GEMS Instrument Performance and Science

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NASA/GSFC

Outline

GEMS Overview

- X-Ray Polarimetry Instrument
- Mission Design

Polarimeter Design and Performance

X-ray Polarimetry Science Objectives

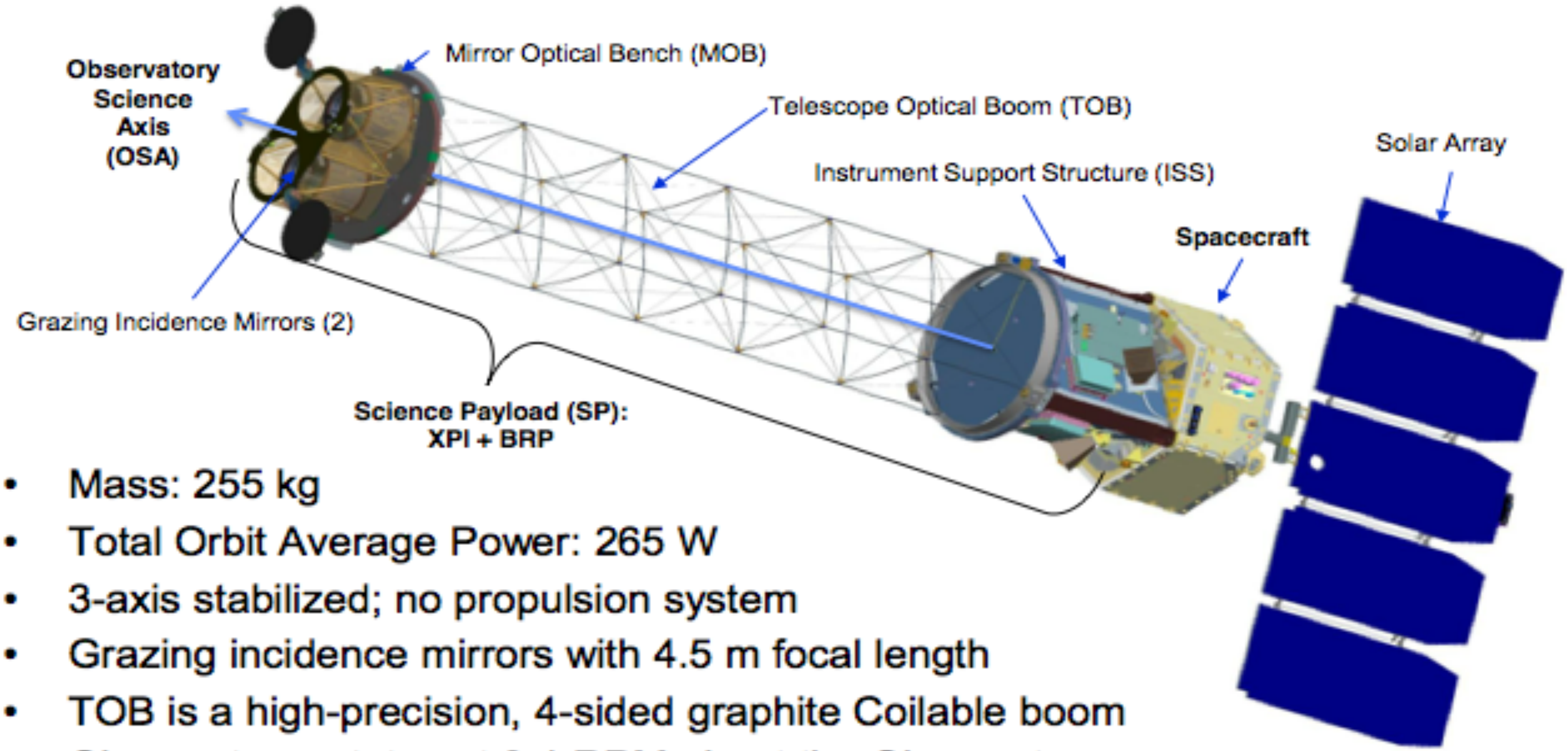
- black holes, neutron stars

Timeline

GEMS was selected as the second SMEX mission in 2009

- Mission to measure the polarization of faint, persistent sources
- TPC Polarimeter behind mirrors with 10 arcmin FoV
- TPC Polarimeter reached TRL-6 (2011)
- GEMS successful PDR (2012)
- GEMS not confirmed due to predicted cost over-run (2012): "..Unacceptable cost, schedule, and technical risk of an AO-selected, cost capped mission.."
  - GSFC Management issues have been addressed
- Polarimeter flight detector components assembled and performance tested (2013)
- Design improvements implemented (2014)
- Performance tests and TRL-6 tests in progress (2014)
  - Many flight components have already been fabricated

The Observatory

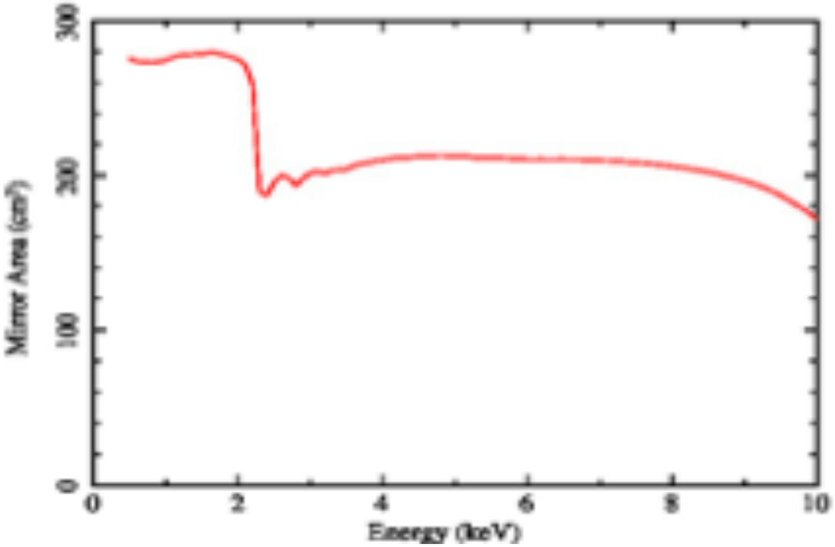


- Mass: 255 kg
- Total Orbit Average Power: 265 W
- 3-axis stabilized; no propulsion system
- Grazing incidence mirrors with 4.5 m focal length
- TOB is a high-precision, 4-sided graphite Coilable boom
- Observatory rotates at 0.1 RPM about the Observatory Science Axis (OSA) for X-ray polarization measurements
- Continuous science data gathering during ground contacts (normally two contacts per day)

The mission design

- Spacecraft bus from Orbital (proven heritage of AIM & GALEX)
- Low Earth Orbit at 575 km
- 28.5 degree inclination
- Pointing 90 $^{\circ}$ ± 30 $^{\circ}$ from the sun
- Long pointings (1 - 60 days)
- ~ 50 % duty cycle (considering earth occultations and South Atlantic anomaly passages with the voltage off)
- All the sky passes overhead in 6 months
- Mission Operations at Orbital's multisatellite facilities
- Downlink once per day
- Uplink once per week
- 35 sources observable to important sensitivity limits in 9 months
- 2 year lifetime capability enables 15 months of General Observer program

