X-ray Polarimetry Observations of Black Holes in X-ray Binaries and Tests of General Relativity

Henric Krawczynski, June 19, 2012

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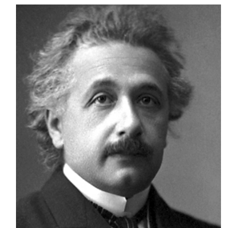
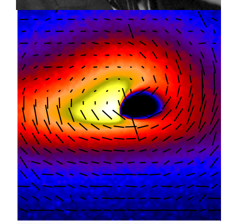
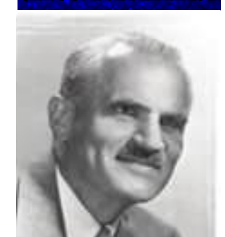
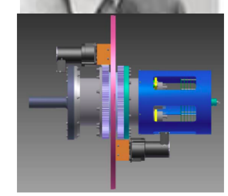






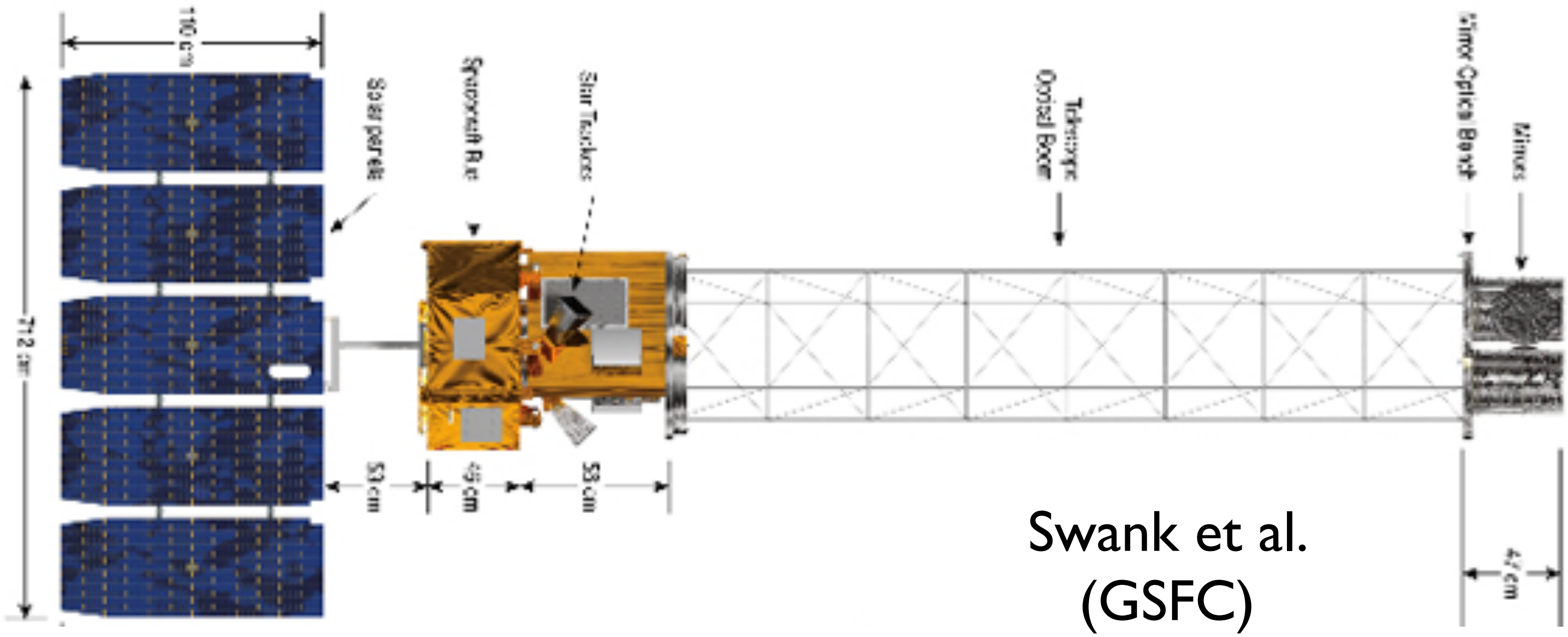


Plan of talk:

(1) Two experiments: *GEMS* & *X-Calibur*.

(2) Tests of General Relativity with X-ray Polarimetry [ApJ,in press, arXiv:1205.7063].

Soft X-ray Polarimetry with GEMS (Gravity and Extreme Magnetism SMEX)



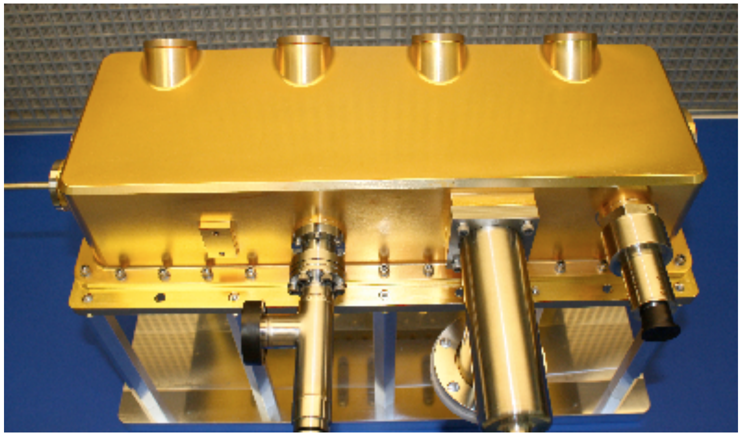
Swank et al.
(GSFC)

GEMS:

- Bandpass: 2-10 keV (student exp.: 0.5 keV)I
- 10^6 s observation of 1 mCrab source: ~2% MDP.

- Cancelled on June 7, 2012.

Soft X-ray Polarimetry with GEMS

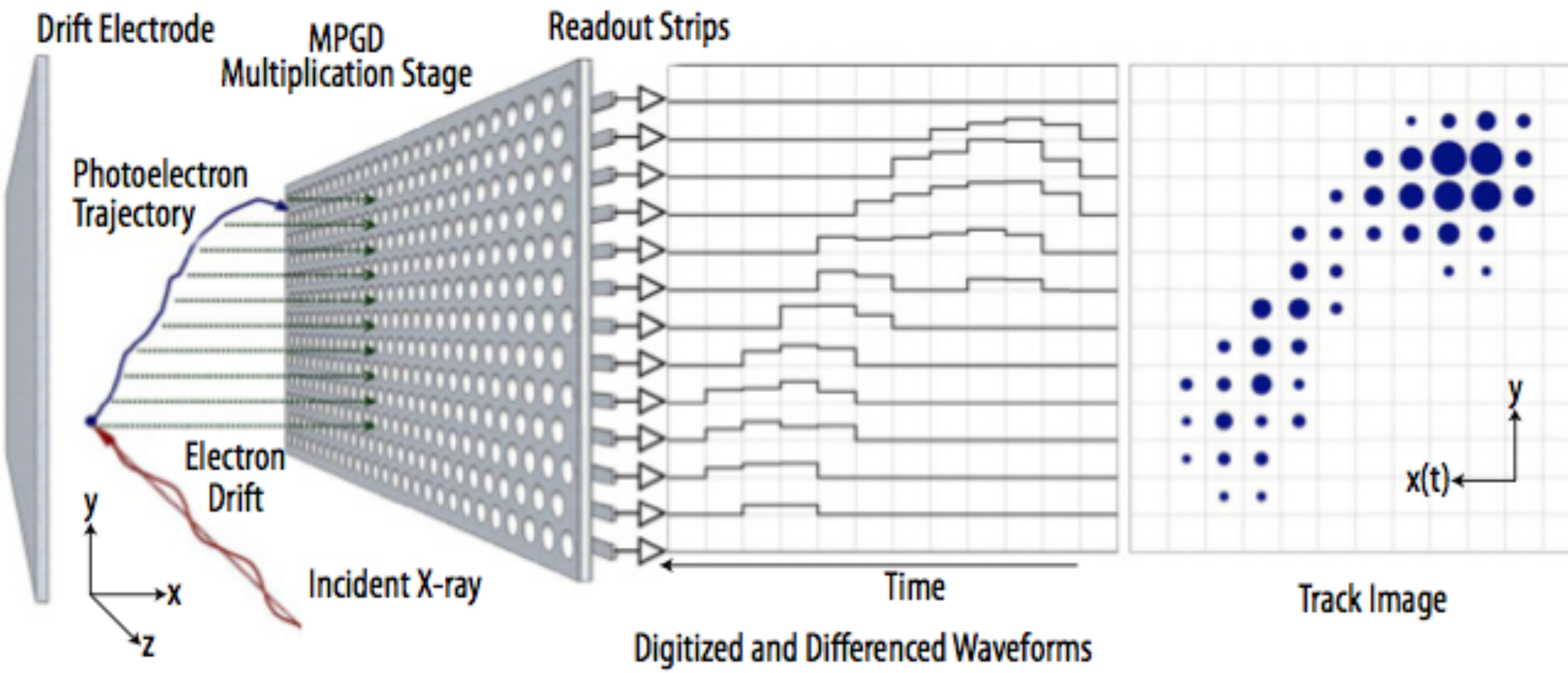


Mirrors:
• Conical segments, F=4.5m.
• Collection area of 2 mirror assemblies: A_{eff} ~950 cm^2 at 2 keV.

