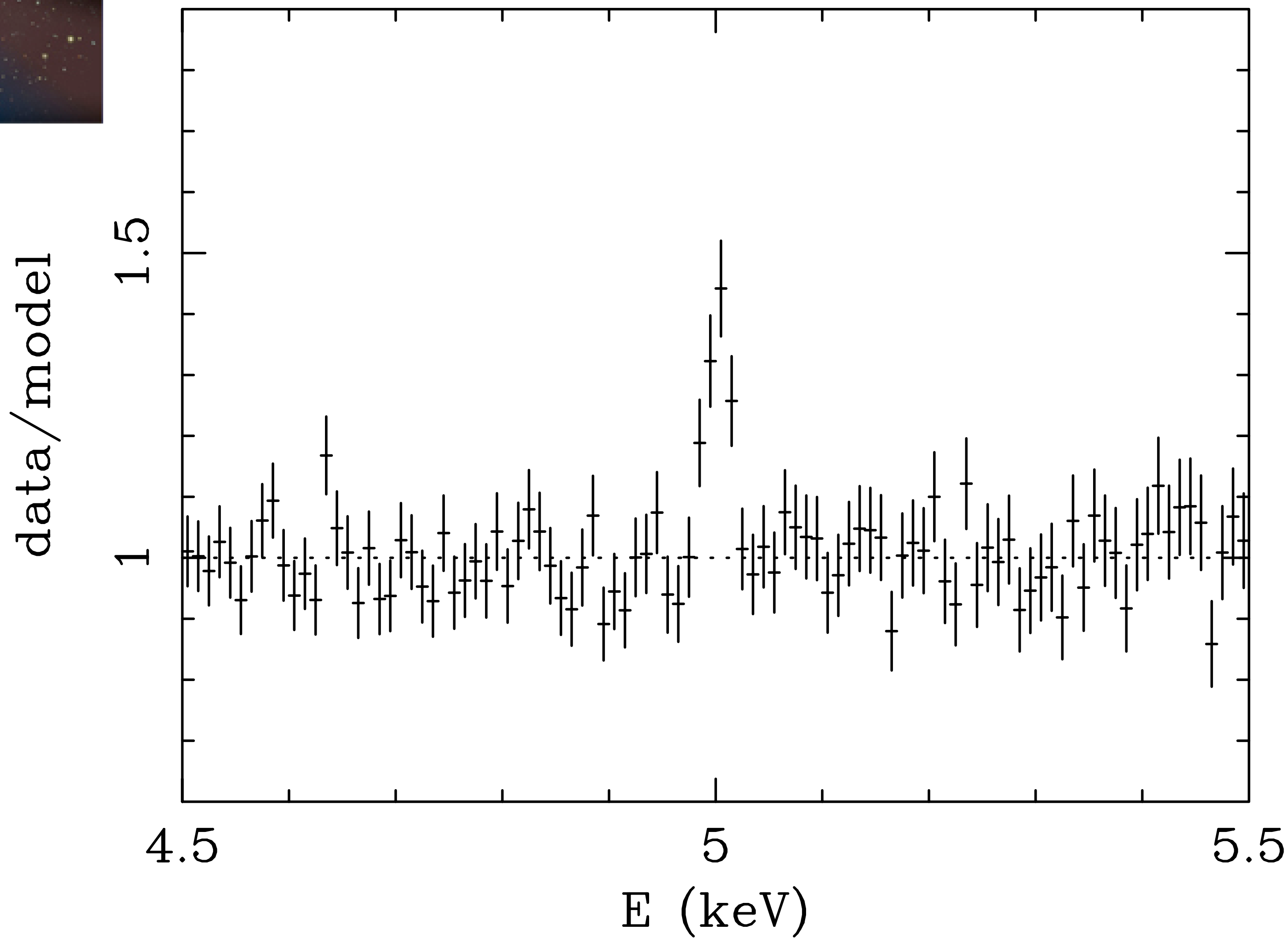


Keplerian Orbital Timescales

	$10^6 M_\odot$	$10^7 M_\odot$	$10^8 M_\odot$	$10^9 M_\odot$
$6r_g$	140 s	1.4 ks	0.17 d	1.7 d
$10r_g$	320 s	3.2 ks	0.37 d	3.7 d
$20r_g$	894 s	8.9 ks	1.0 d	10.4 d
$100r_g$	10 ks	1.2 d	11.6 d	115.7 d
$1000r_g$	3.7 d	36.6 d	366 d	10 years



Constellation-X Simulation



- Simulation of 5 ks observation, I = 10% of main line ($5x10^{-6}$ ergs s^{-1})
- Measurement of line energy in this example is dominated by energy scale systematics (~1 eV), not statistics

Observational Evidence of Hot Spots

- Many cases of claimed "hot spot" emission in AGN spectra:

  MCG -6-30-15 (Iwasawa et al 1999)

