Polarization Effects Near Black Holes

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X-ray Polarimetry 2004

Why Worry About Black Holes?

- Prodigious X-ray Output of Accreting Black Holes

- Data on Accreting Black Holes

- Tests Strong Field Relativity

Some Black Hole Candidates

- Stellar Mass Candidates with "Confirmed" Black Holes (HMXBs)

Object	Mass ($M_\odot$)	F_X (μJy)	E_{max} (keV)
V518 Per	3.2 – 13.2	3×10^3	8×10^2
LMC X-3	5.9 – 9.2	60	50
LMC X-1	4.0 – 10.0	30	20
V616 Mon	8.7 – 12.9	5×10^4	30
MM Vel	6.3 – 8.0	8×10^2	4×10^2
KV UMa	6.5 – 7.2	40	1.5×10^2
GU Mus	6.5 – 8.2	3×10^3	5×10^2
IL Lupi	7.4 – 11.4	1.5×10^4	2×10^2
V381 Nor	8.4 – 10.8	7×10^3	2×10^2
V1033 Sco	6.0 – 6.6	3.9×10^3	8×10^2
V821 Ara	—	1.1×10^3	4.5×10^2
V2107 Oph	5.6 – 8.3	3.6×10^3	10^2
V4641 Sgr	6.8 – 7.4	1.3×10^4	20
V406 Vul	7.6 – 12	1.5×10^3	2×10^2
V1487 Aql	10.0 – 18.0	3.7×10^3	5×10^2
Cyg X-1	6.9 – 13.2	2.3×10^3	$2 - 5 \times 10^3$
QZ Vul	7.1 – 7.8	1.1×10^4	3×10^2
V404 Cyg	10.1 – 13.4	2×10^4	4×10^2

(McClintock & Remillard, astro-ph/0306213)

- Super Massive Black Holes (AGN)

What Black Holes Can't Do

- **Affect Distant Emission ($r \gtrsim 10M$)**

- **Create Polarization**

$\longrightarrow$ **Use Thomson Scattering**

$$\Pi = \frac{1 - \cos^2 n_i}{1 + \cos^2 n_i}$$

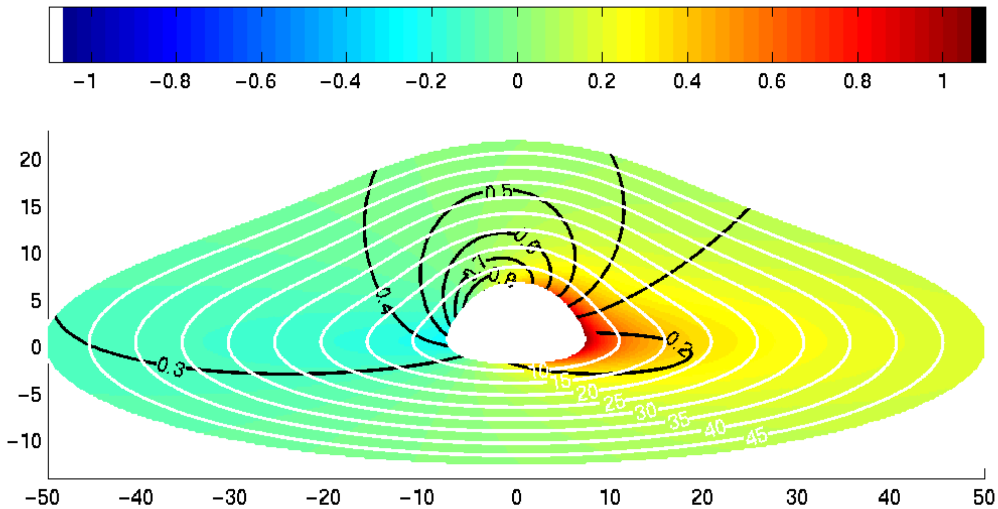
What Black Holes Can Do

- Gravitational Redshift & Doppler Boost
- Gravitational Lensing
- Rotate Polarization via Parallel Propagation
- Rotate Polarization via Lorentz Boosts