Mirrors have heritage fromASCA, Suzaku, BBXRT



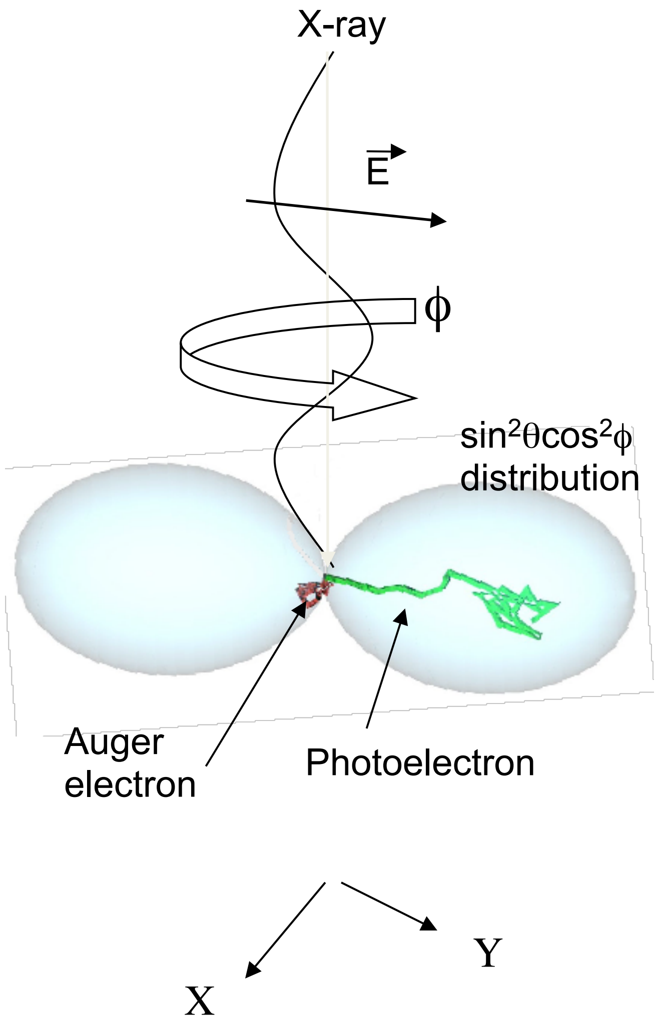
Mirrors are fabricated in quadrants

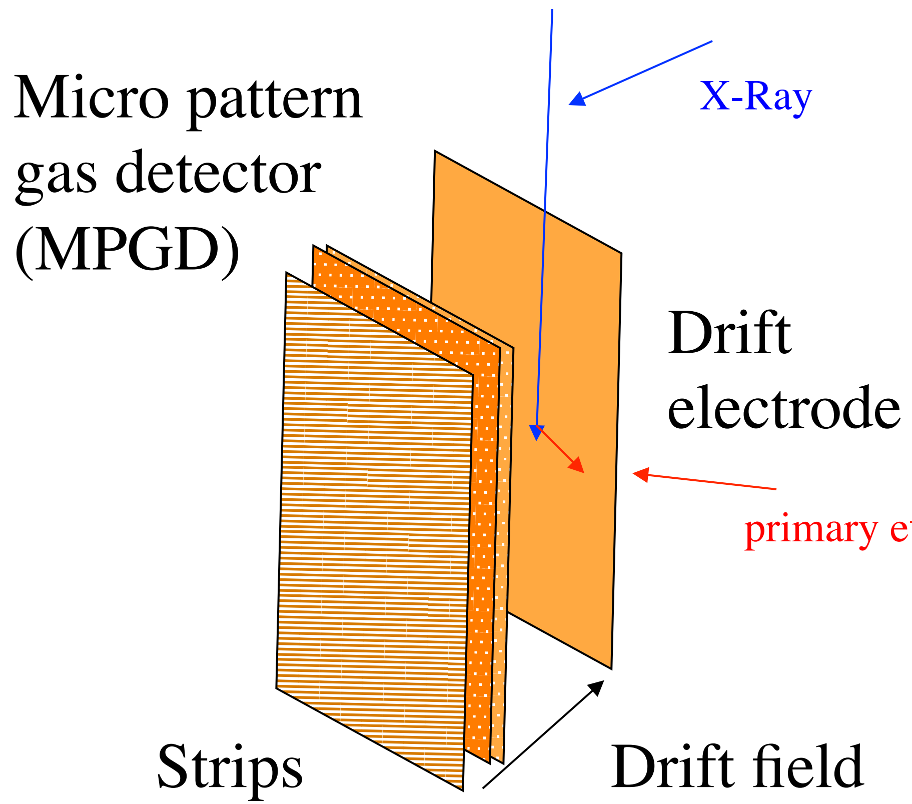
Area for one mirror

Telescope optical boom is coilable with 4.5m focal length

A Time Projection Chamber (TPC) is used to track the photoelectron paths

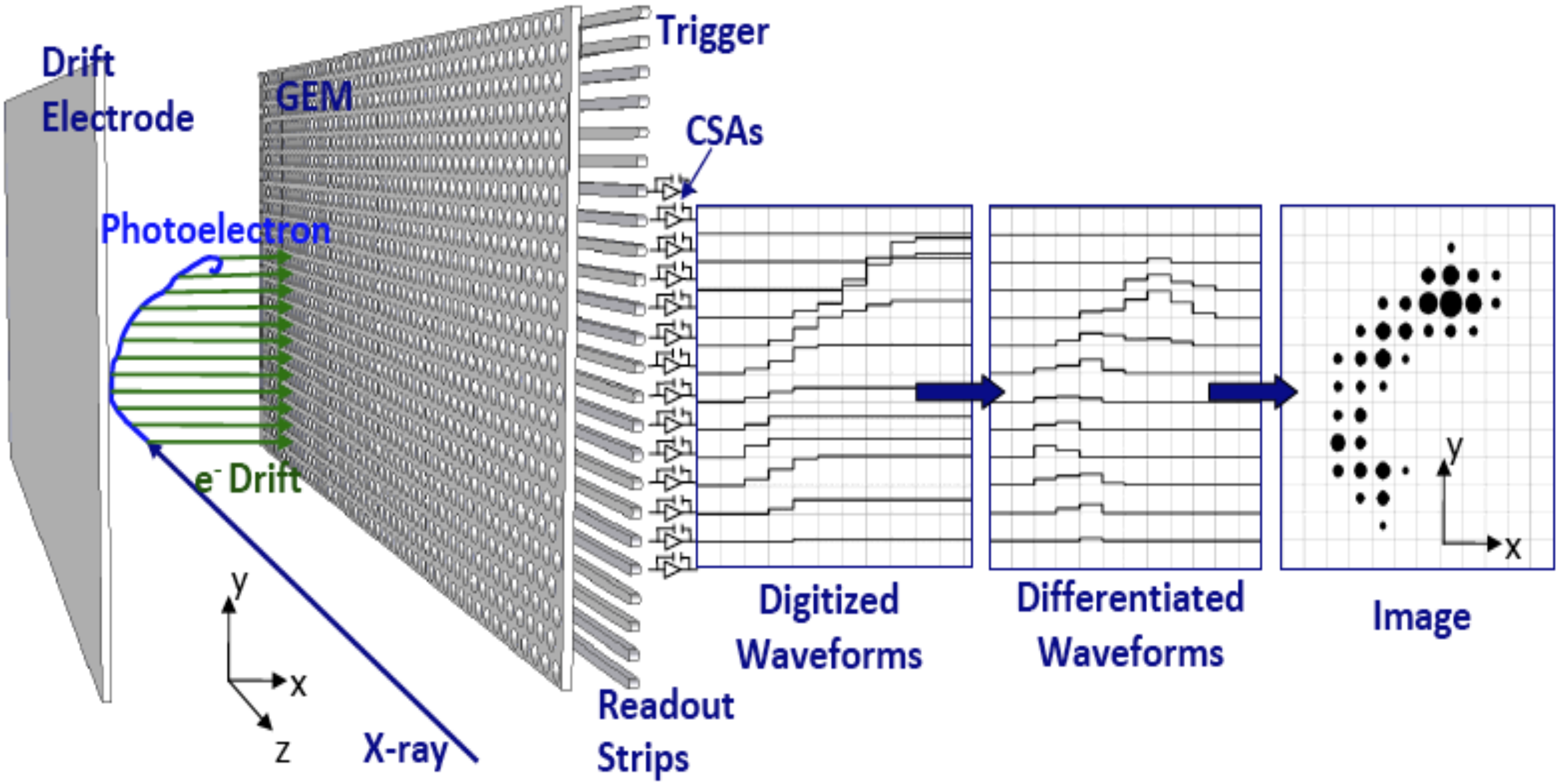
Measures the projection of the electron track in the X-Y plane with time and space measurements





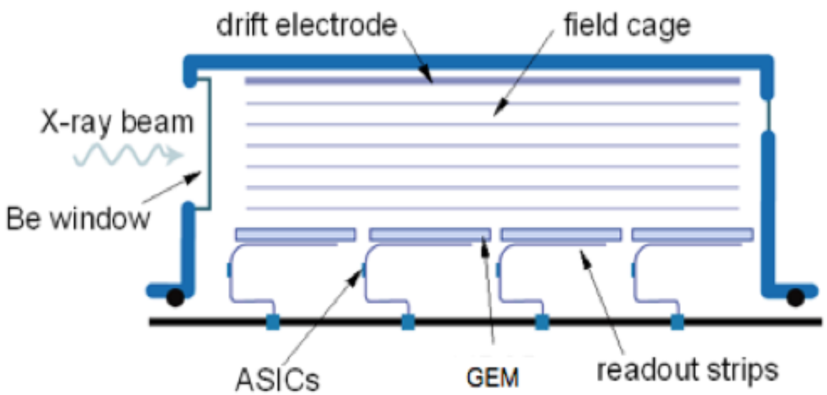
The TPC

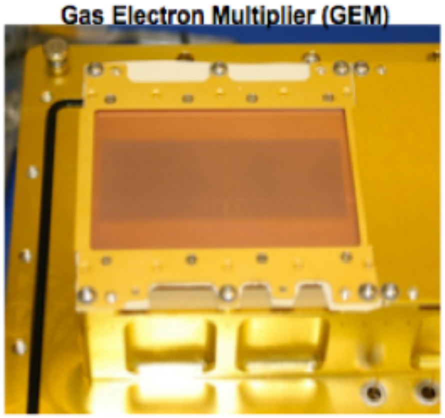
- Image pixels are formed by readout strip pitch (y) and drift velocity/sampling rate (x)
- Quantum efficiency (depth) is perpendicular to readout (drift) direction

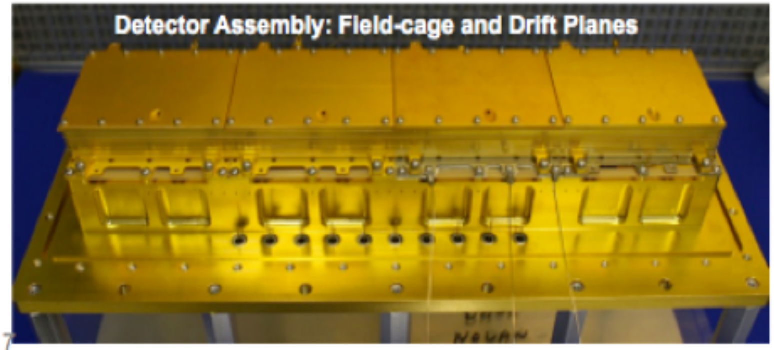


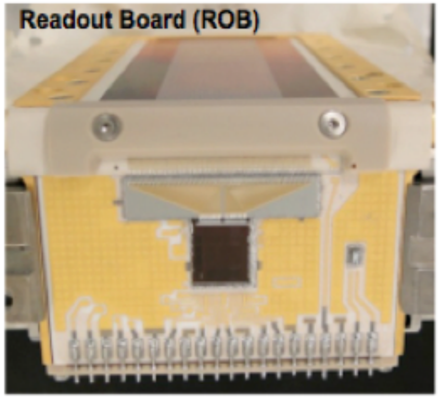
GEMS Detectors

- Each polarimeter: Four 7.8 cm detectors contained in 190 T DME
- QE: ~60% at 3 keV