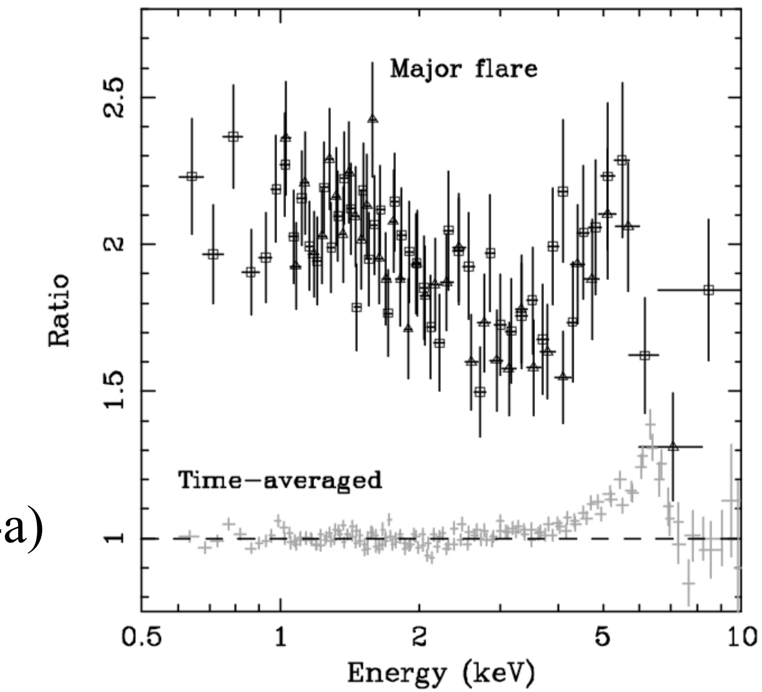
  ESO 198-G24 (Guainazzi 2003)

  NGC 3516 (Turner et al 2002, Iwasawa et al 2004a)

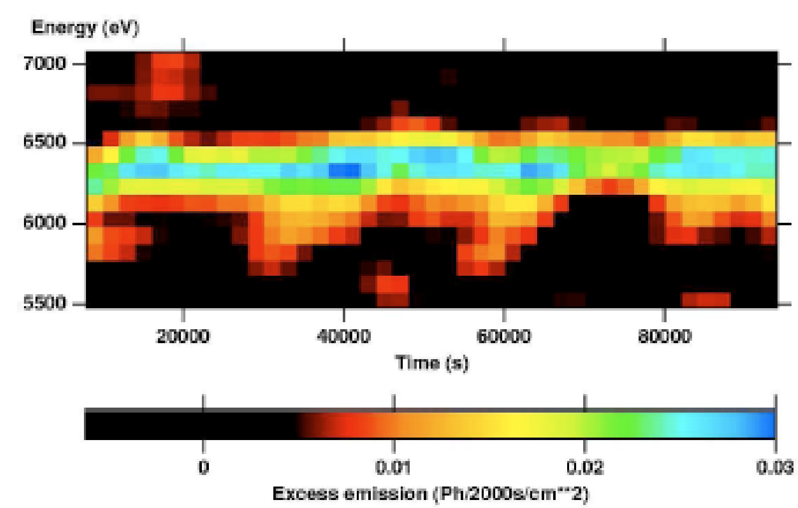
  IRAS 18325-5926 (Iwasawa et al 2004b)

  Mkn 766 (Turner et al 2006)

- Simulations show *Constellation-X* will easily be able to measure the energies of the spikes ($E_{\rm min}$ and $E_{\rm max}$), even for weak hot spots

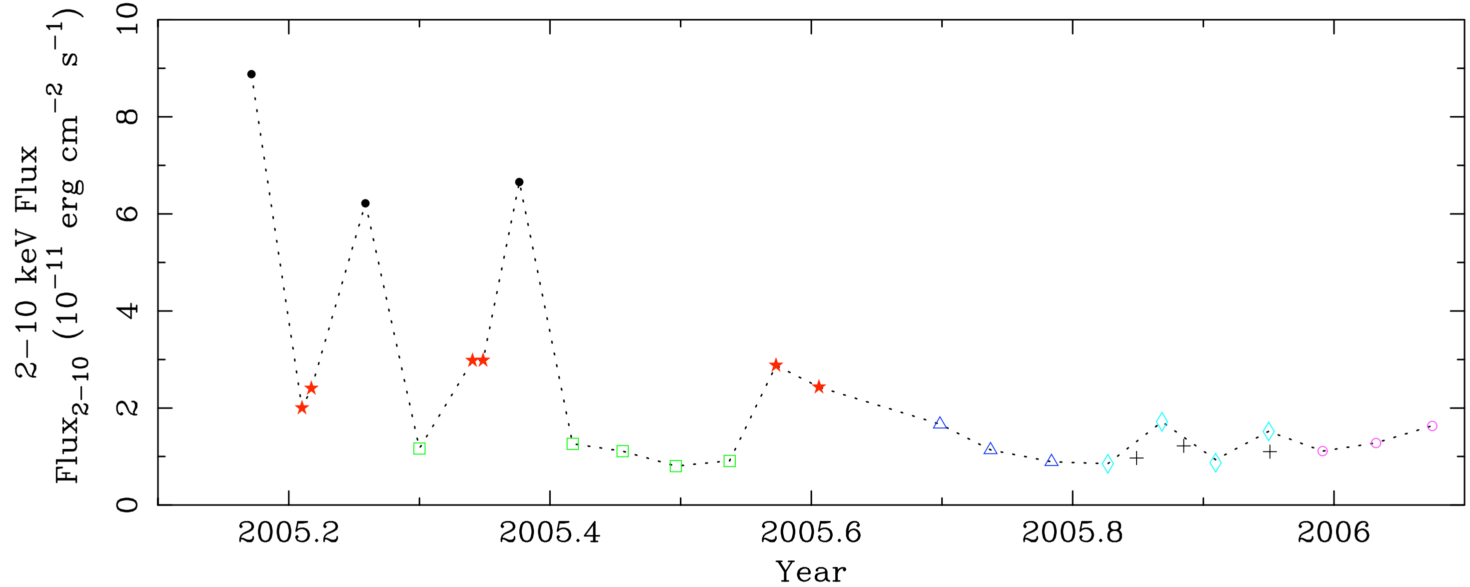


MCG -6-30-15, Iwasawa et al (1999)