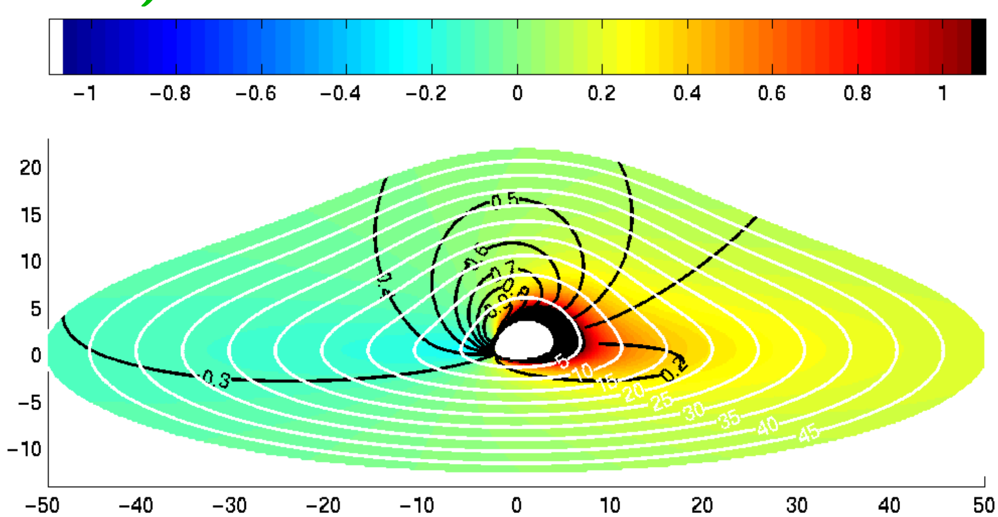
$\longrightarrow$ Depolarization & Rotation

Redshifts and Lensing

- **Keplerian Disk Around Non-Rotating BH**



- **Keplerian Disk Around Rotating BH ($a = 0.98$)**



Parallel Propagation

- **Definition:**

$$f^\mu k_\mu = 0 \quad \text{and} \quad k^\mu \nabla_\mu f^\nu = 0$$

- **Properties**
  - $f^\mu k_\mu =$ constant
  - $f^\mu f_\mu =$ constant
  - f^μ does not “rotate” about k^μ

- **Computational Methods**
  - Direct Integration (Stark & Connors, 1977, Nature, 266, 429)
  - Penrose-Walker Constant (Connors & Stark, 1977, Nature, 269, 128)

$$K_{\mathrm{PW}} = (\alpha - i\beta)(r - ia\cos\theta)$$
$$\alpha = (k^t f^r - k^r f^t) + a\sin^2\theta(k^r f^\phi - k^\phi f^r)$$
$$\beta = (r^2 + a^2)\sin\theta(k^\phi f^\theta - k^\theta f^\phi) - a\sin\theta(k^t f^\theta - k^\theta f^t)$$

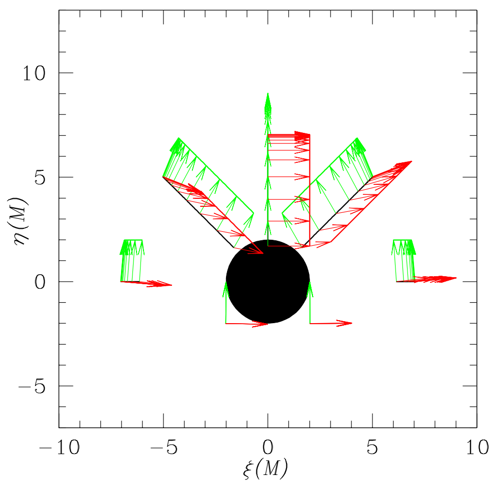
  - Stoke’s Parameters (Broderick & Blandford, 2003, MNRAS, in press)

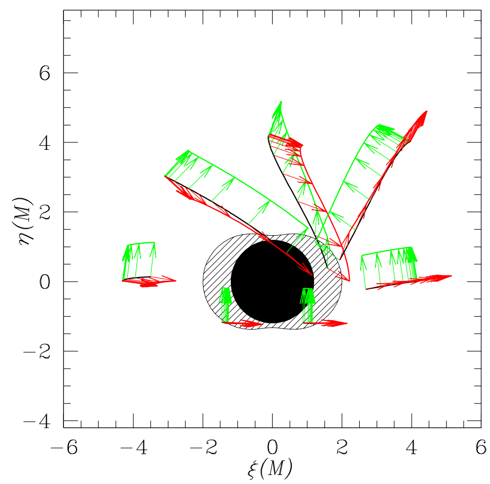
$$\frac{d\phi}{d\tau} = \hat{e}_1^\mu k^\nu \nabla_\nu \hat{e}_{2\,\mu}$$
$$\frac{dN_Q}{d\tau} = -\frac{d\phi}{d\tau} N_U$$
$$\frac{dN_U}{d\tau} = \frac{d\phi}{d\tau} N_Q$$

Parallel Propagation cont.