Two **Photoelectric Effect Polarimeters**, each:
- 4 Time Projection Chambers.
- 30 cm demethyl ether at 0.25 atm.
- 99% absorption at 2 keV, 10% at 8 keV.
- μ ~ 0.2 … 0.6.

(Black et al. 2010)

Tracking of Photo-Electrons



Present technology: high efficiency ***or*** imaging.

Observation plan:

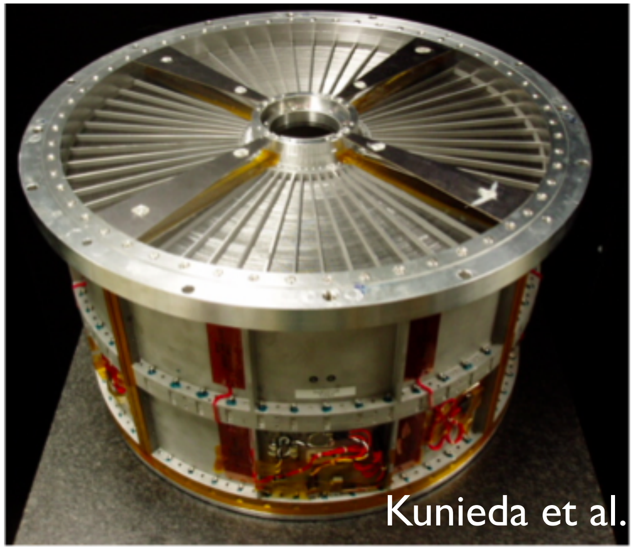
- X-ray binaries (0.8 Msec): Cyg X1, GRS 1915+105, LMC X-3, 1E1740.7-2942+ToO.
- AGNs (4.9 Msec): Cen A, MCG 6-30-15, NGC 5548, 3C271, NGC4151, NGC1068.
- Blazars (0.8 Msec): Mrk 421, 1ES 1959+650, PKS 2155-314, Mrk 501.

Hard X-ray Polarimetry with *X-Calibur*

- **Compton Polarimeter:**
  - Balloon: 25 keV - 70 keV,
  - Satellite: 5 keV - 100 keV.
- One-day balloon flight from Fort Sumner (NM) in Fall 2013: Crab, Cyg X-1, GRS 1915+105, Her X-1 (4-10% MDP), Mrk 421 (36% MDP).
- Longer balloon flights 2015 & 2016 (with bigger mirror?).

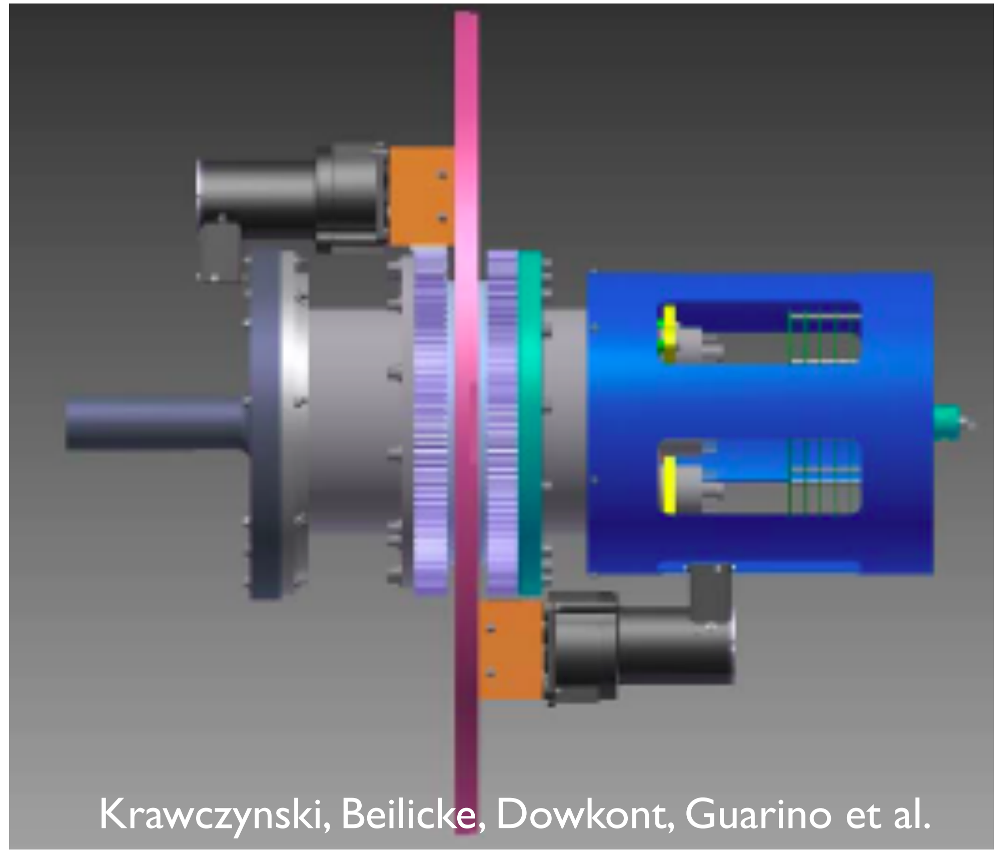
InFOCμS gondola with 8m optical bench (Tueller et al., NASA GSFC)

Hard X-ray Polarimetry with *X-Calibur*



255 shell Al mirror with $50\ cm^2$ area at 30 keV (Pt/C coating).

Nagoya Univ.



Rotating Compton Polarimeter.