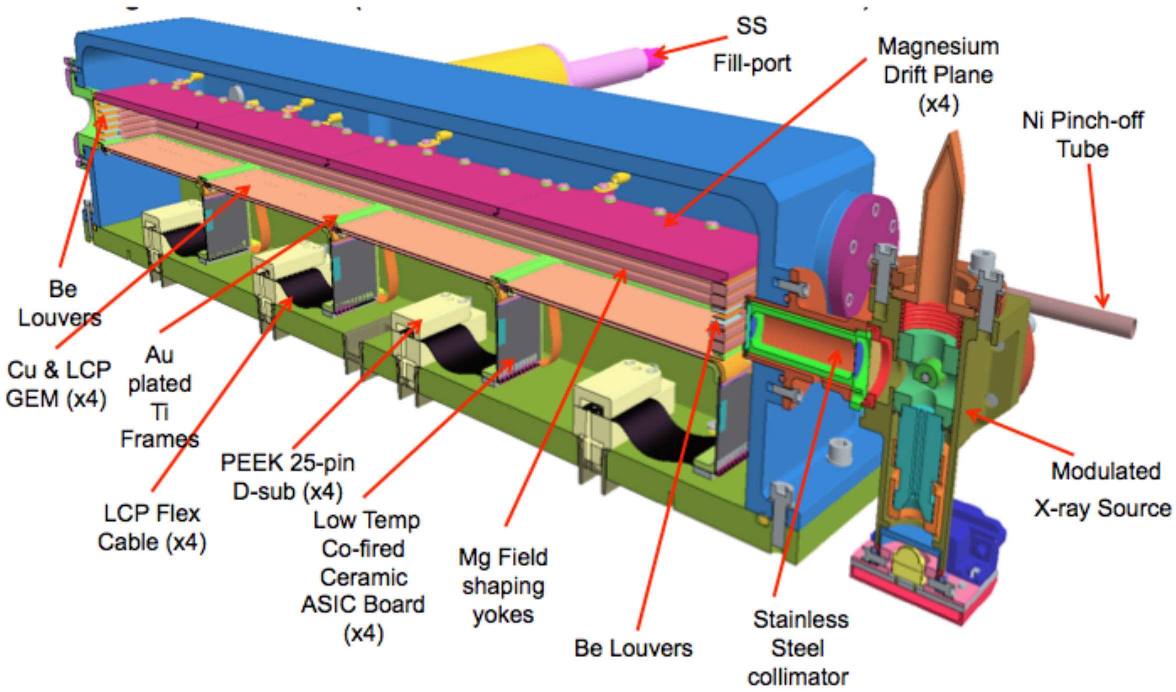




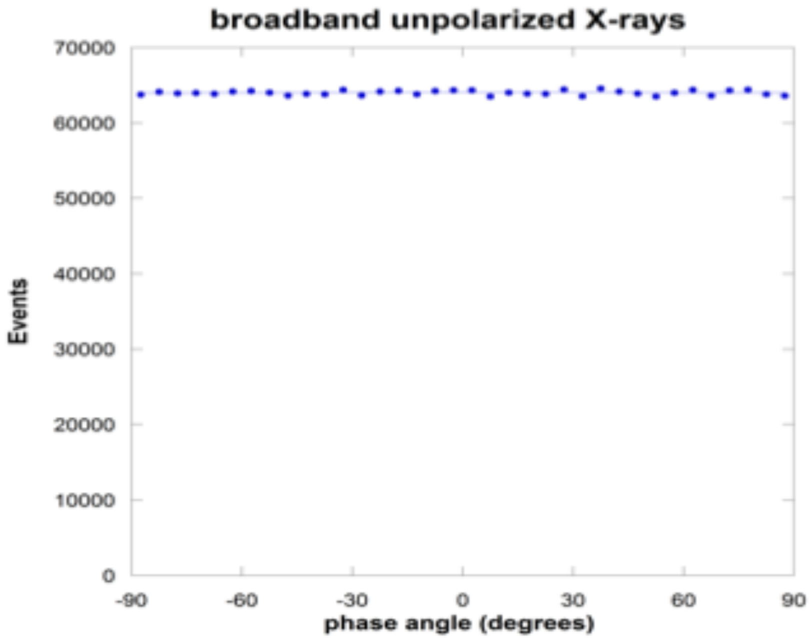


Polarimeter Materials

Every exposed surface is gold coated to minimize contamination and background (absorbs 4.5 keV from Ti)

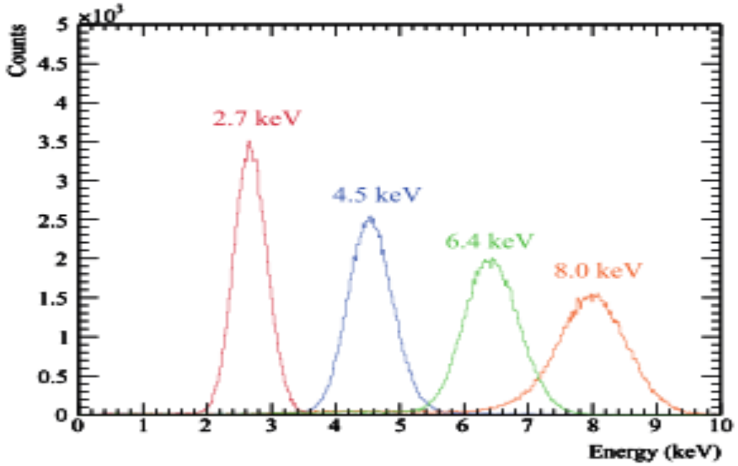


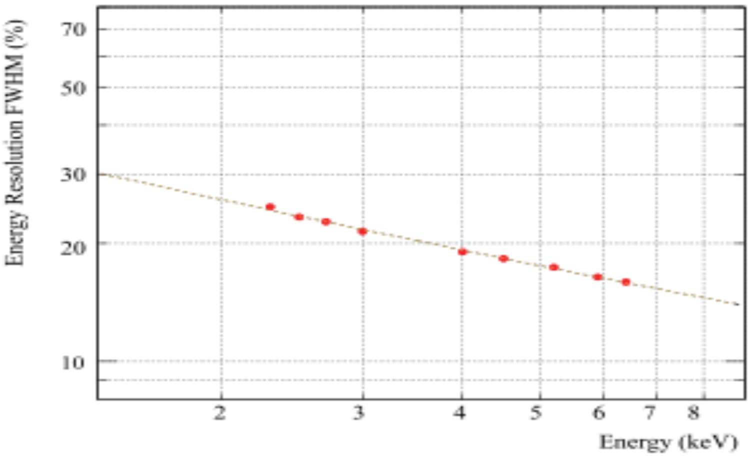
Detector response to unpolarized light



Response to unpolarized light shows acceptable systematics
Modulation factor μ=0.07%±0.09%, χ^2=1.46
Broadband input spectrum up to 5 keV. 2 x 10^6 photons

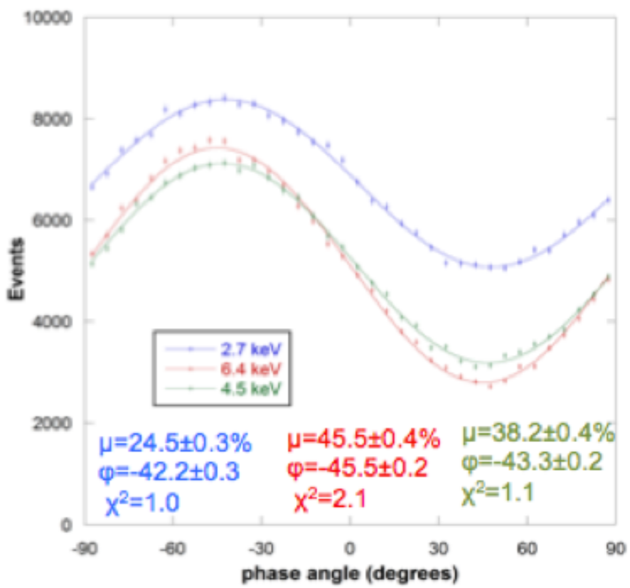
Energy resolution

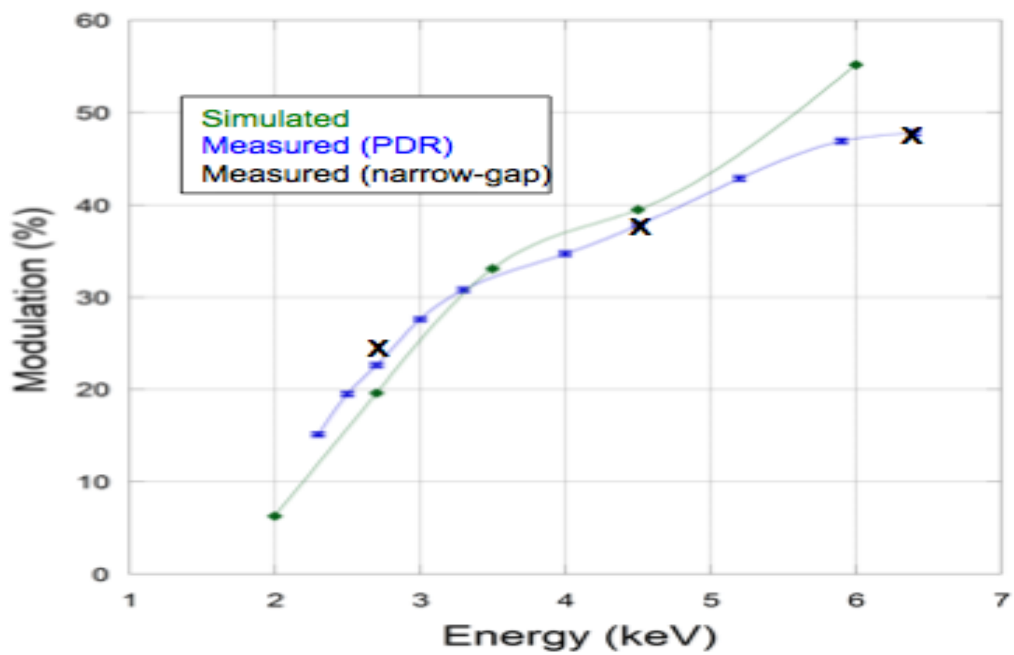




Energy Spectra at four incident energies (2.7, 4.5, 6.4 and 8.0)