- $\Theta = 75$

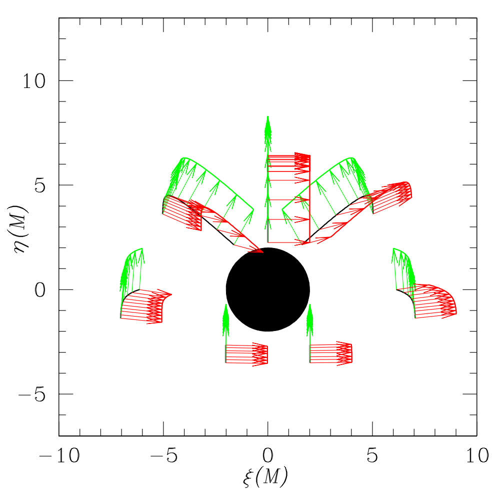
$a = 0$ $a = 0.98$

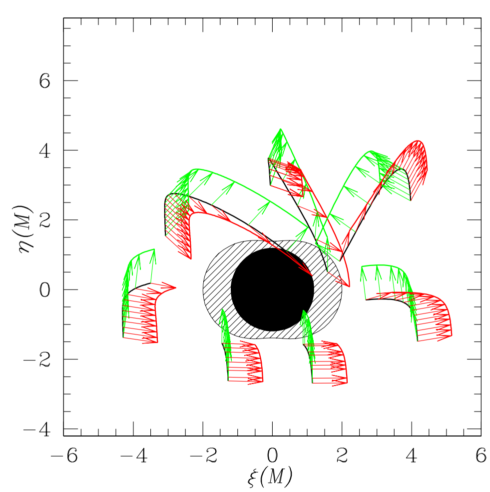




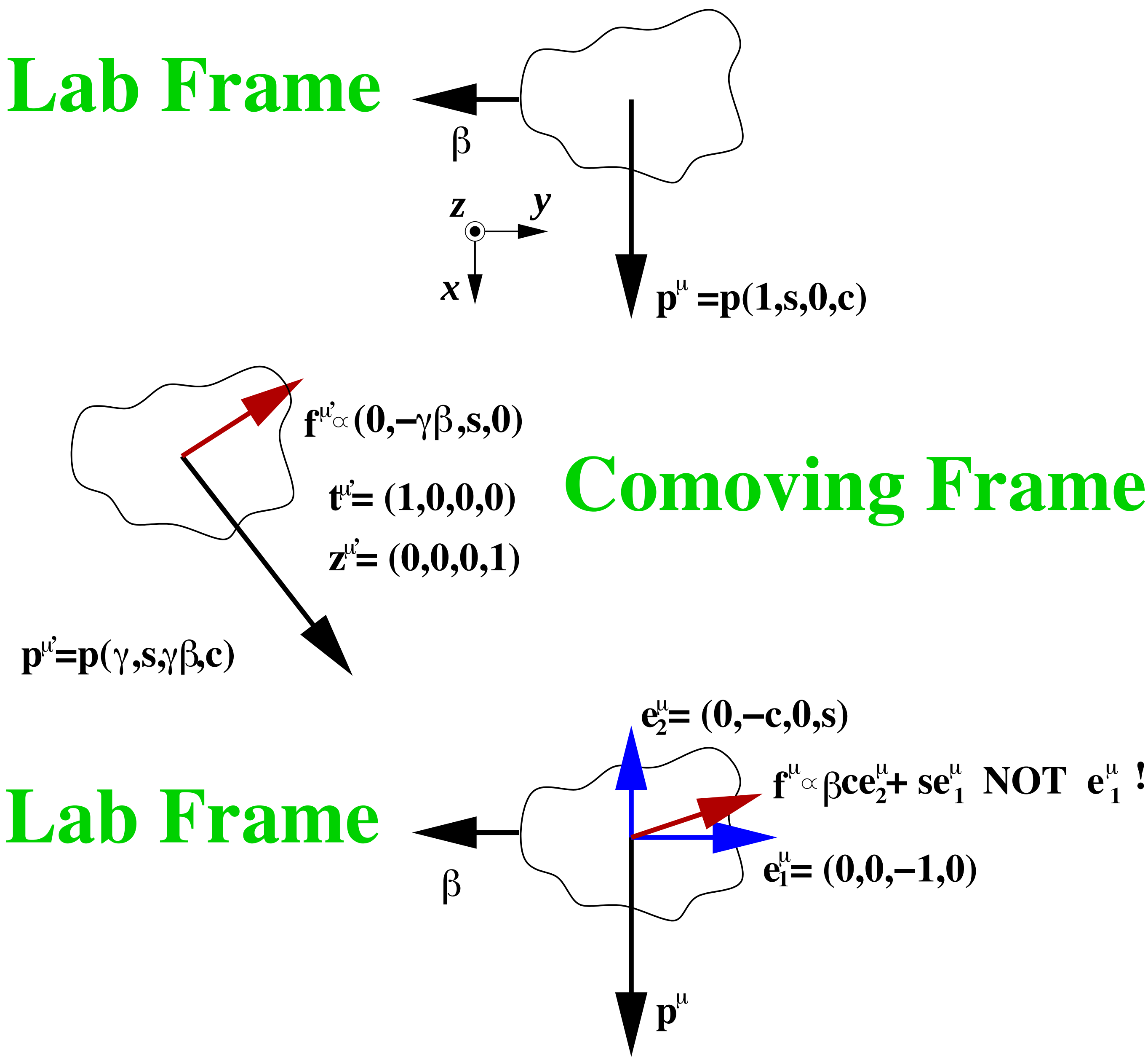
- $\Theta = 70$

$a = 0$ $a = 0.98$





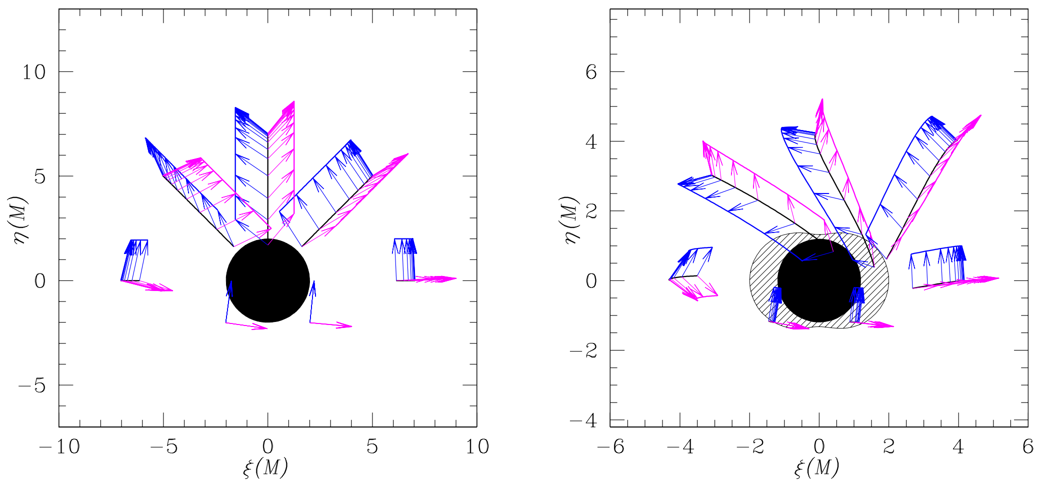
Lorentz Boosts



Lorentz Boosts cont.