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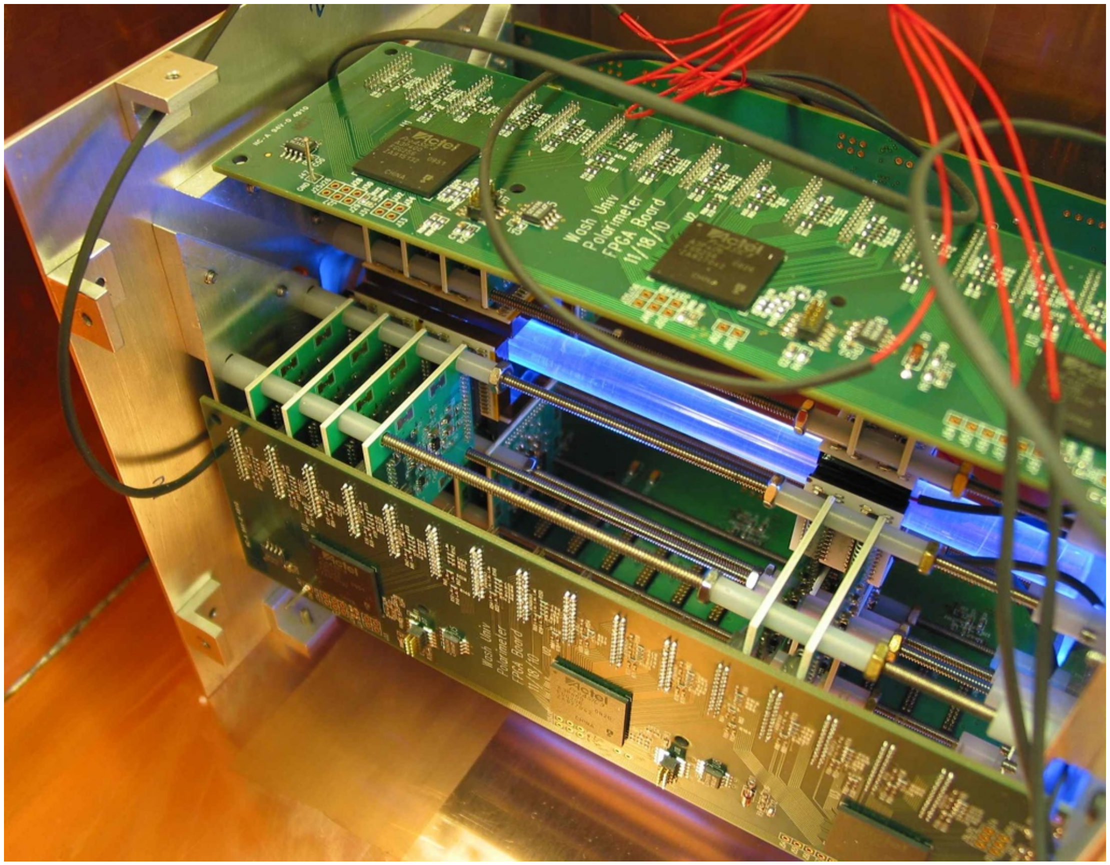
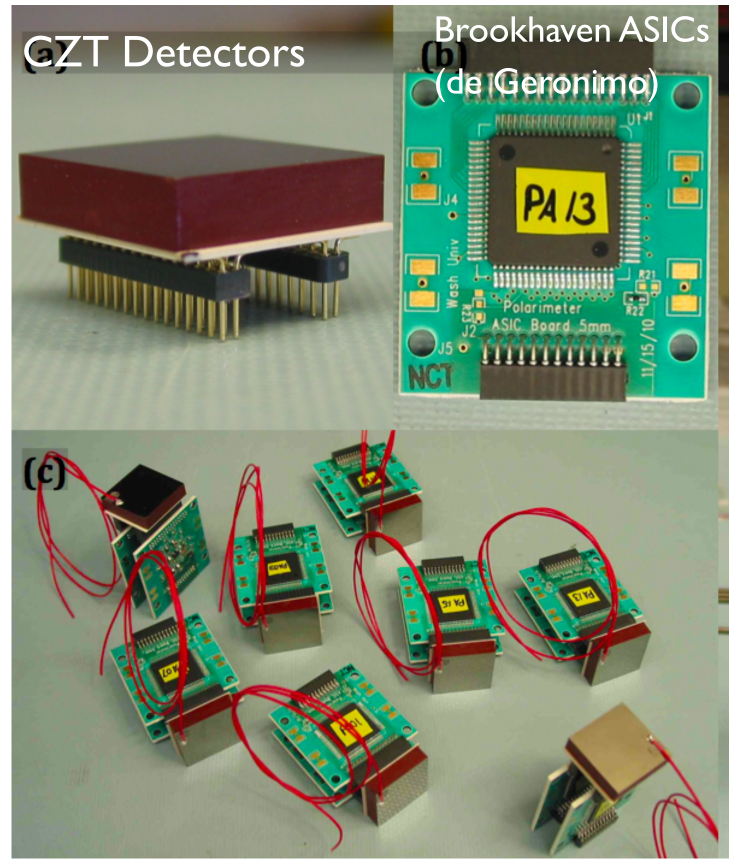
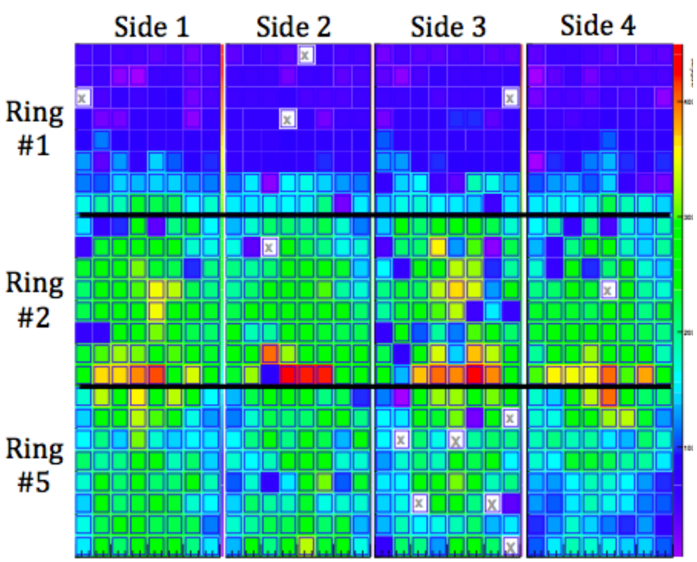
Hard X-ray Polarimetry with *X-Calibur*

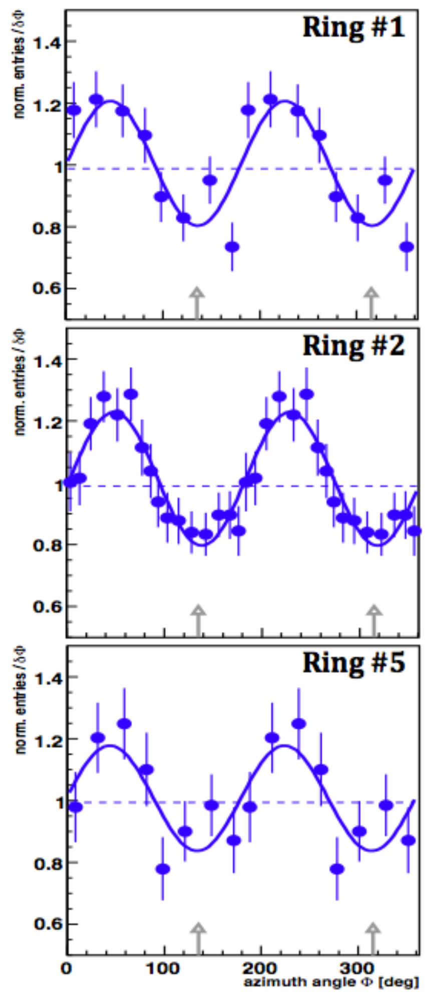




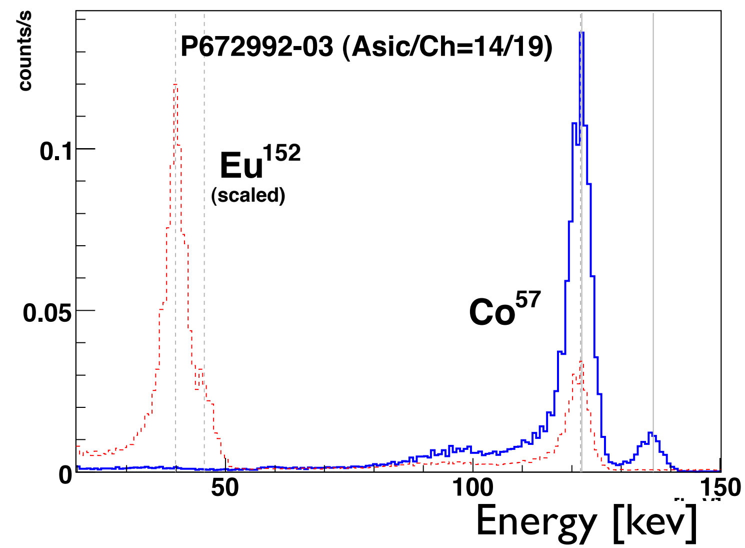
X-Calibur Test Results

Test with 55% polarized beam (288 keV):