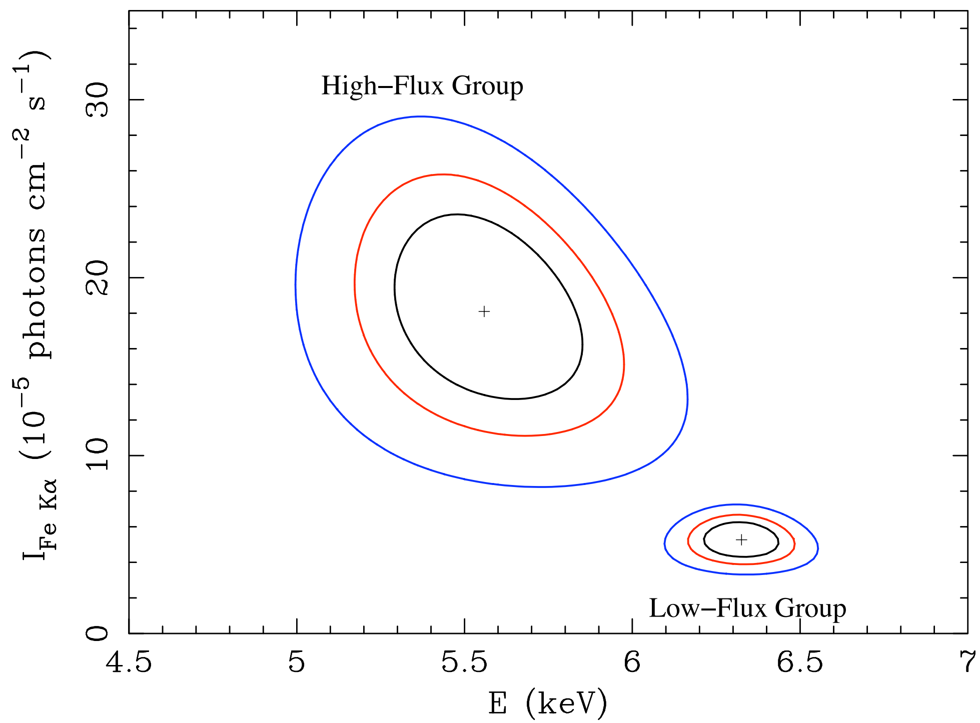


NGC 3516, Iwasawa et al (2004)