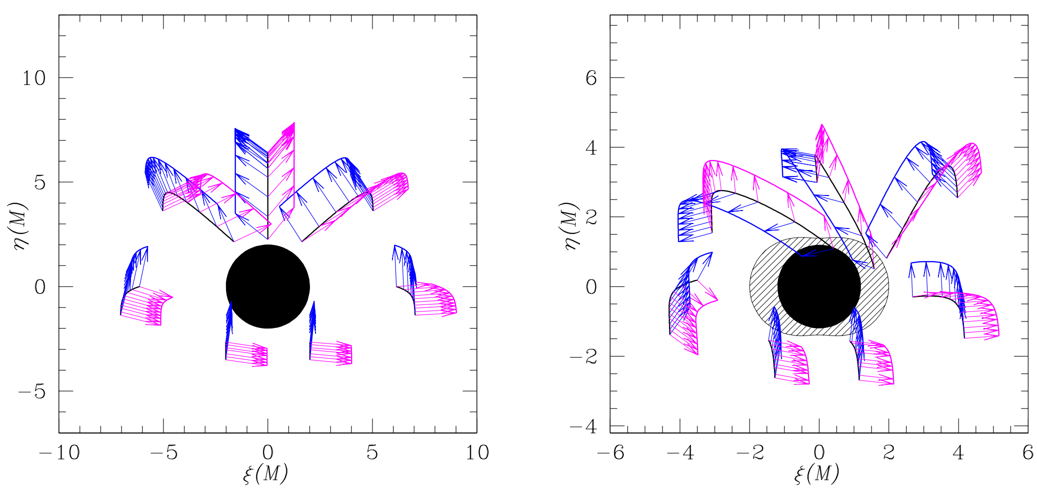
- $\Theta = 75^\circ$

$a = 0$ $\qquad\qquad$ $a = 0.98$



- $\Theta = 70^\circ$

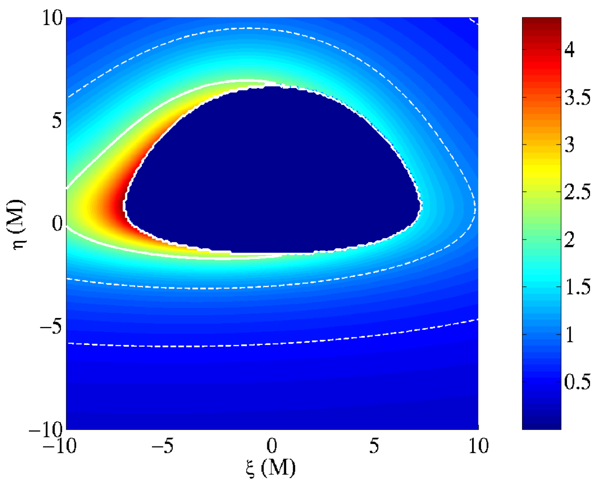
$a = 0$ $\qquad\qquad$ $a = 0.98$

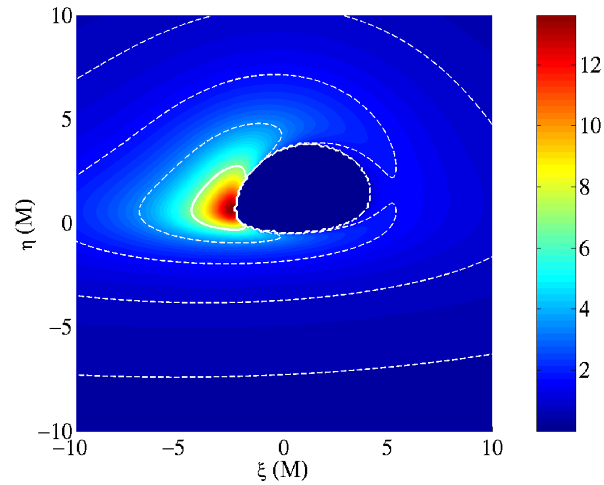


Polarization Maps for $\Pi = 1$

- **Stoke's I**