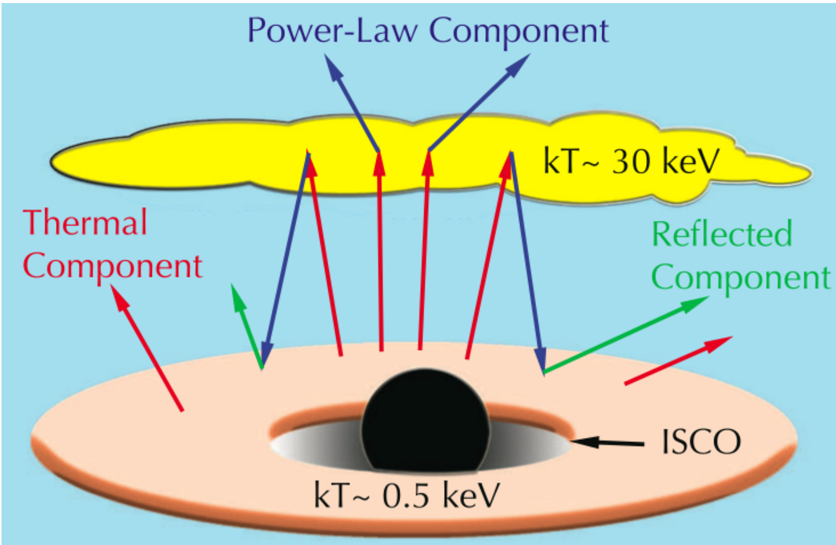
Energy spectrum:

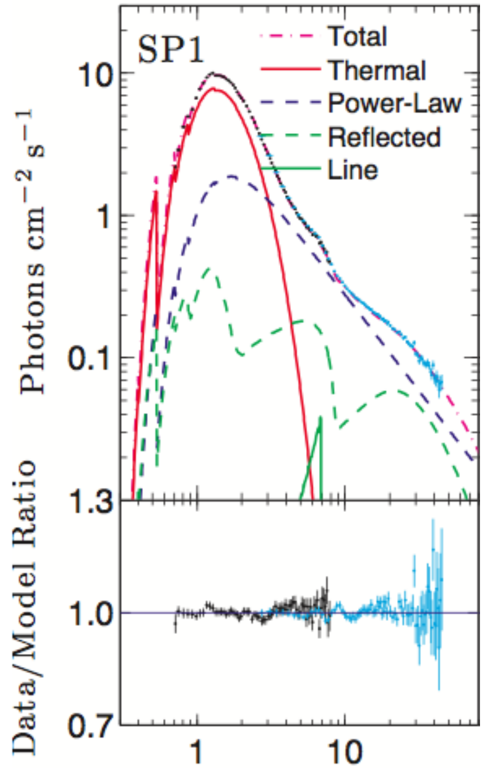


μ = 0.4 at 288 keV

Spectral Fit to Thermal State Data

Gou et al. 2011:





$$a_* = \frac{cJ}{GM^2} > 0.97\,(3\sigma)$$

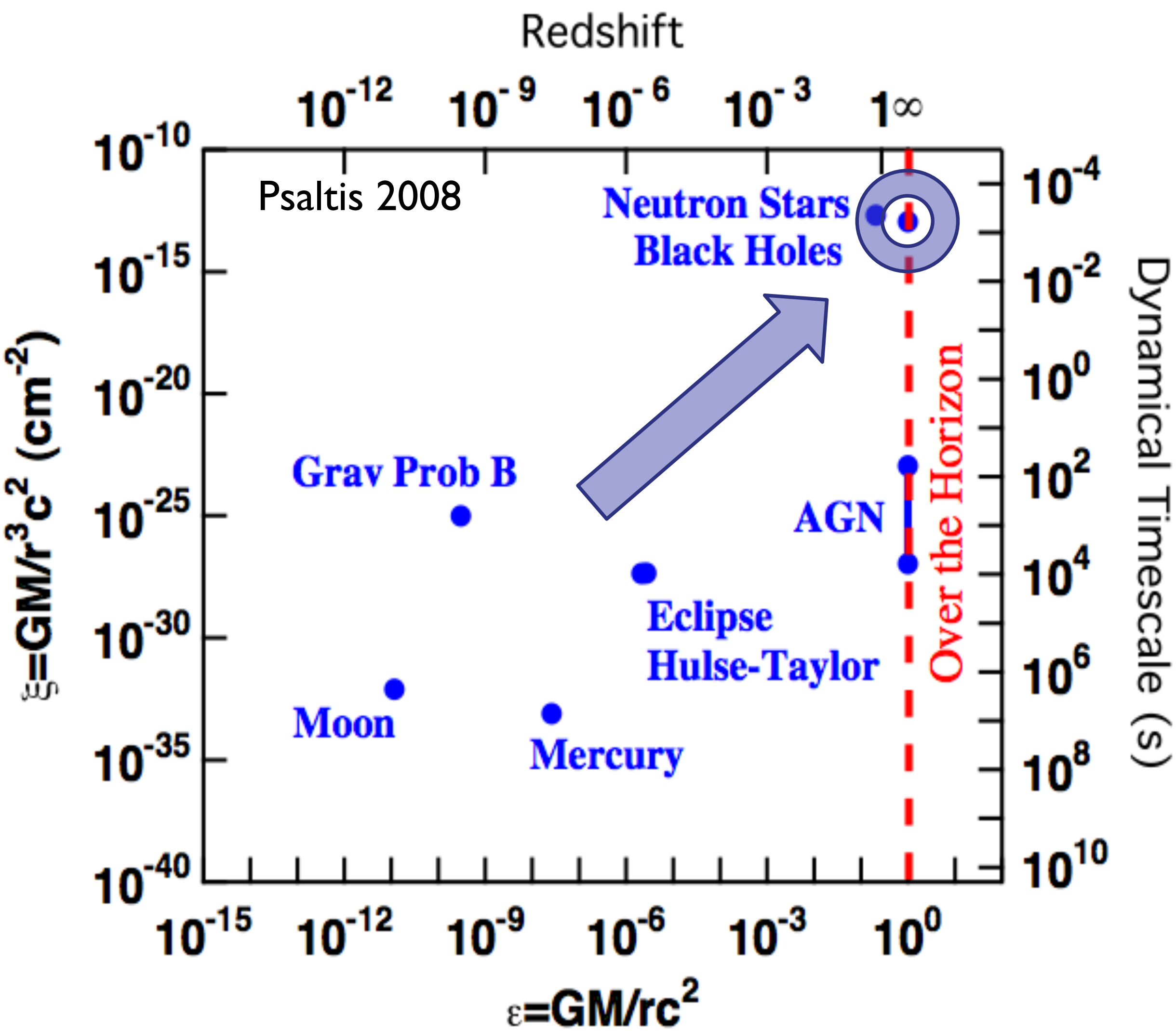
Black Hole	a_*	Reference
A0620–00	0.12 ± 0.19	Gou et al. (2010)
XTE J1550–564	$0.34^{+0.20}_{-0.28}$	Steiner et al. (2010b)
M33 X-7	0.84 ± 0.05	Liu et al. (2008, 2010)
LMC X-1	$0.92^{+0.05}_{-0.07}$	Gou et al. (2009)

Kulkarni et al. 2011

X-ray polarimetry adds additional observables:

- Test Accretion Disk Models.
- Test No-Hair Theorem of GR.
- Constrain corona geometry.

Test of General Relativity in Strong-Gravity Regime



Strong GR Tests:

- Imaging of SMBHs;
- Stars Orbiting SMBHs.
- Fe K-α line;
- X-ray polarization;
- Gravitational waves.