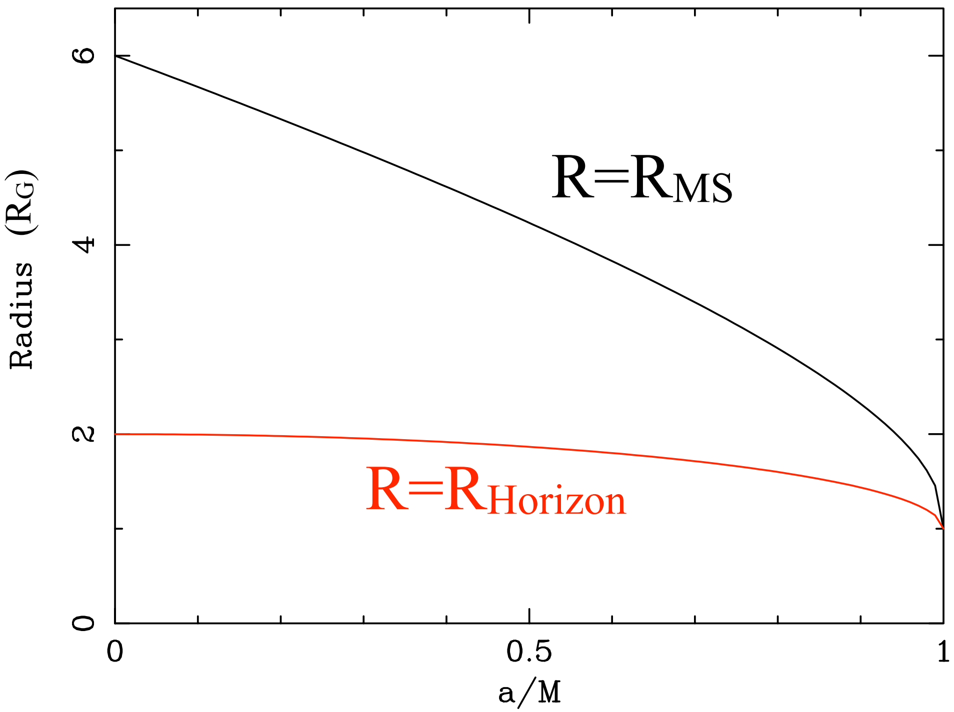
Observational Evidence

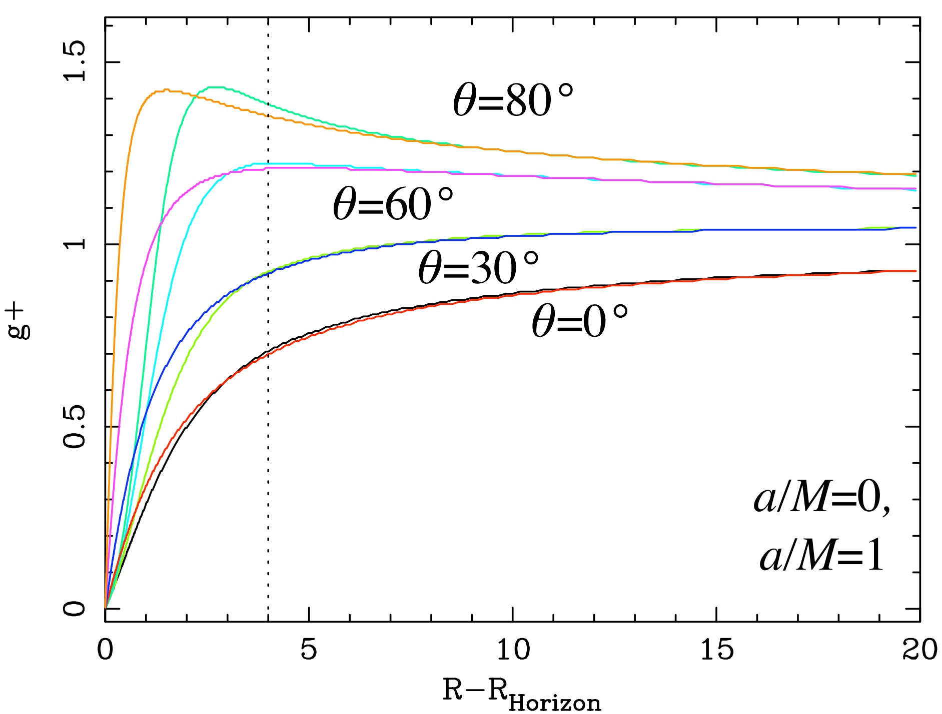


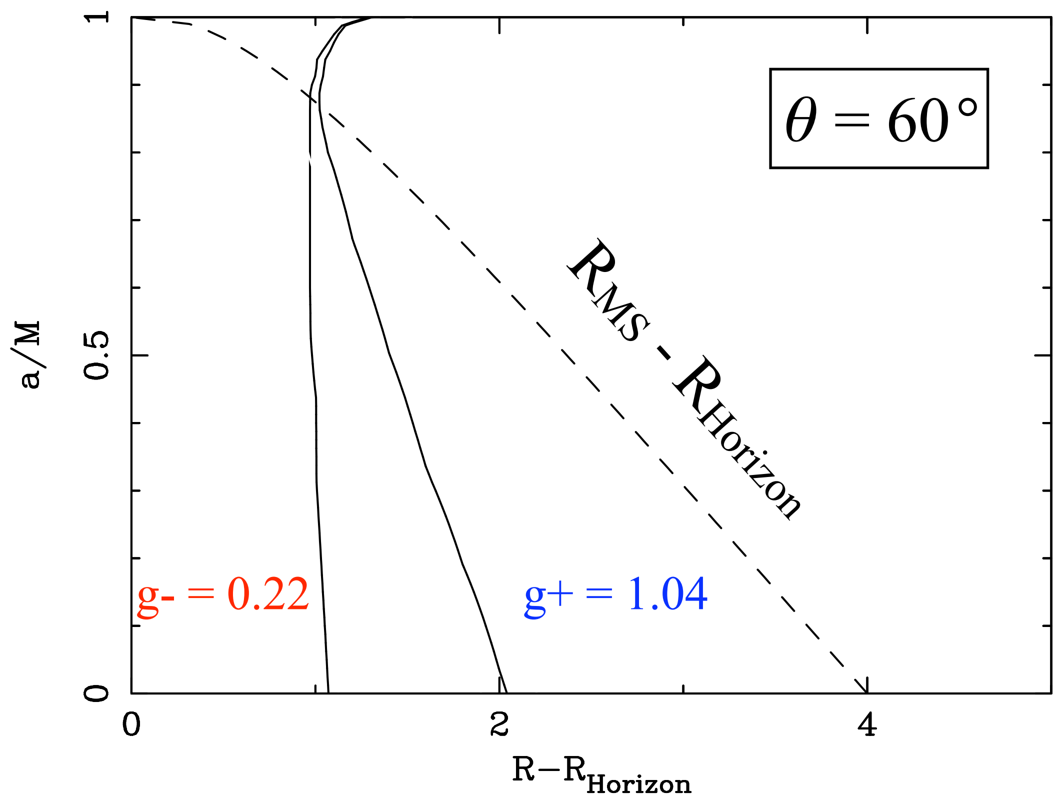
- Year-long observation campaign of **NGC 2992** with *RXTE*
- Flux varied by a factor of ~10 on short timescales (days-weeks)
- During the 3 highest-flux observations, a highly redshifted (E~5.6 keV), broadened Fe Kα line dominated ⇒ emission originated close to the black hole



Murphy et al (2007)