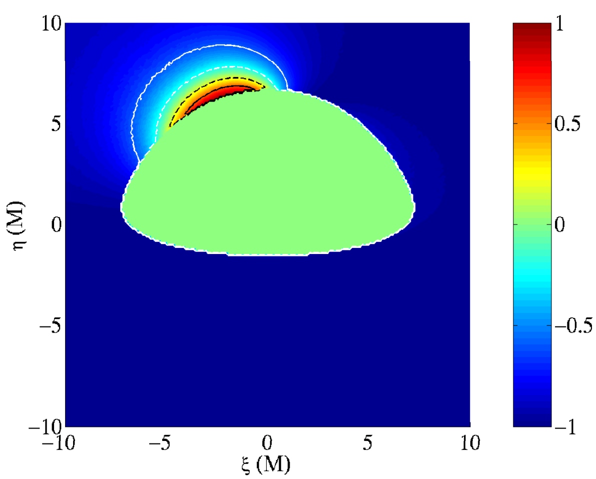
$a = 0$ $\qquad$ $a = 0.98$

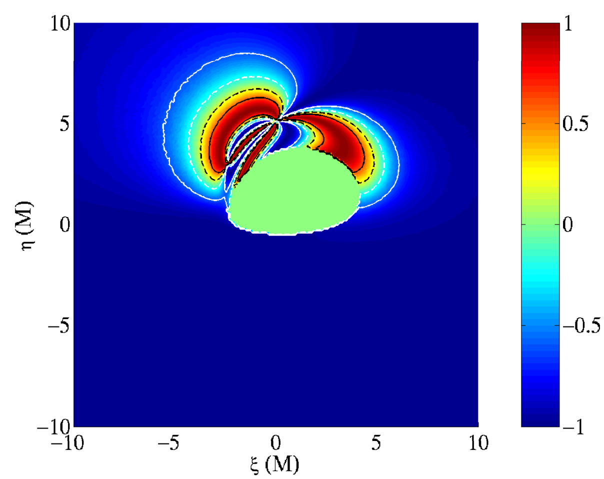




- **Stoke's Q/I**

$a = 0$ $\qquad$ $a = 0.98$

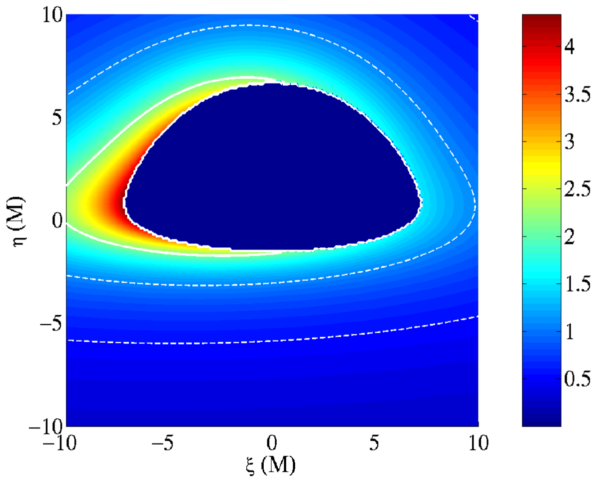




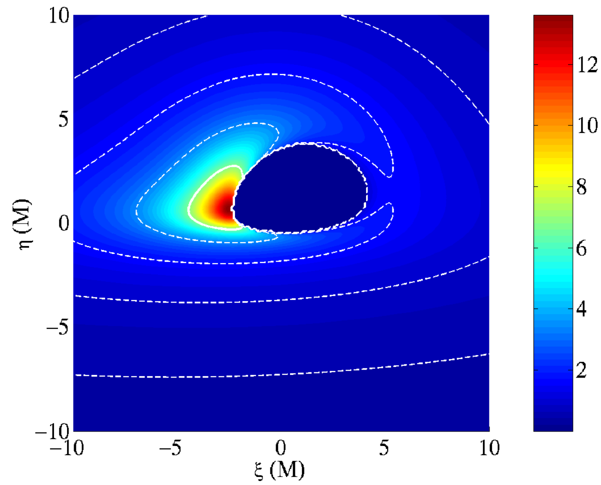
Polarization Maps for Thomson Scattering