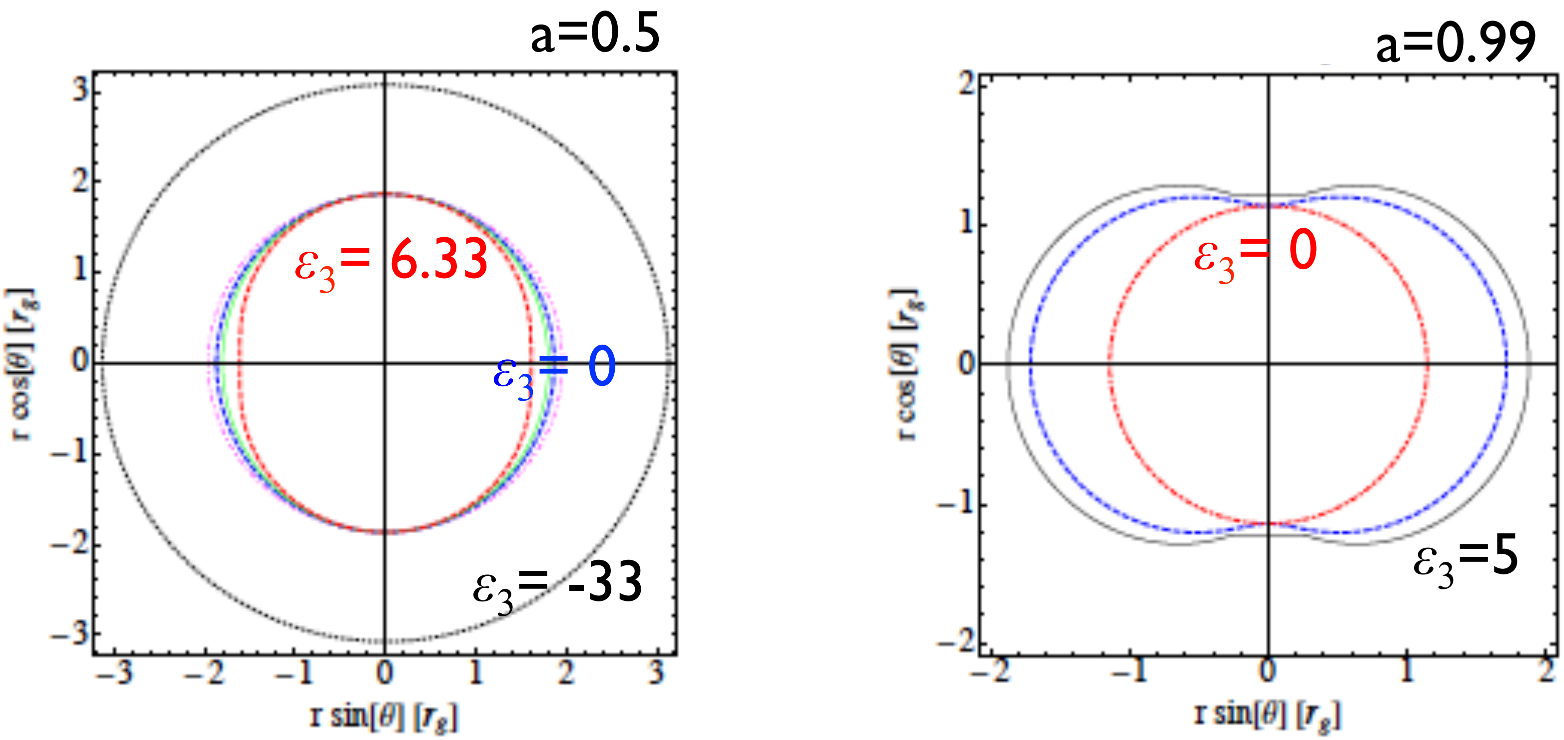
Probe GR With X-Ray Polarization?

Quantitative evaluation of effect of non-GR metrics:

- Based on phenomenological axially symmetric metrics proposed by Johannsen & Psaltis 2011 (metrics from alternative gravity theories: Yunes & Pretorius (2009), Konno et al. (2009), Pani et al. (2011).
- Parameters: M, a, ε_3. Deviation from Kerr Metric: ε_3.
- Calculate modified properties of accretion disk ➔ ray tracing ➔ predicted observational signatures.

	Model	$M\ [M_\odot]$	$\dot{M}\ [10^{18}\,\mathrm{g\,s^{-1}}]$	a	ϵ_3
Kerr Metrics	A	10	2.45	0	0
	B	10	1.7	0.5	0
	C	10	0.90	0.9	0
	D	10	0.53	0.99	0
Non-GR Metrics	E	10	4.00	0.5	-30.6
	F	10	2.33	0.5	-5
	G	10	1.27	0.5	2.5
	H	10	0.88	0.5	6.33
	I	10	1.88	0.99	-5
	J	10	1.49	0.99	-2.5

Event Horizons in Boyer-Lindquist Coordinates



Numerical Simulations - Details

Stable Circular Orbits:

$$\left(\frac{dr}{d\tau}\right)^2 = 0 \quad \frac{d}{dr}\left(\frac{dr}{d\tau}\right)^2 = 0$$

$$p_\theta = p^\theta = 0 \qquad p^2 = -1$$

$$\rightarrow \mathbf{p}$$

Thin disk, zero torque at ISCO
(Shakura & Sunyaev, 1973,Novikov & Thorne,1973, Page & Thorne, 1994):

$$\dot{M} \ \& \ \mathbf{p}(r) \ \Rightarrow \ F(r)$$

F(r): energy dissipation in plasma frame.

Page & Thorne (1994):

$$ds^2 = -e^{2\nu}dt^2 + e^{2\psi}(d\phi - \omega dt)^2 + e^{2\mu}dr^2 + dz^2$$

$$F(r) = \frac{\dot{M}_0}{4\pi} e^{-(\nu+\psi+\mu)} f(r)$$

$$f(r) \equiv \frac{-p^t{}_{,r}}{p_\phi} \int_{r_{\rm ISCO}}^{r} \frac{p_{\phi,r}}{p^t} dr$$

Numerical Simulations - Details

Emission & scattering:

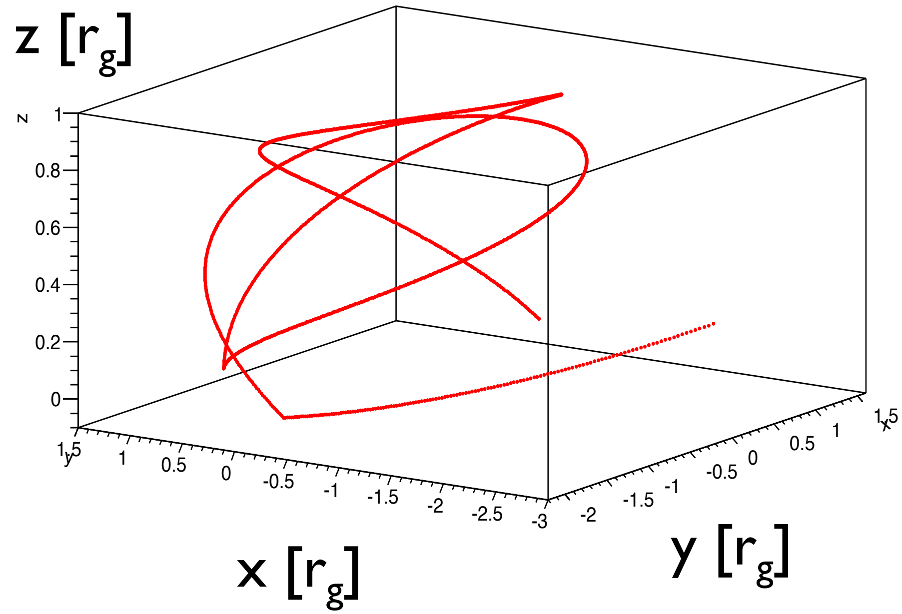
- Blackbody with "spectral hardening" by f=1.8;
- Initial polarization & polarization-change from scattering: Chandrasekhar (1960).
- Neglect Faraday rotation.

Parallel transport of **k** and **f** (4th Ord. Runge-Kutta):

$$\frac{d^2x^\mu}{d\lambda'^2} = -\Gamma^\mu{}_{\sigma\nu}\frac{dx^\sigma}{d\lambda'}\frac{dx^\nu}{d\lambda'}$$

$$\frac{df^\mu}{d\lambda'} = -\Gamma^\mu{}_{\sigma\nu}f^\sigma\frac{dx^\nu}{d\lambda'}$$