Response to polarized X-rays





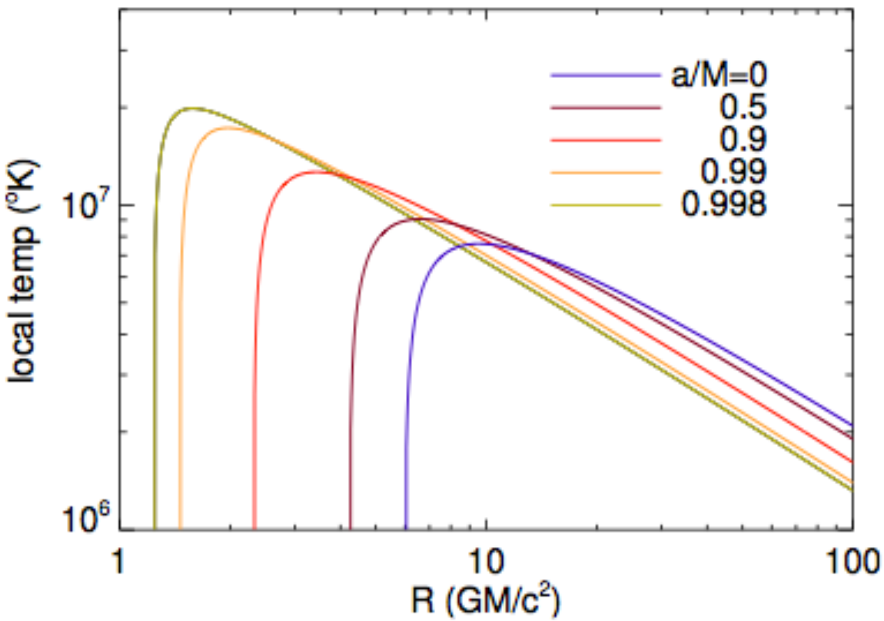
Modulation and polarization measured at three energies using 100% polarized X-rays are consistent with simulations and meet requirements

X-ray polarimetry addresses a wide range of science topics

- Black holes: spin measurement, coronal geometry
- Rotation powered pulsars: location/mechanism of emission, viewing angles
- Magnetars: field geometry, outburst mechanism
- Blazars: field geometry, emission mechanisms: leptonic vs. hadronic jet composition
- Shell supernova remnants: field geometry
- Accreting pulsars: accretion column geometry, QED tests
- Plus:
    - Cataclysmic variables: accretion column structure
    - Low mass X-ray binaries: accretion flow structure
    - Active stars: geometry of flare region
    - Structure of nearby jets, eg. cen A
    - Tests of fundamental physics (Lorentz invariance)

Black Hole – Thermal state

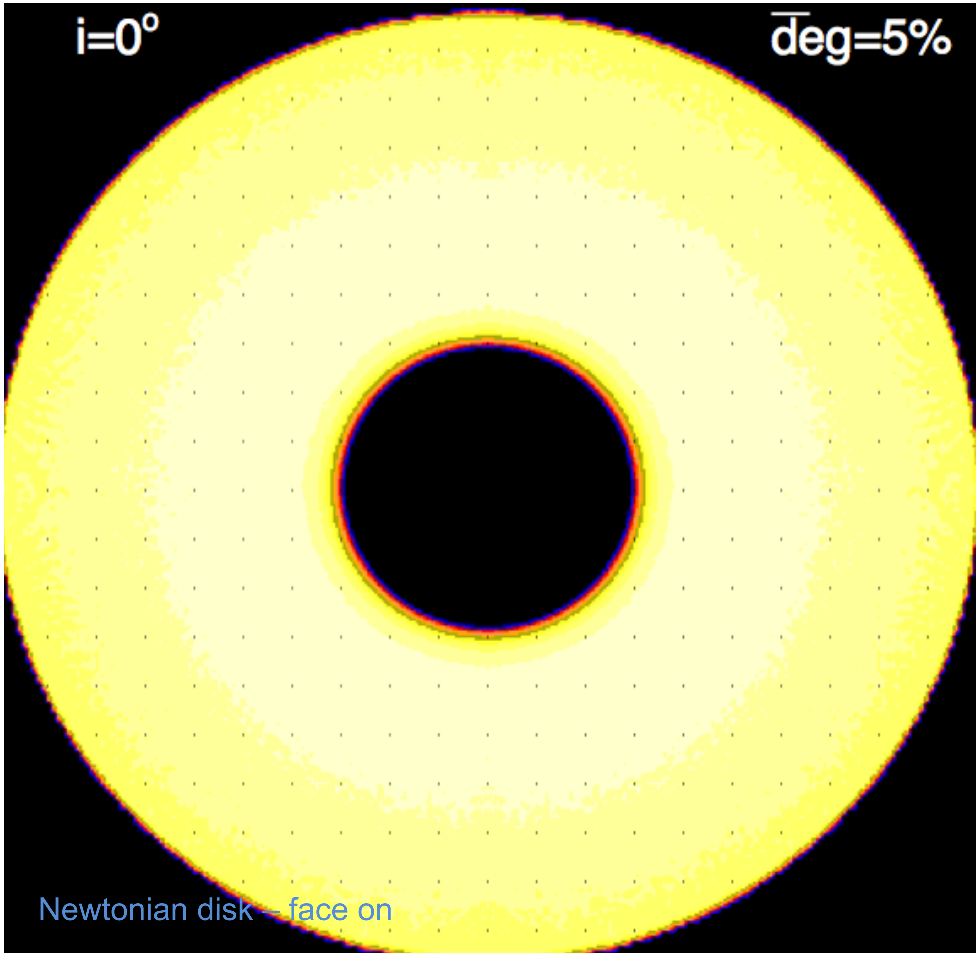
- $T(R)$ increases towards BH
- $T(R) \sim M^{-1/2}\dot{M}^{1/4}$
- most of the flux from $R \lesssim 10R_S$
- GR $\rightarrow$ last stable orbit (ISCO)
- position of ISCO function of BH mass, spin



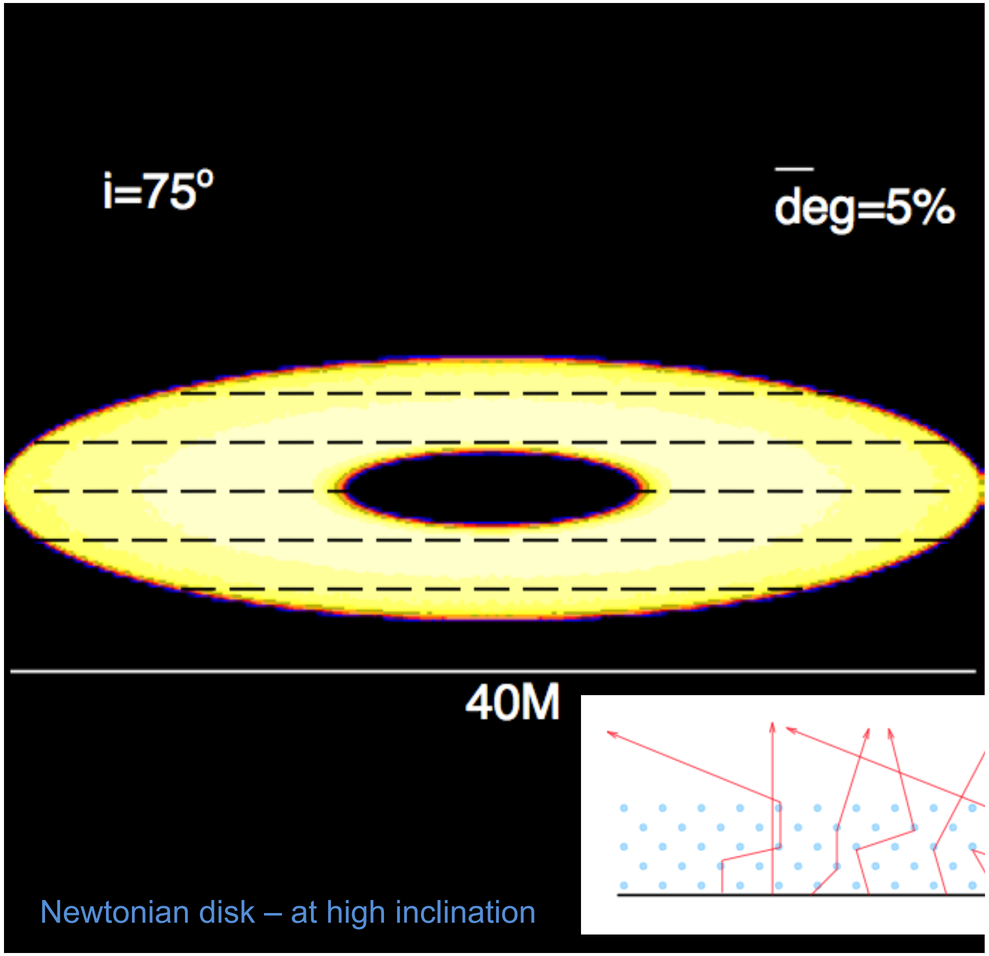
Novikov & Thorne (1973)

Emission characteristics depend on Environment (M-dot), Black Hole (Spin), and geometry (inclination). Special/General Relativity are important.