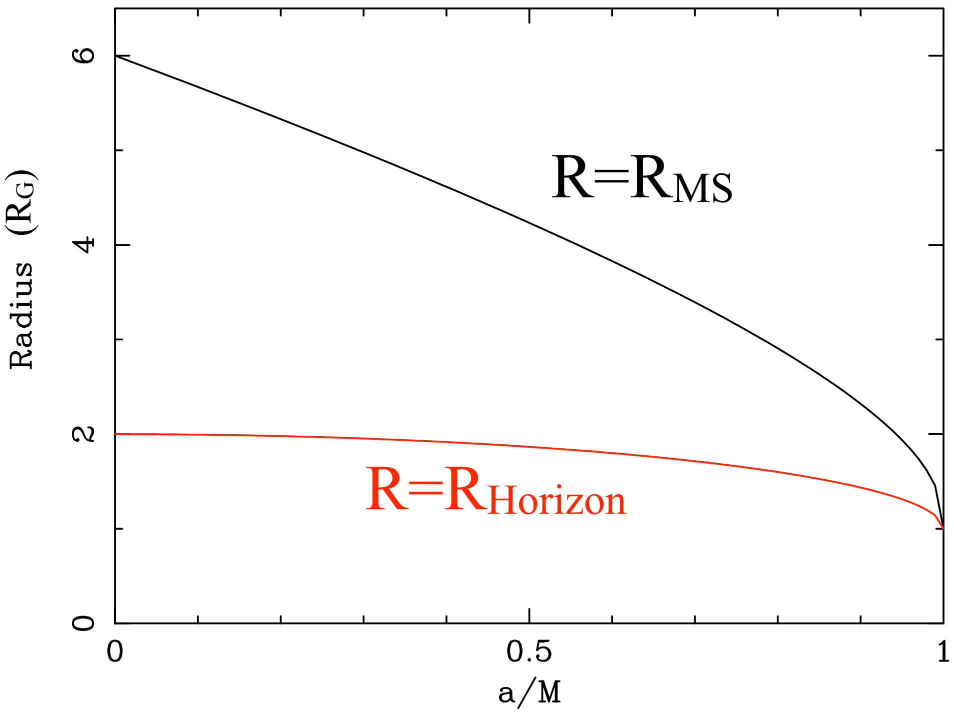


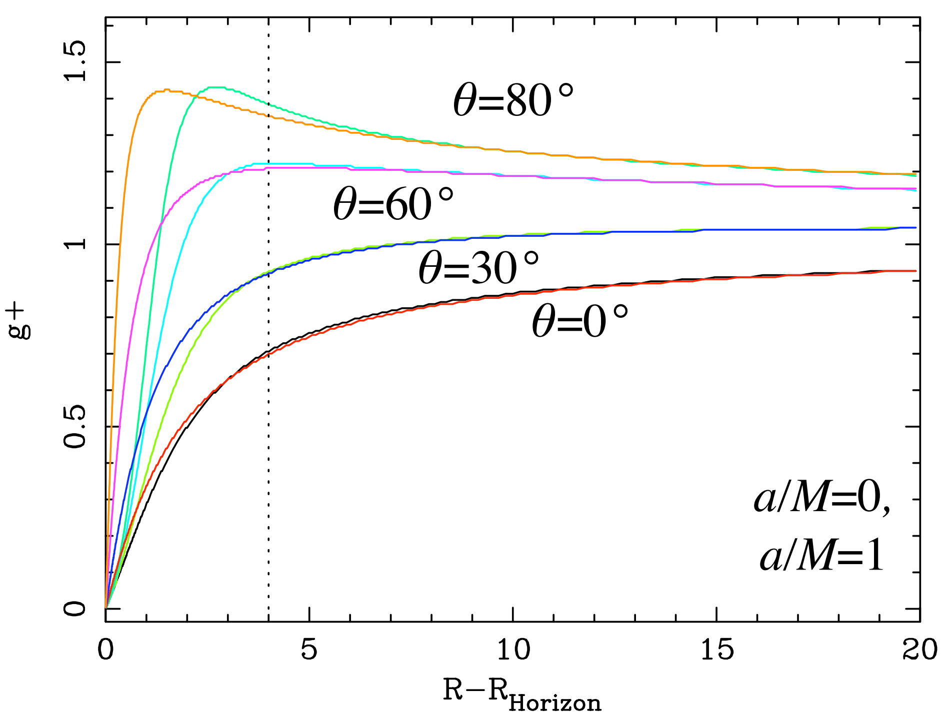




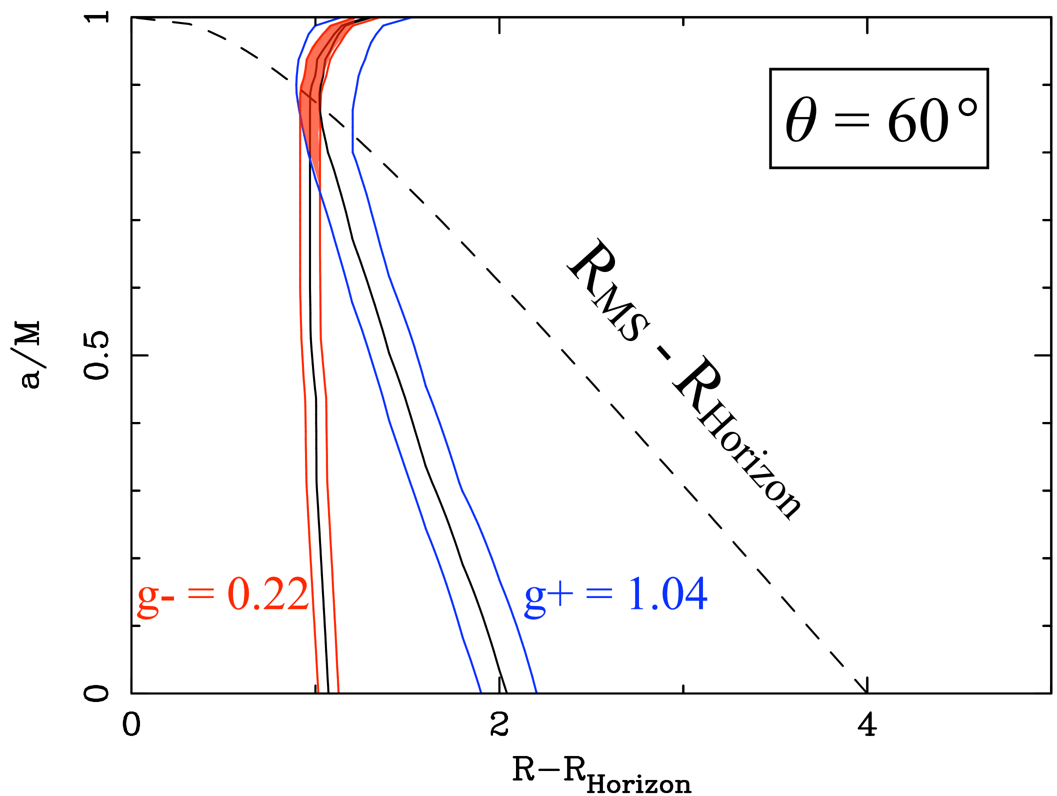
$\Rightarrow a/M \sim 1,$