- **Stoke's I**

$a = 0$

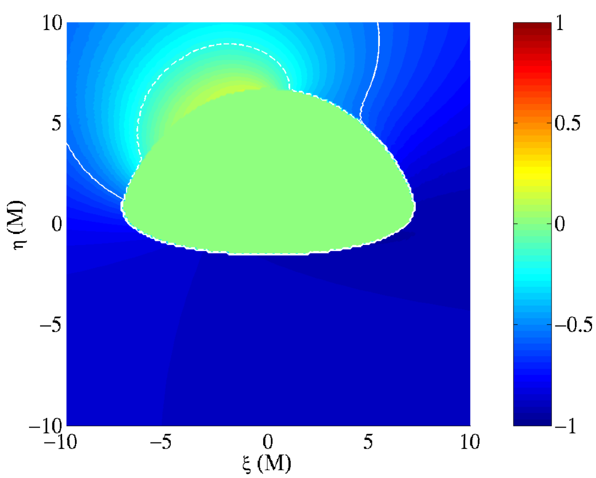


$a = 0.98$

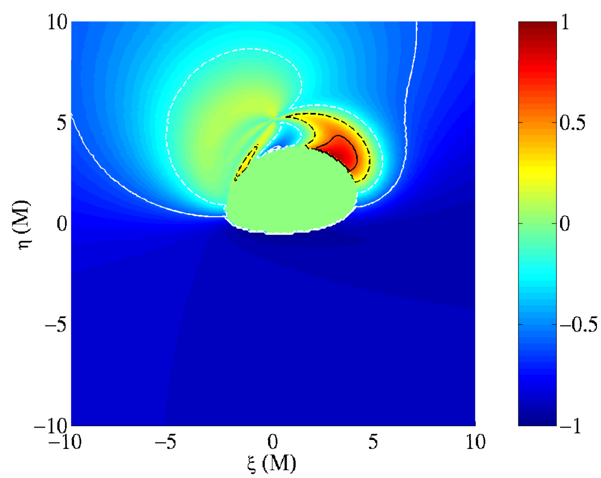


- **Stoke's Q/I**

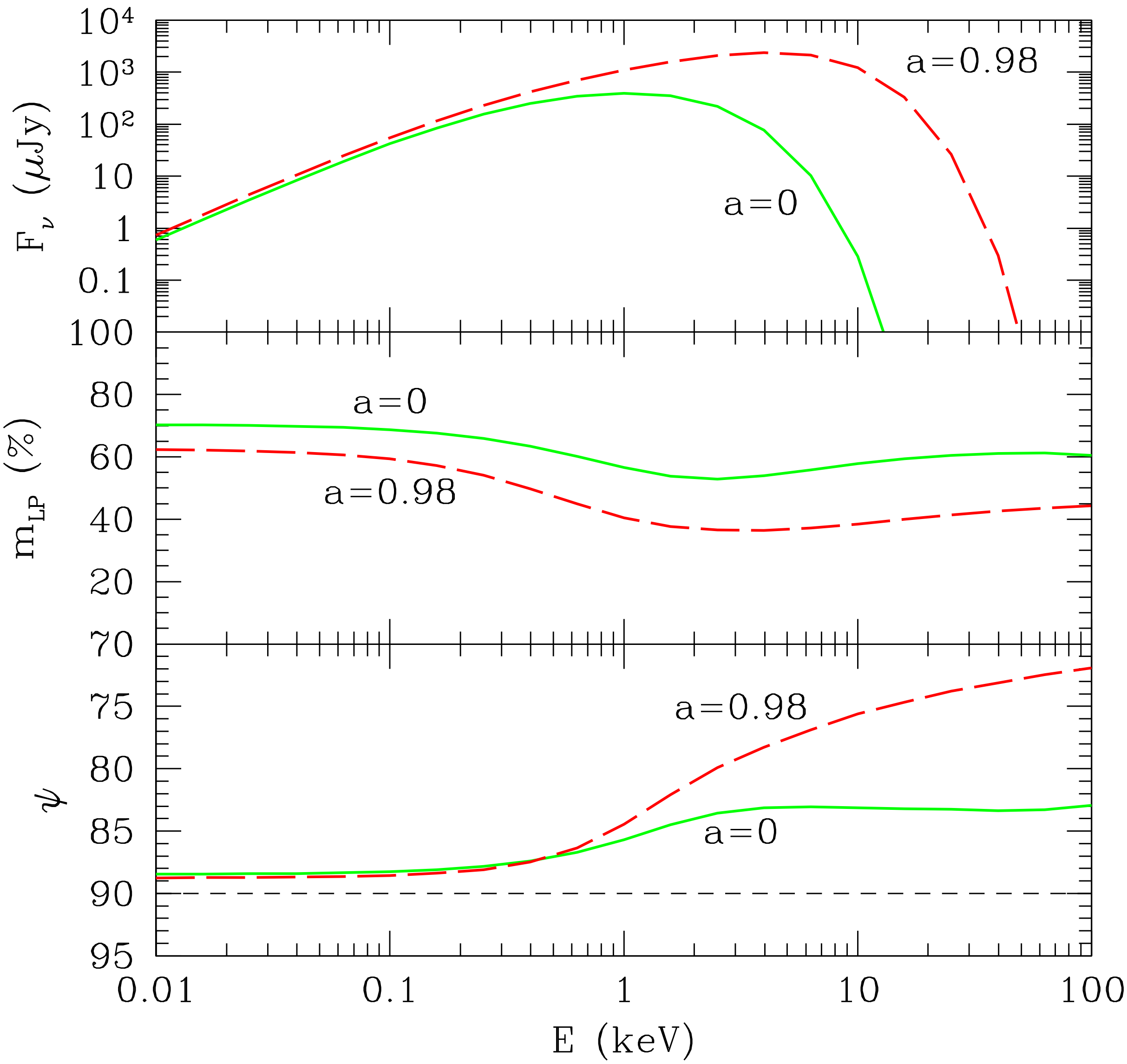
$a = 0$