Example photon trajectory:



$$k^2 = 0 \qquad f^2 = 1 \qquad \mathbf{k}\cdot\mathbf{f} = 0$$

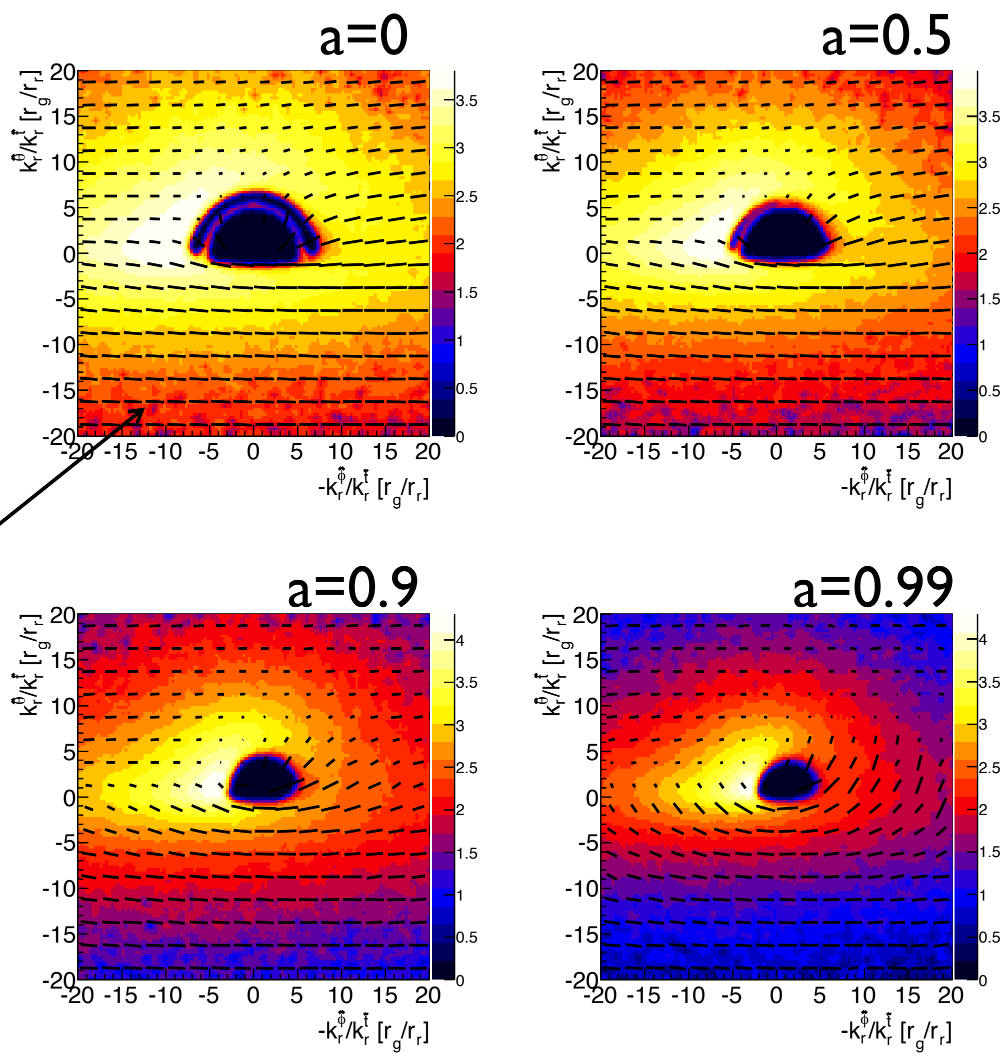
$$\frac{dN}{dt\,dr\,d\phi} = \sqrt{-g_{tr\phi}}\frac{F}{<\hat{E}>}$$

Results: Kerr Black Holes (a=0…0.99, ε_3=0)

$M = 10\ M_{sun}$
$L_{Disk} = 0.1\ L_{edd}$
$i=75^\circ$

Color-scale: log. intensity

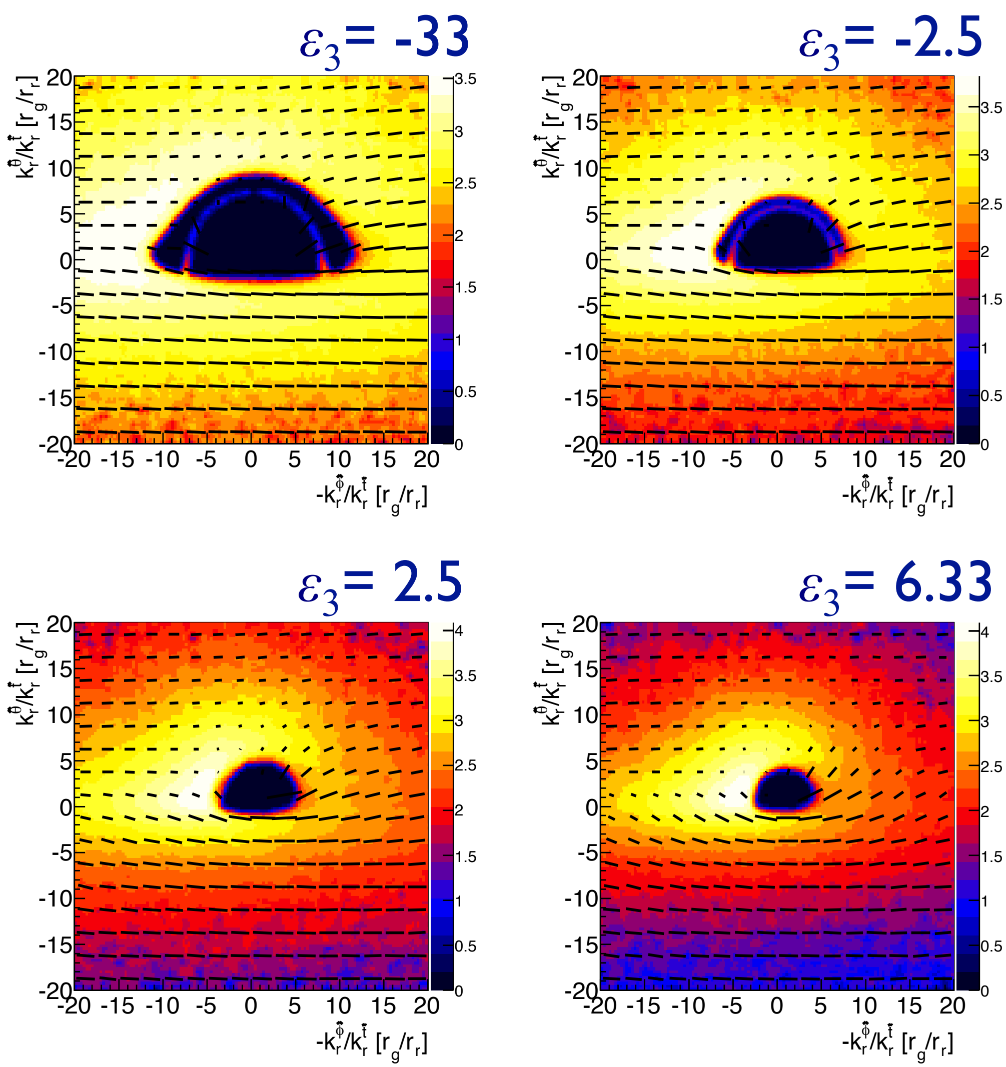
Pol. Degree: 4%



Larger BH-Spin: Increased Dominance of Scattered Emission.

Results: a=0.5, ε_3= -33 … 6.33

M = 10 M_{sun}
L_{Disk} = 0.1 L_{edd}
i=75°

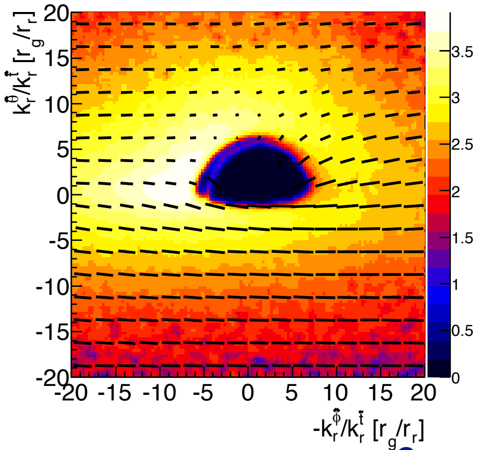


$\varepsilon_3 \neq 0$:
- Different ISCO;
- Modified photon trajectories.