$R\text{-}R_{\mathrm{H}} \sim 1.2$





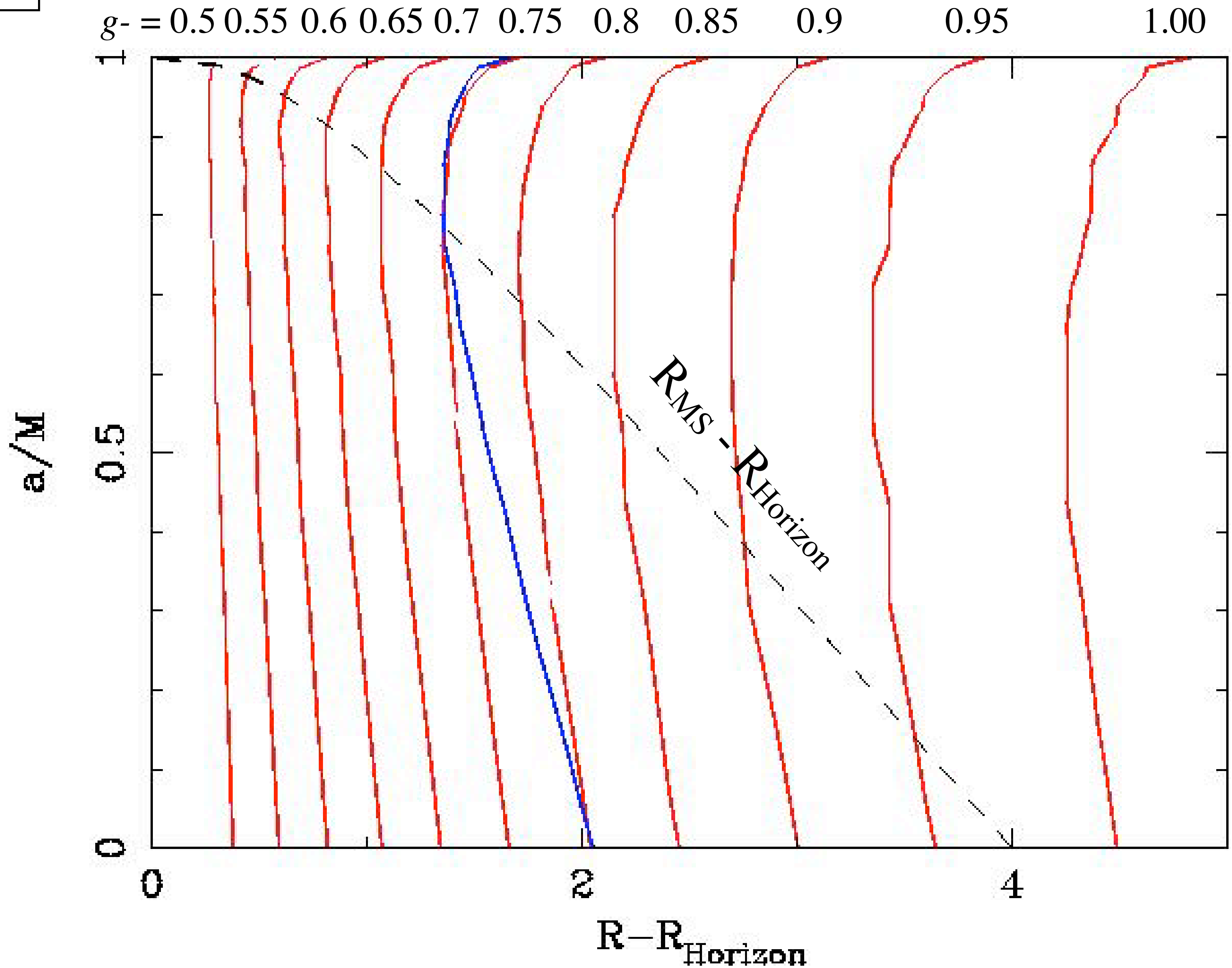
Uncertainty in ionization state of Fe:
± 4.2%