$a = 0.98$



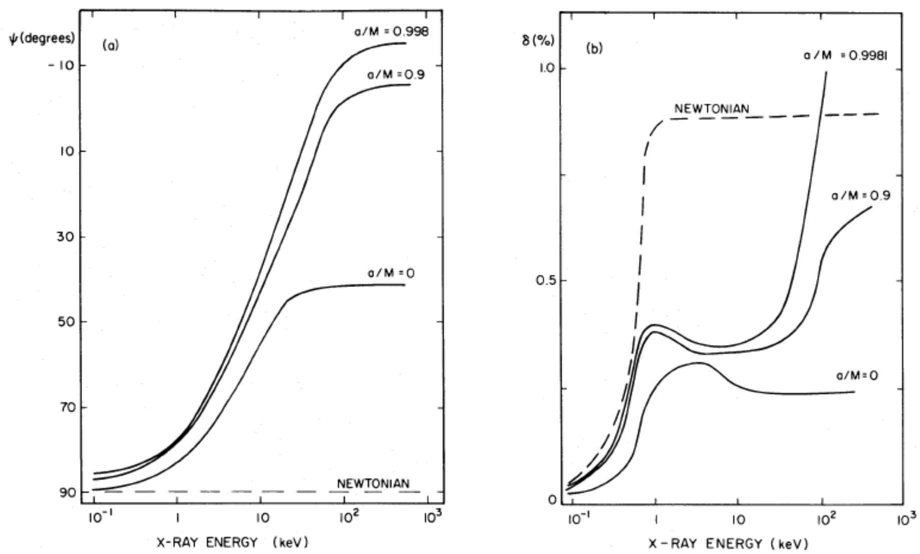
Integrated LP vs. Energy



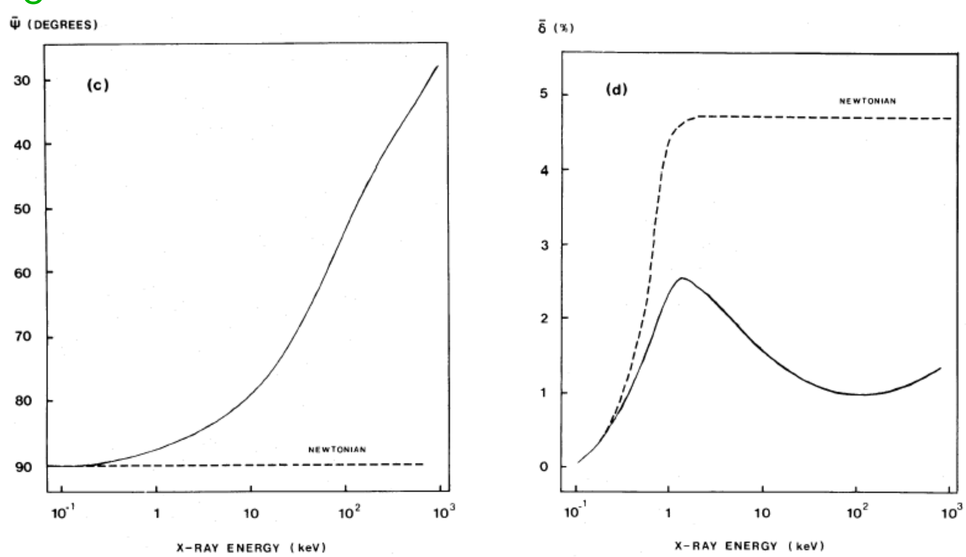
α Disk Models

(Connors, Piran & Stark, 1980, ApJ, 235, 224)