Polarized Image of black hole accretion disk

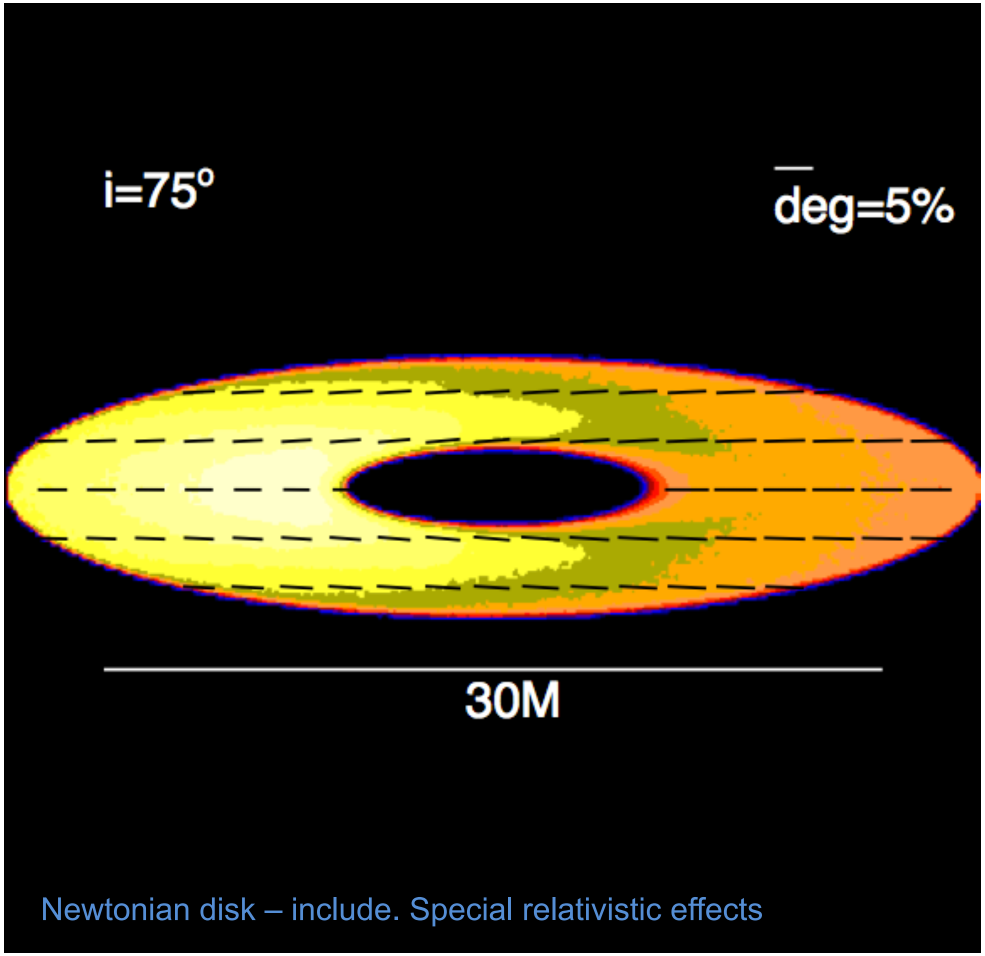


Polarized Image of black hole accretion disk

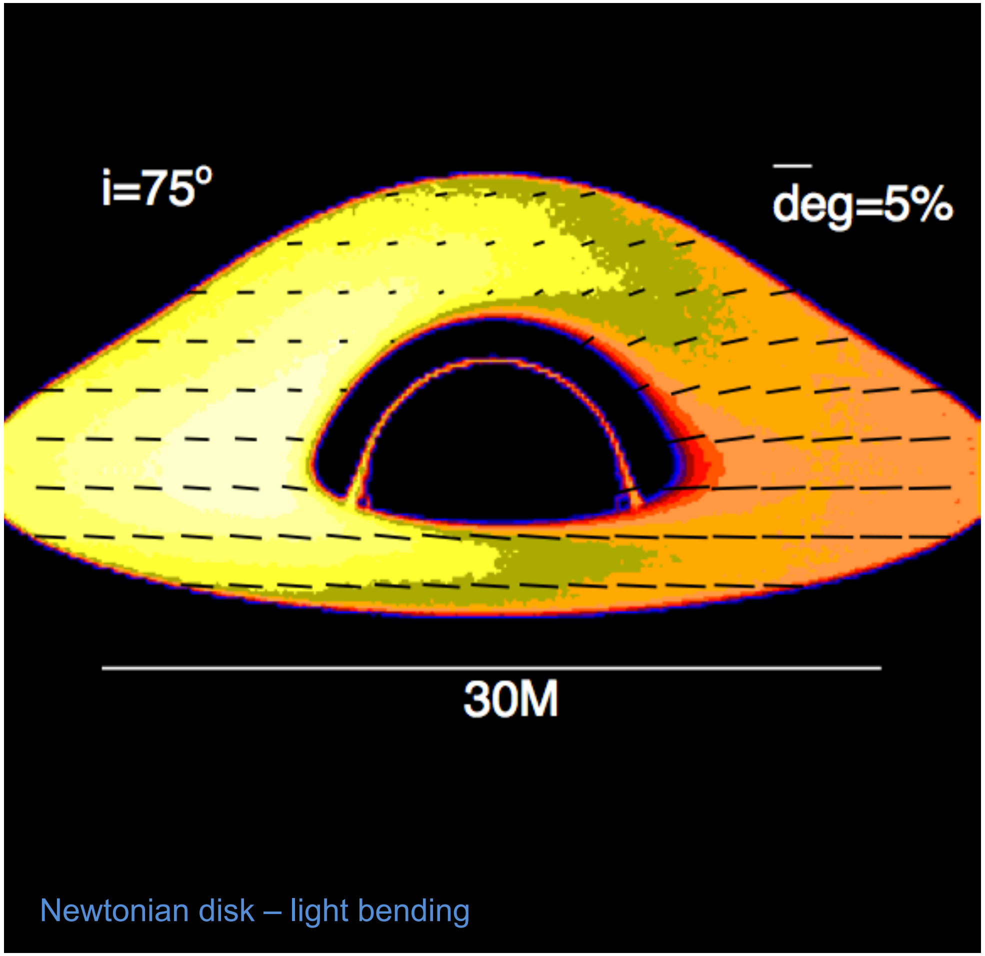


Newtonian disk – at high inclination

Polarized Image of black hole accretion disk



Polarized Image of black hole accretion disk