$\Rightarrow a/M > 0.75,$

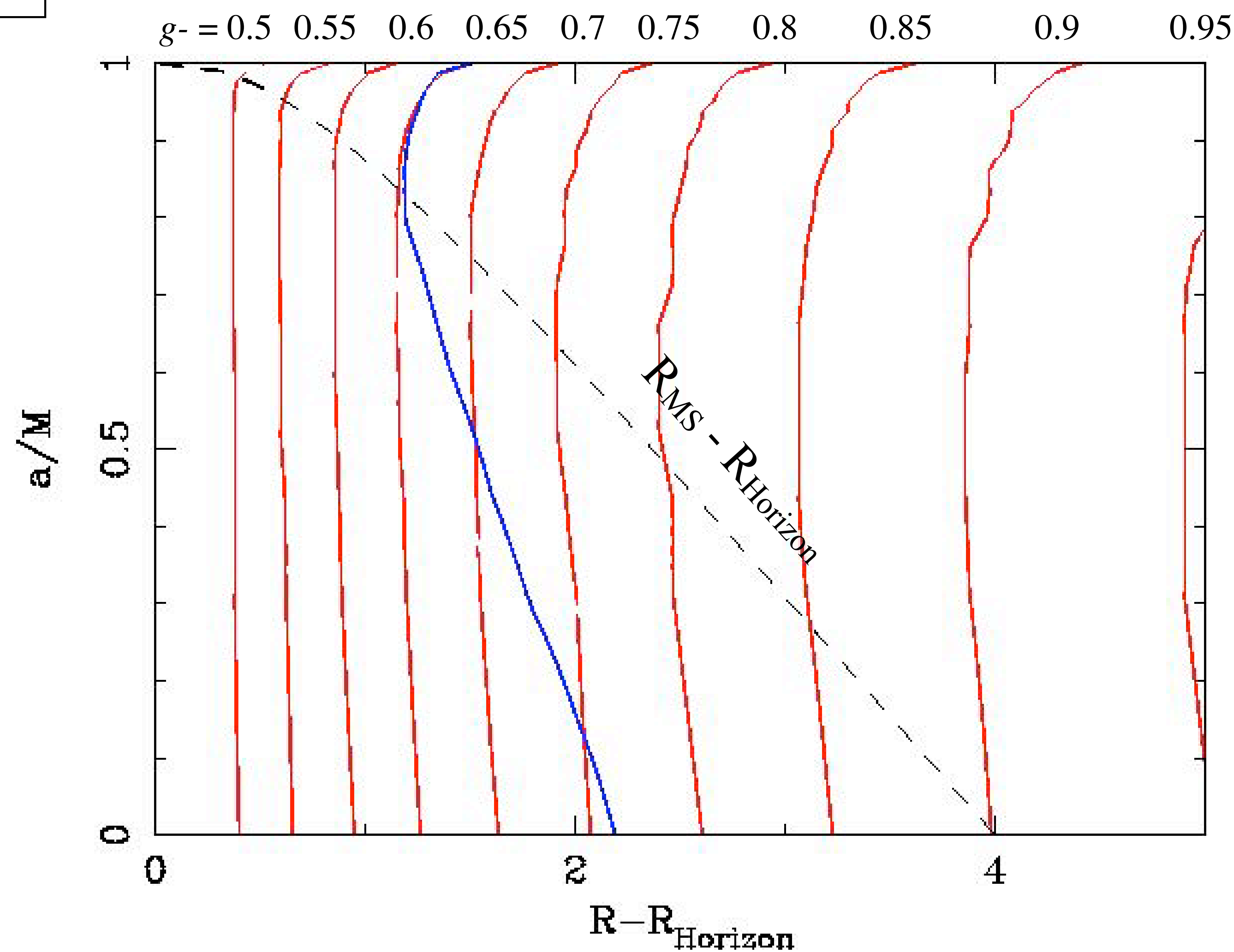
$1.0 < R\text{-}R_H < 1.5$

$\theta = 30°$



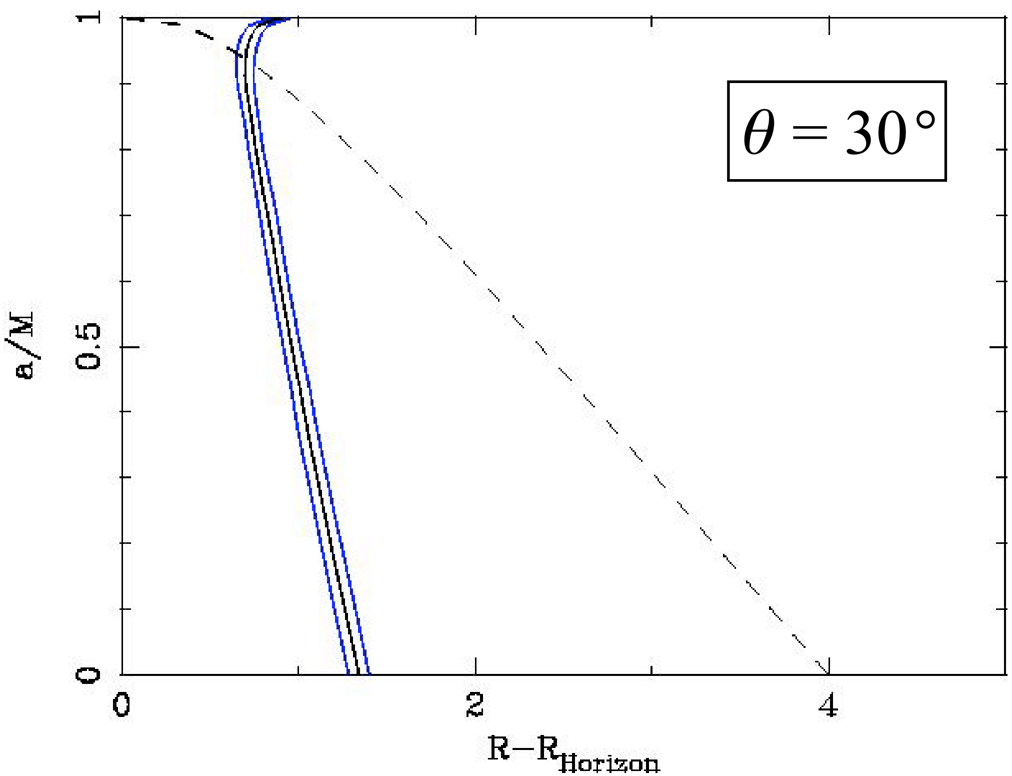
g- = 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1.00
a/M
1
0.5
0
0
2
4
R−R_Horizon
R_MS - R_Horizon