- $\Theta_0 = 41.4^\circ$



- $\Theta_0 = 75.5^\circ$, $a = 0.998$

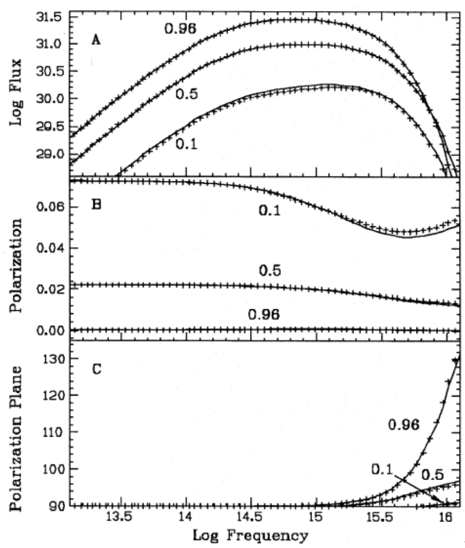


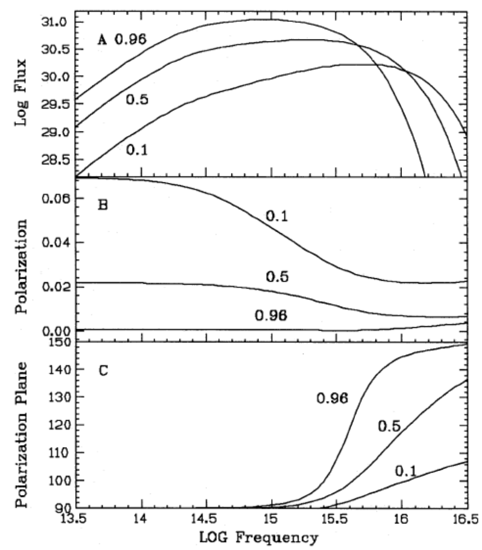
GR α Disk Models of AGN

(Laor, Nezter & Piran, 1990, MNRAS, 242, 560)

- **Black Body**

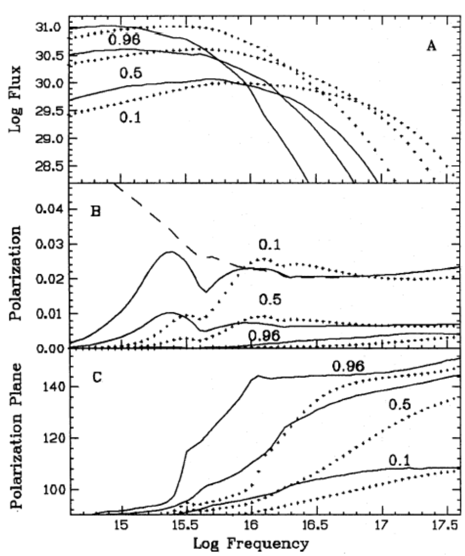
$a = 0$ $a = 0.998$

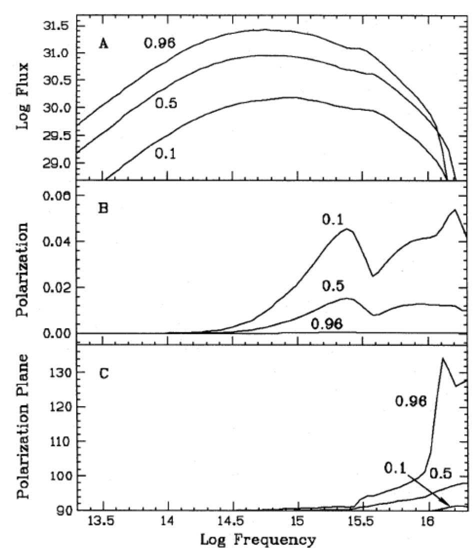




- **Electron Scattering Atmosphere**

$a = 0$ $a = 0.998$





Summary

- GR & SR Depolarize and Rotate LP
- Effects are Achromatic $\longrightarrow$ E Dependence from $T(r)$
- Requires an Intrinsic Polarization

Caveats

- Assumed Flat Disk
- Assumed Intrinsic Polarization Mechanism

Further Information

- Stark & Connors, 1977, Nature, 266, 429
- Connors & Stark, 1977, Nature, 269, 128
- Connors, Piran & Stark, 1979, ApJ, 235, 224
- Laor & Netzer, 1989, MNRAS, 238, 897
- Laor, Netzer & Piran, 1990, MNRAS, 242, 560
- Chen & Eardley, 1991, ApJ, 382, 125
- Agol, 1996, Thesis, UCSB
- Bao, Wiita, Hadrava, 1996, PRL, 77, 12
- Bao, Hadrava, Wiita, Xiong, ApJ, 1997, 487, 142
- Bao, Wiita, Hadrava, 1998, ApJ, 504, 58