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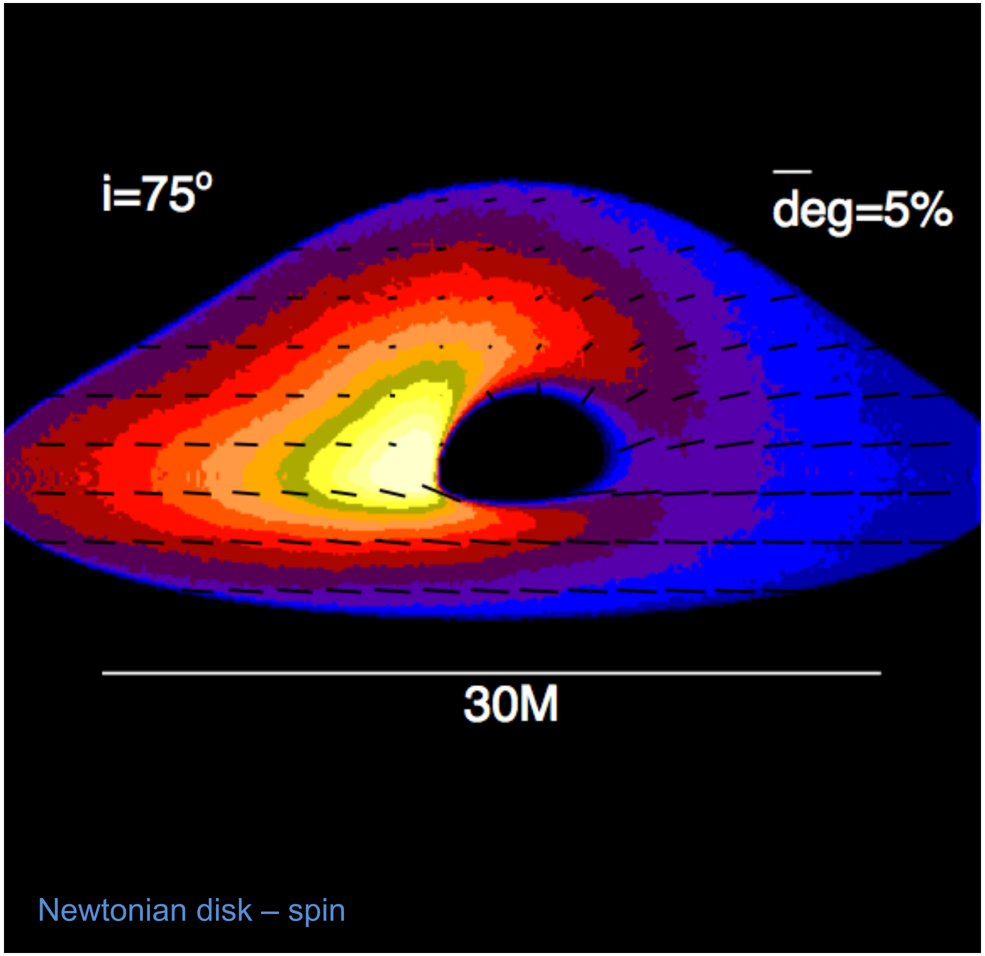
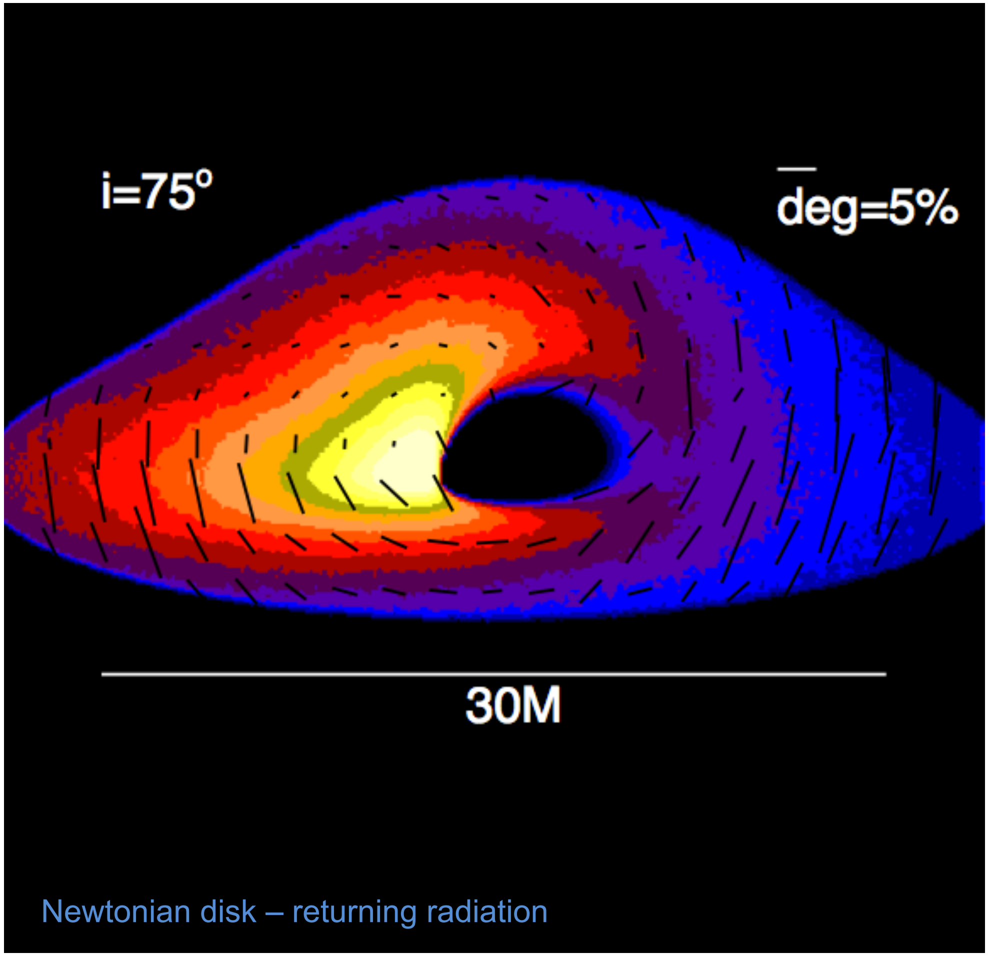
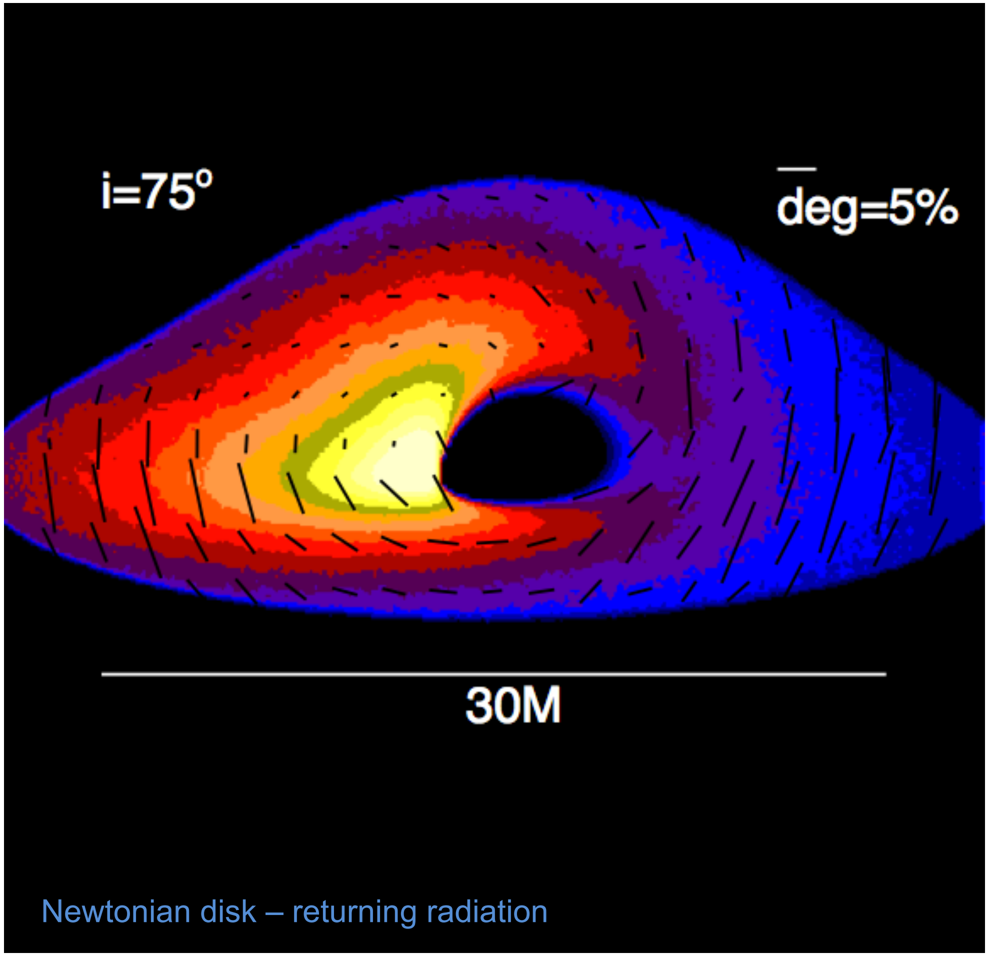


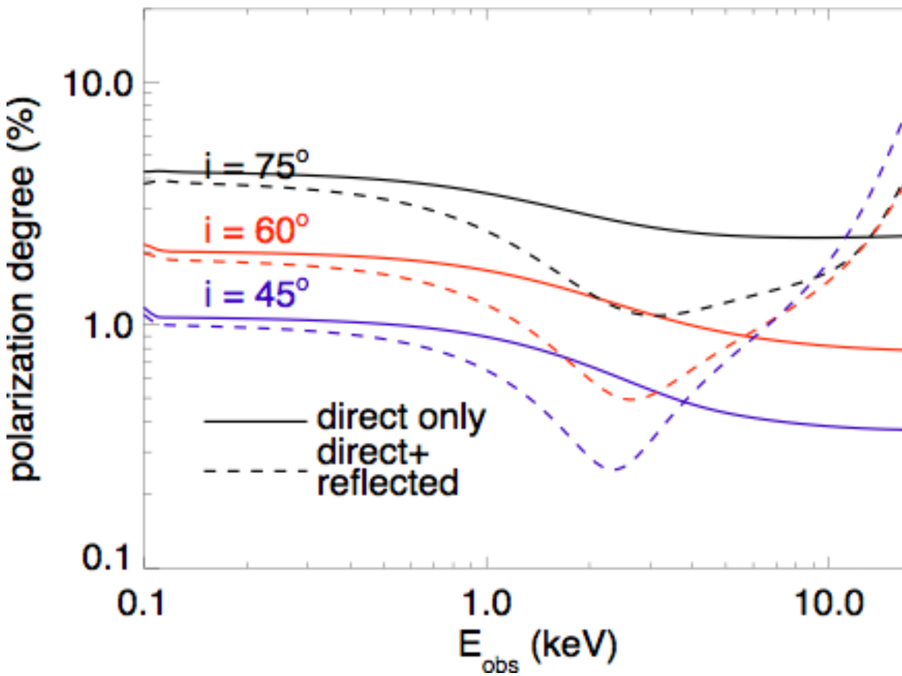
Polarized Image of black hole accretion disk