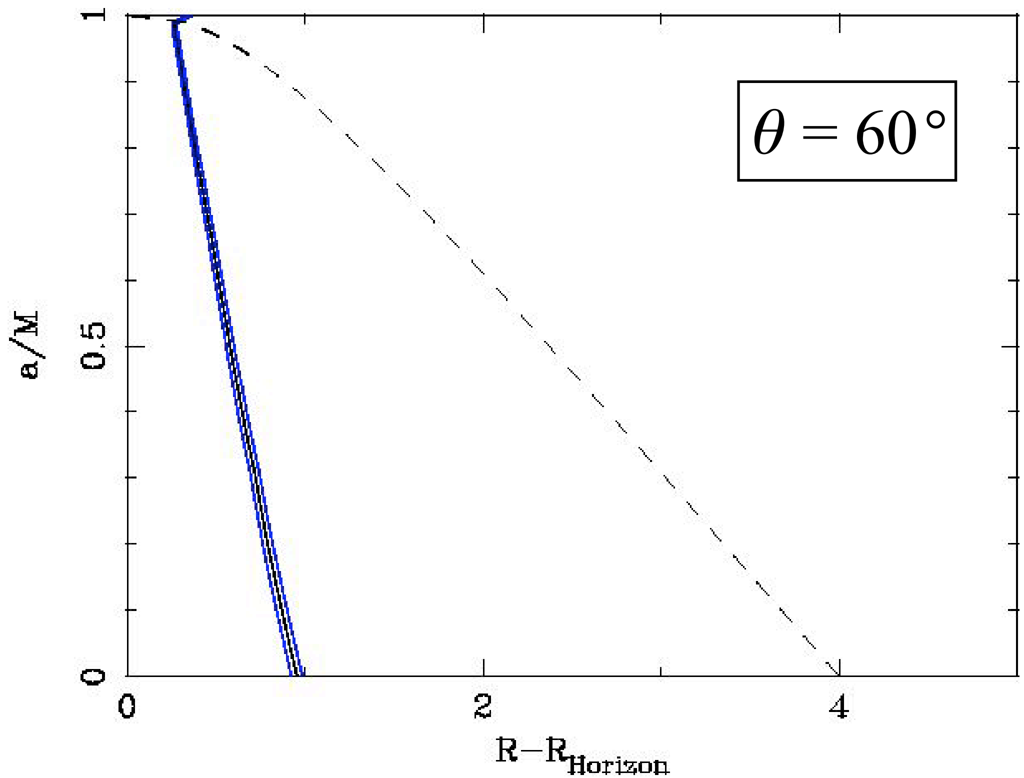
$\theta = 60°$



g- = 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95
a/M
1
0.5
0
0
2
4
R−R_Horizon
R_MS - R_Horizon

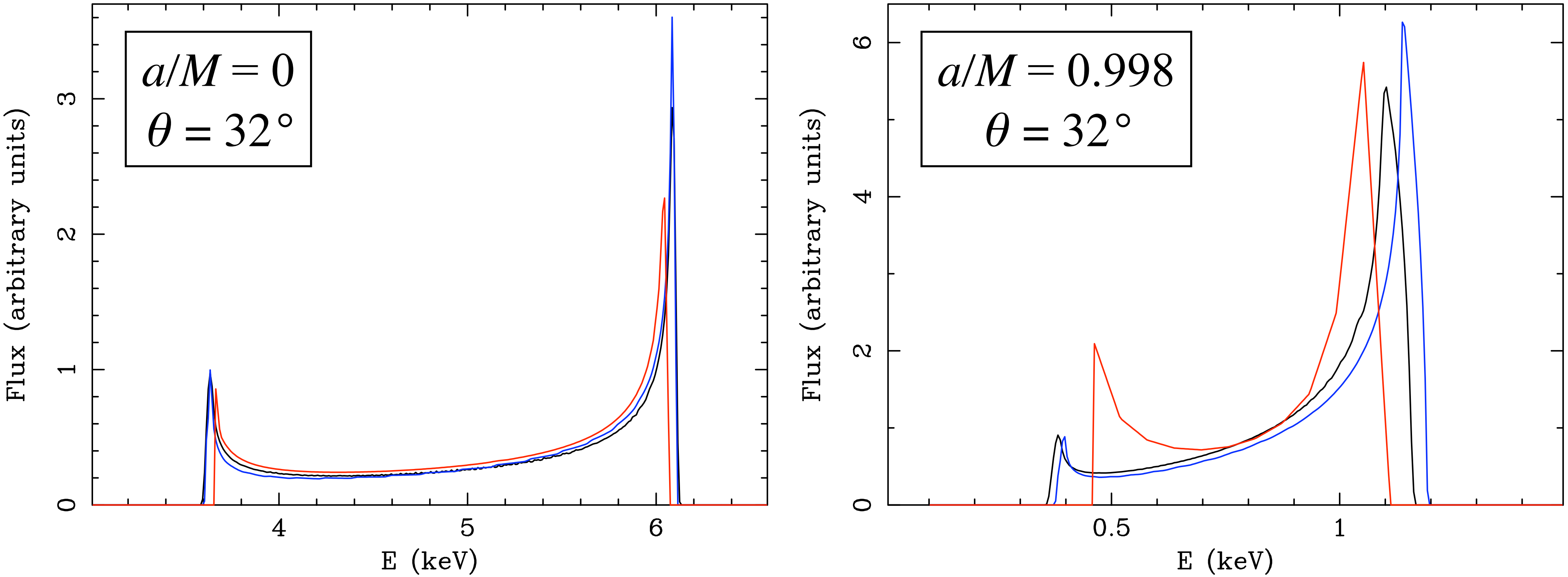
Blue Peak (g+) Contours





- As *g*+ increases, spin vs. distance contours get wider
- Energy shifts become less sensitive to spin at larger radii

Accuracy of Theoretical Models



Ky (non-axisymmetric) - Dovciak et al. 2004
Xskdline - Beckwith & Done 2004
Kerrdisk - Brenneman et al. 2006

- For high resolution spectroscopy, accuracy of calculations must be improved

Conclusions

- It is difficult to constrain BH spin independent of assumptions about radial emissivity and emission inside the marginally stable orbit
- We quantified the uncertainties on spin in terms of key observational measurements and found that, although distance to localized emission can be constrained, the spin remains elusive
- Combined with temporal analysis, this may be the most accurate way to measure BH mass
- To measure other parameters of accretion disks (inclination, ionization state, emissivity, spatial scales), numerical models of the Kerr metric must be improved in parallel with improved instrumentation