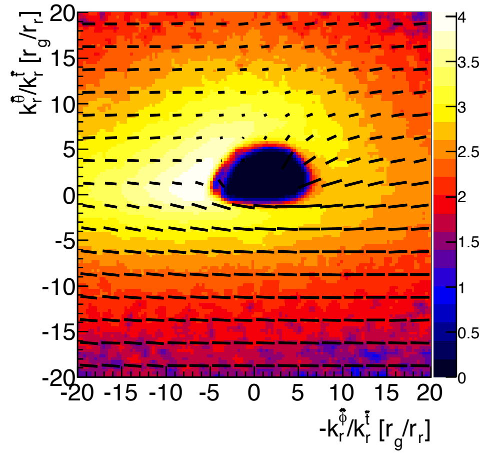
Results: a=0.99, ε_3= -5, -2.5

M = 10 M_{sun}
L_{Disk} = 0.1 L_{edd}
i=75°

ε_3= -5

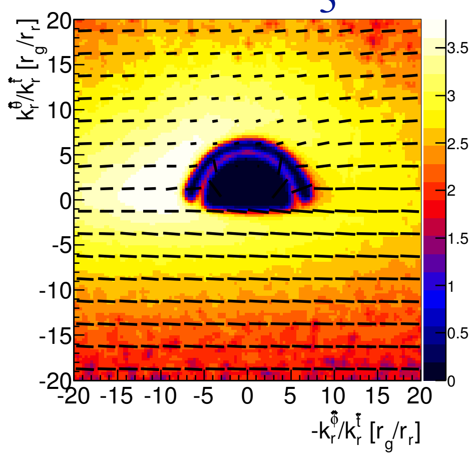


ε_3= -2.5



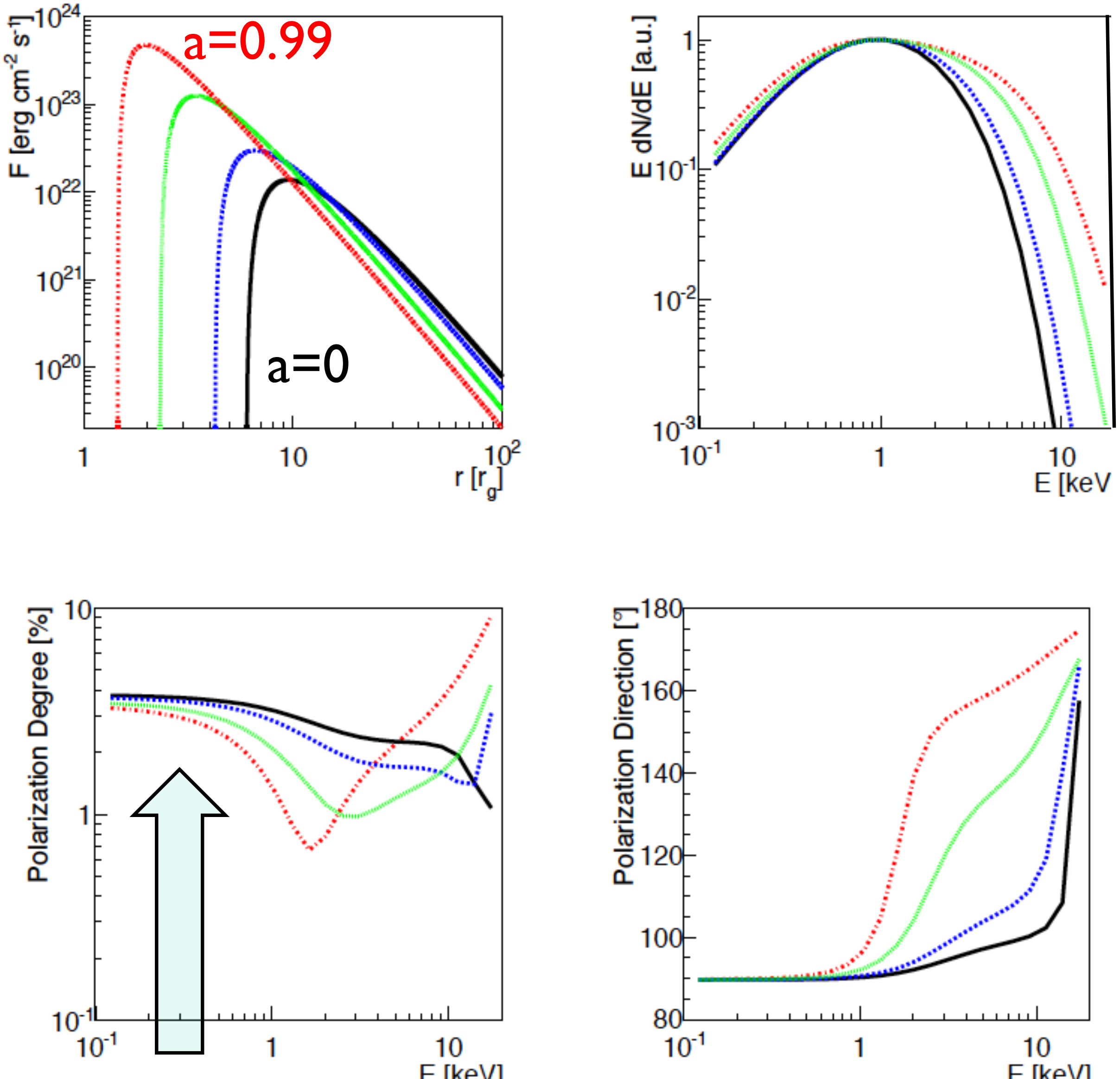
Kerr Black Hole with a=0

ε_3= 0



Same angular size, different spin…

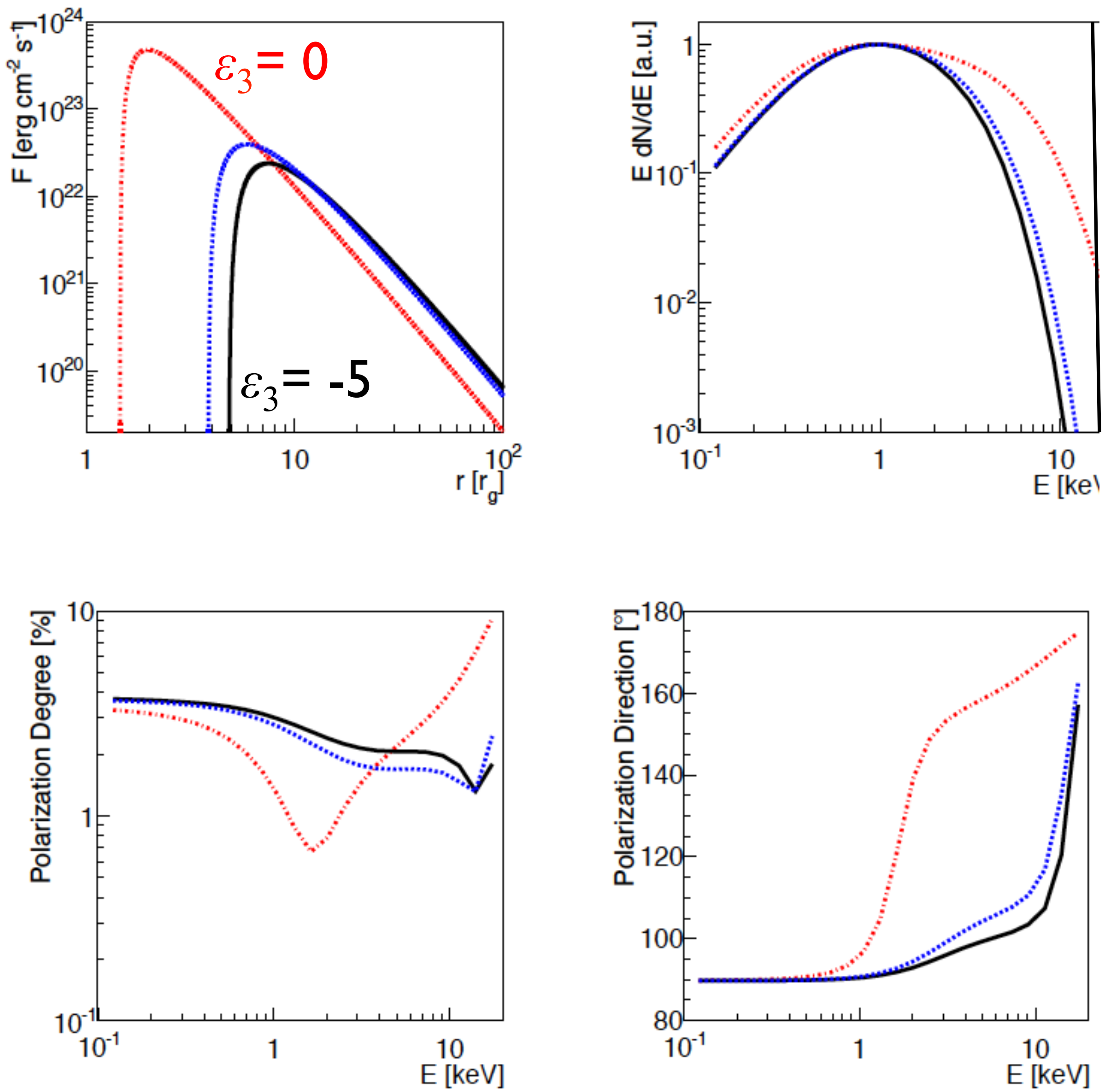
Results: Energy Spectra (Kerr, a=0...0.99)



➔ X-ray polarimetry gives black hole spin (Connors et al. 1980, Schnittman & Krolik 2009).