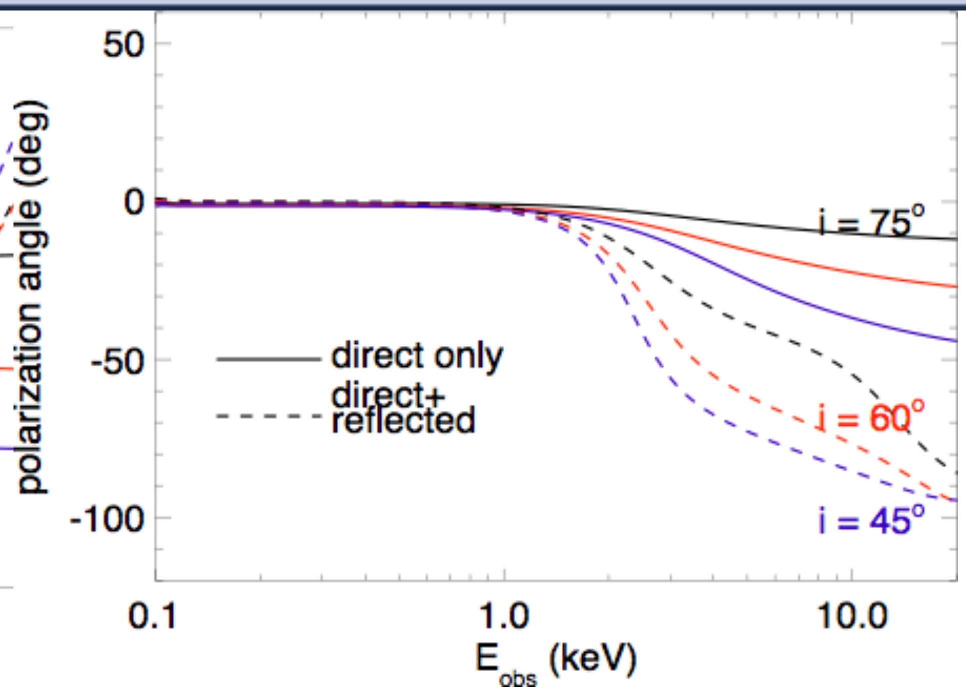


Polarized Image of black hole accretion disk



Two regimes in black hole polarization behavior -



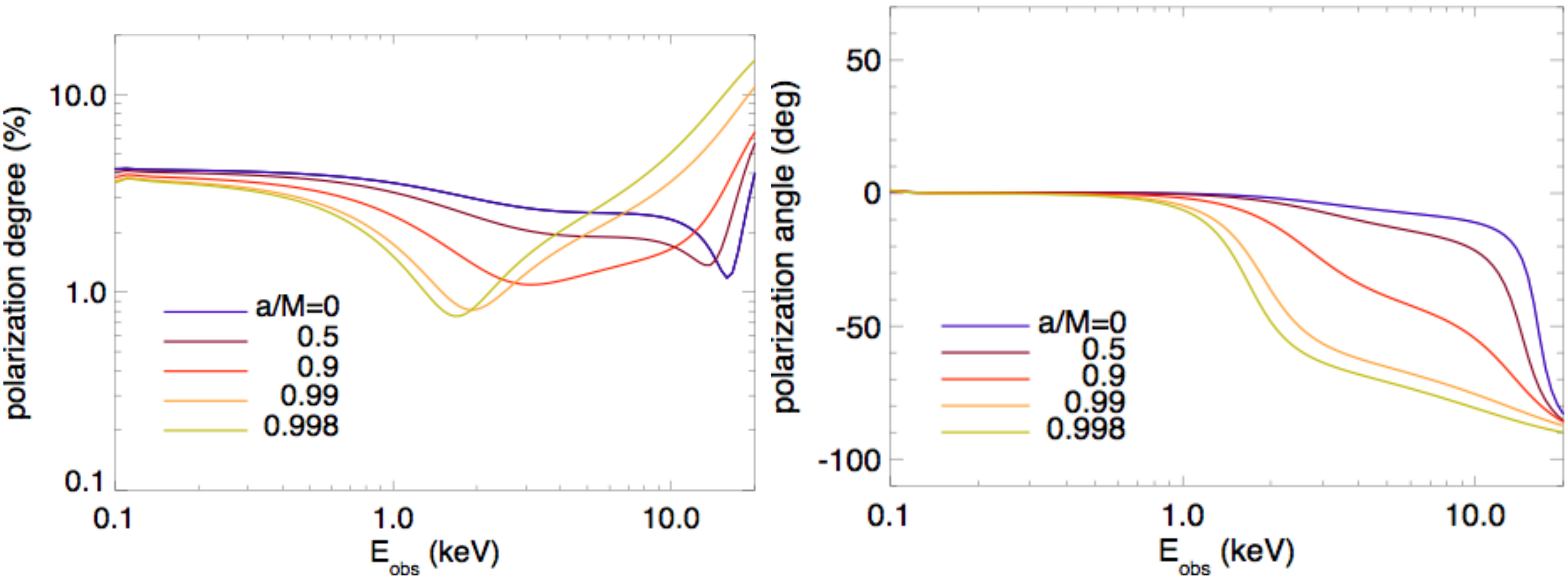


(Schnittman and Krolik 2009)

- At lower X-ray energies, photons are emitted far from the black hole
- Relativistic effects are weak
- Position angle is parallel to disk plane and is a function of inclination, as predicted by Chandrasekhar

- At higher energies, relativistic effects become important
- polarization direction becomes perpendicular to disk and fractional polarization increases

Strength of return radiation is sensitive to spin

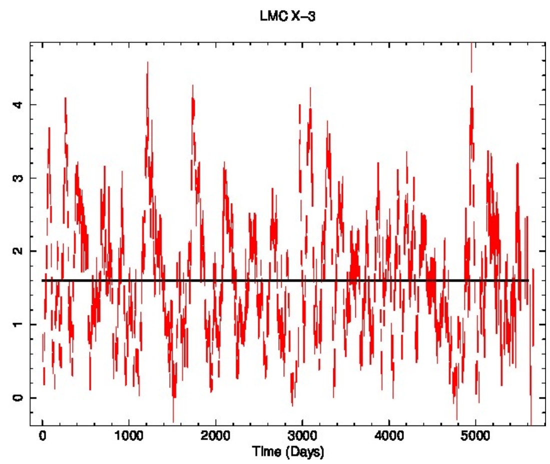


(Schnittman and Krolik 2009a)

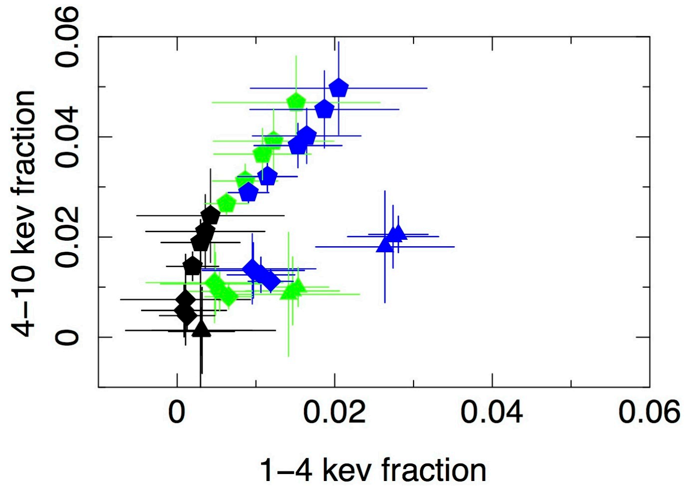
- Strength of return radiation depends on spin
- Therefore, transition energy between the direct and return-dominated regimes, and strength of high energy polarization, depend on spin

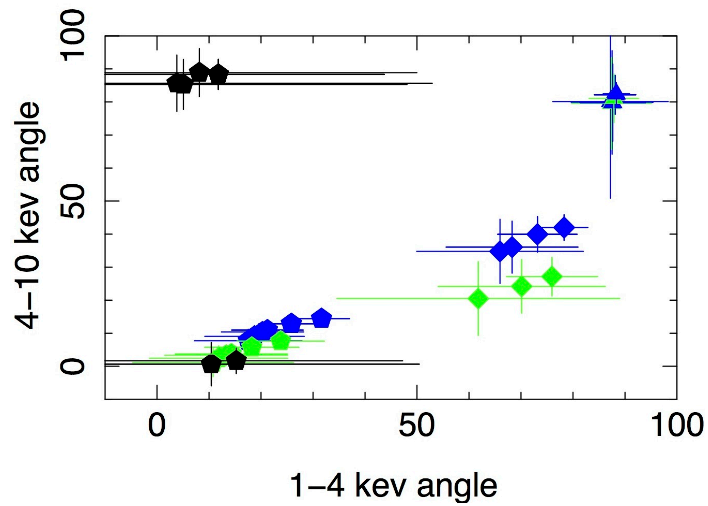
Black Hole soft state– LMC X3

- Soft state is most straightforward for measurement of black hole spin, inclination
- Black hole sources do not stay in soft state
- Simulations in 2 energy bands show that spin and inclination determination is robust against changes in black hole intensity state