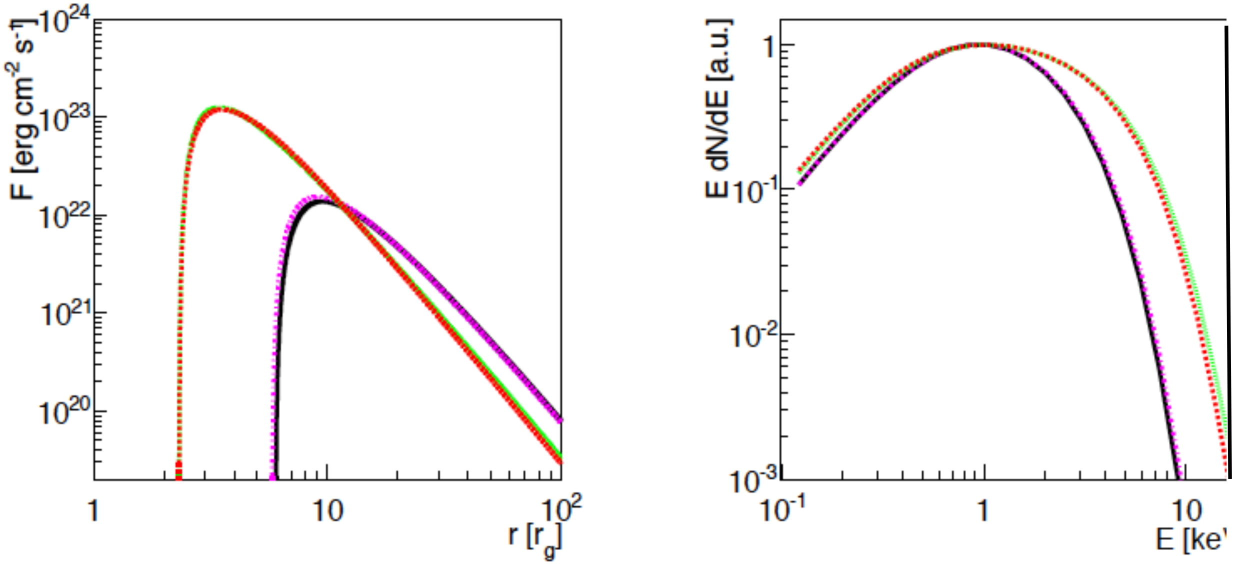
Faraday rotation (Davies et al. 2009)

Results – Energy Spectra (a=0.99, ε_3= -5… 0)



➔ Metric influences observational signatures.

Degeneracy between a and ε_3



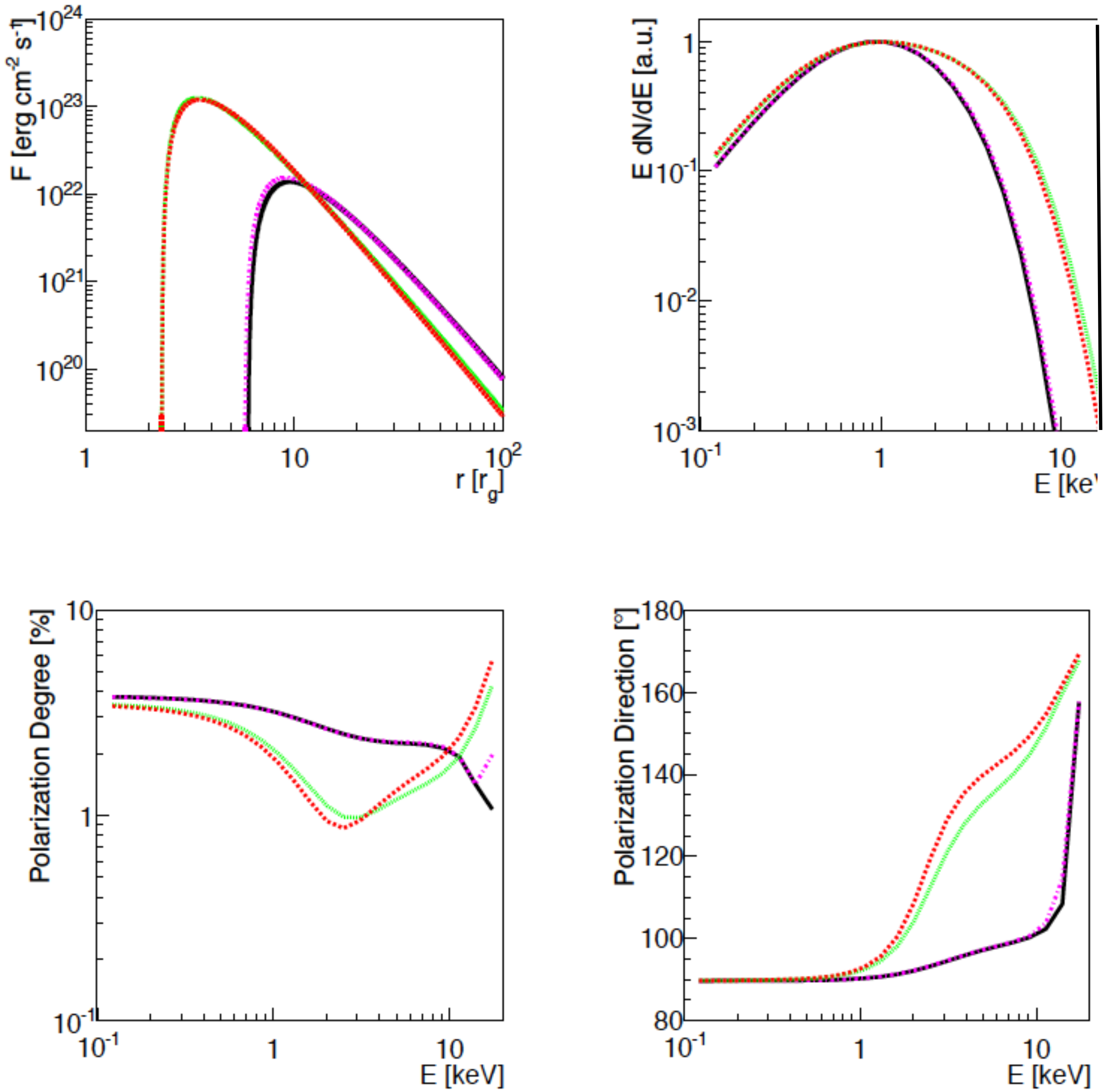
a=0.9 ε_3= 0

a=0.5 ε_3= 6.3

a=0 ε_3=0

a=0.5 ε_3= -5

Results - Energy Spectra: GR vs. non-GR



a=0.9
ε_3= 0

a=0
ε_3=0

a=0.5
ε_3= 6.3

a=0.5
ε_3= -5

➔ a and ε_3 largely degenerate.

GR tests limited to ε_3 <<-1 or a➔1.

Summary: X-Ray Polarimetric Studies of Black Holes

High-efficiency X-ray polarimeters:

- ***GEMS 2-10 keV polarimeter:*** not confirmed.
- ***X-Calibur 25-60 keV***: first flight in 2013.
- Other experiments: *ASTRO-H*, *Pogo*, *GRAPE*, …

X-Ray Polarimetric Observations of Black Holes in X-ray Binaries:

- Access B-field of accretion disks (Davis et al. 2009).
- Limited sensitivity to underlying spacetime (this work); similar for Fe K-alpha line (Johannsen & Psaltis, 2012) ➔ time resolved studies?

X-Calibur co-workers at Wash. Univ.:

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Research Professor

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Post-Docs

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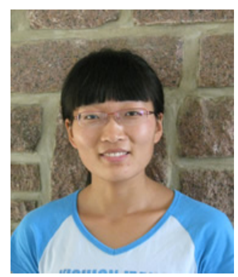

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