Black Hole soft state– LMC X3





10 simulated observations of LMC X3

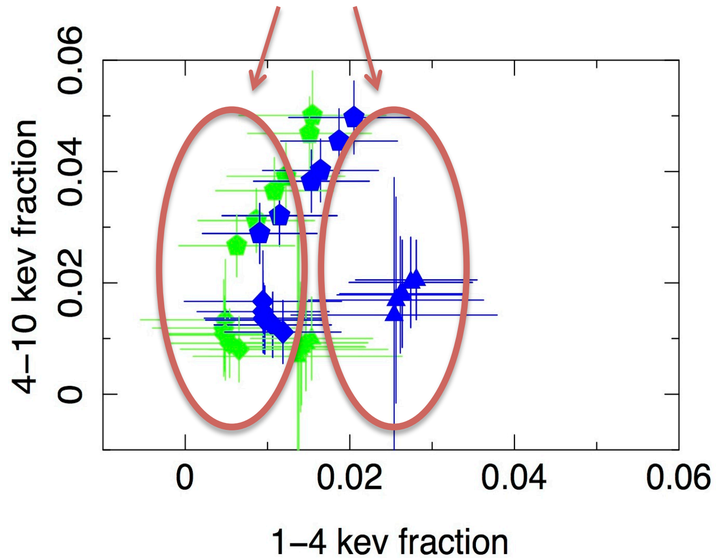
Not sensitive for low inclination; error bar on angle

i=30
i=60
i=75

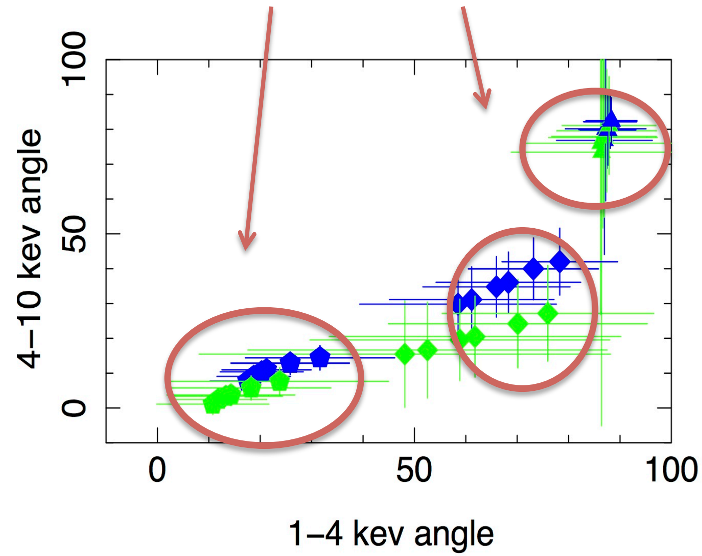
▲ a/m=0
◆ a/m=0.9
⬟ a/m=0.998

Black Hole soft state– LMC X3

Low energy polarization fraction separates high vs low inclination



Low vs. high energy polarization position angle separates spin



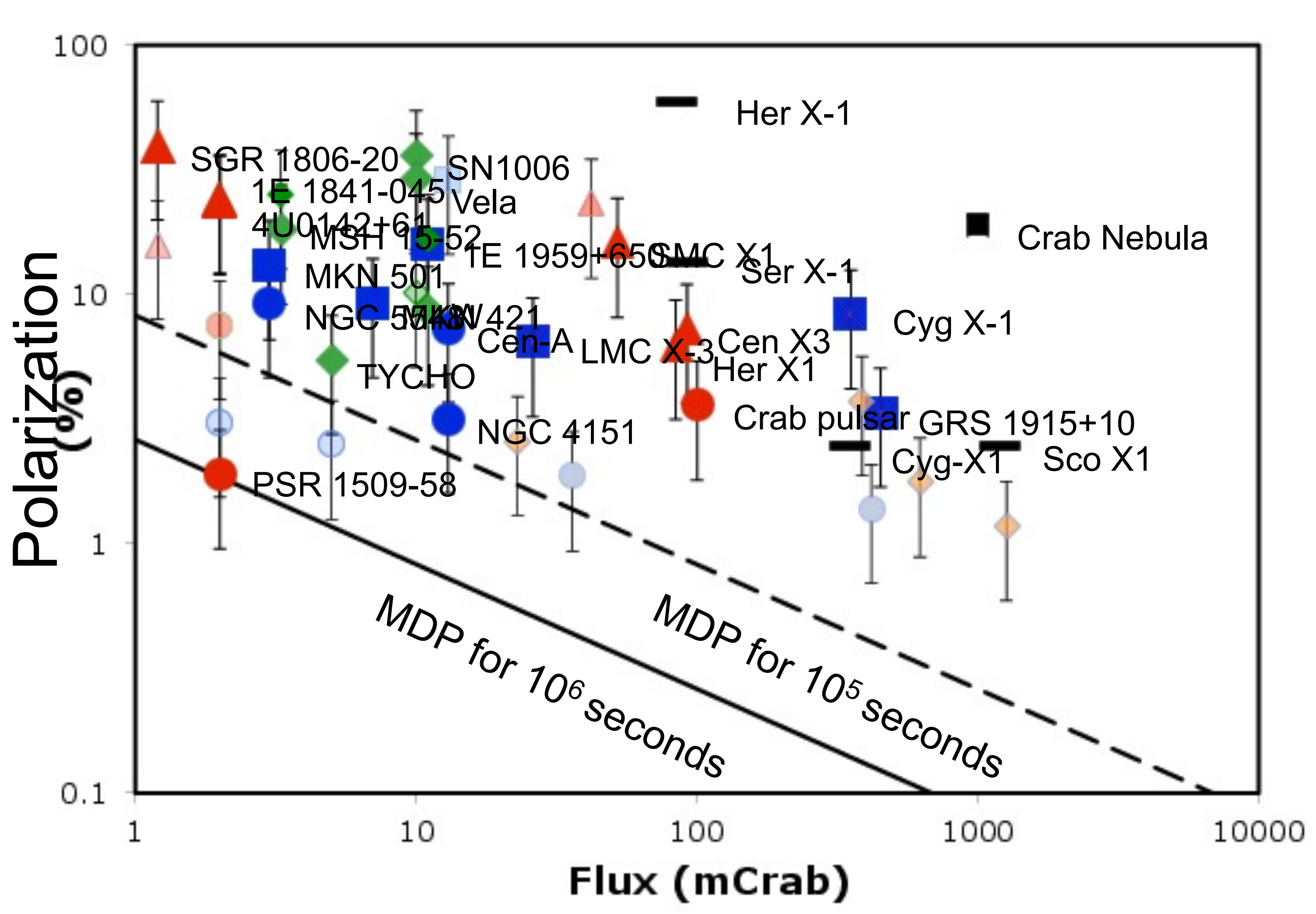
Spin-inclination contours are highly inclined with respect to continuum fitting methods

i=30 ▲ a/m=0

i=60 ◆ a/m=0.9

i=75 ⬟ a/m=0.998

A small mission can make numerous sensitive observations in 6-12 months



Many of the brightest sources in the sky are X-ray binaries

- Binary stars will show signature of inclination and structure in their polarization vs. orbital phase
- If light comes from scattering in one component by the second component then
- i=0 → constant polarization, angle swings π
- i=90 → variable polarization, angle constant
- Attempts to use this in optical have been mixed
- Many bright sources have very uncertain inclinations
- X-rays are more promising
    - X-ray source is likely less extended
    - Companion star and wind are second component
    - Inclination dependence is robust against presence of winds or streams.
- Plus there is information about the circumstellar gas in polarization signal
- We have made models for single scattering polarization from binaries for various scenarios

Astron. Astrophys. 68, 415—427 (1978)

Polarisation by Thomson Scattering in Optically Thin Stellar Envelopes

II. Binary and Multiple Star Envelopes and the Determination of Binary Inclinations

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Department of Astronomy, University of Glasgow, Glasgow G12 8QQ, Scotland, U.K.

The Astrophysical Journal, 221:200–210, 1978 April 1

A POLARIMETRIC DETERMINATION OF BINARY INCLINATIONS: RESULTS FOR FIVE SYSTEMS

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Received 1977 August 25; accepted 1977 October 11

ABSTRACT

A method is presented for estimating the orbital inclinations of binary systems from phase-locked polarization variations when those variations arise from certain single-scattering processes, principally scattering by optically thin regions of extrastellar material. In the lowest-order approximation the variable polarization, over an orbital period, twice traces out an ellipse in polarization space. The eccentricity of this ellipse is related to the orbital inclination by $\epsilon = (\sin^2 i)/(1 + \cos^2 i)$. This relation is shown to be quite general, the only restrictions being that: (1) the photometric variability be small; (2) eclipses of the scattering regions do not occur; and (3) the system have mirror symmetry through the orbital plane. The method is then applied to five binaries with known inclinations: AO Cassiopeiae and u Herculis, for which observations have already been published; and Algol, U Sagittae, and V444 Cygni, for which we present our observations for the first time here.

Subject headings: polarization — stars: binaries — stars: eclipsing binaries

I. INTRODUCTION

In papers discussing the phase-locked polarization variations in AO Cassiopeiae (Rudy and Kemp 197… u Herculis (Rudy and Kemp 1977), the variations were shown to be functions of the orbital inclinations. Po… tion curves calculated for the known inclinations of AO Cas and u Her were found to be in good agreemer…

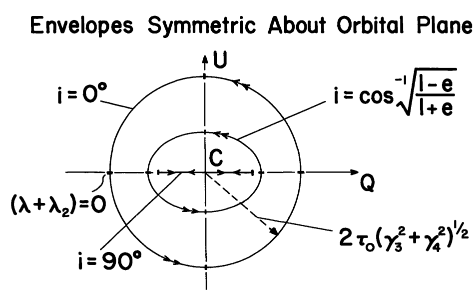
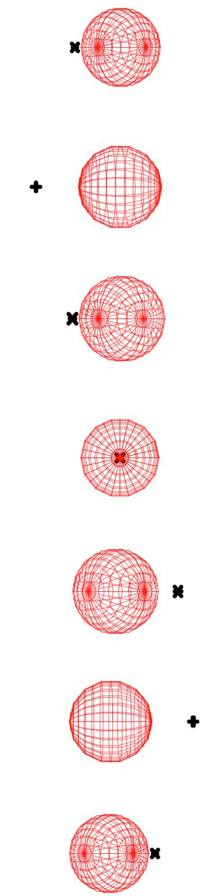
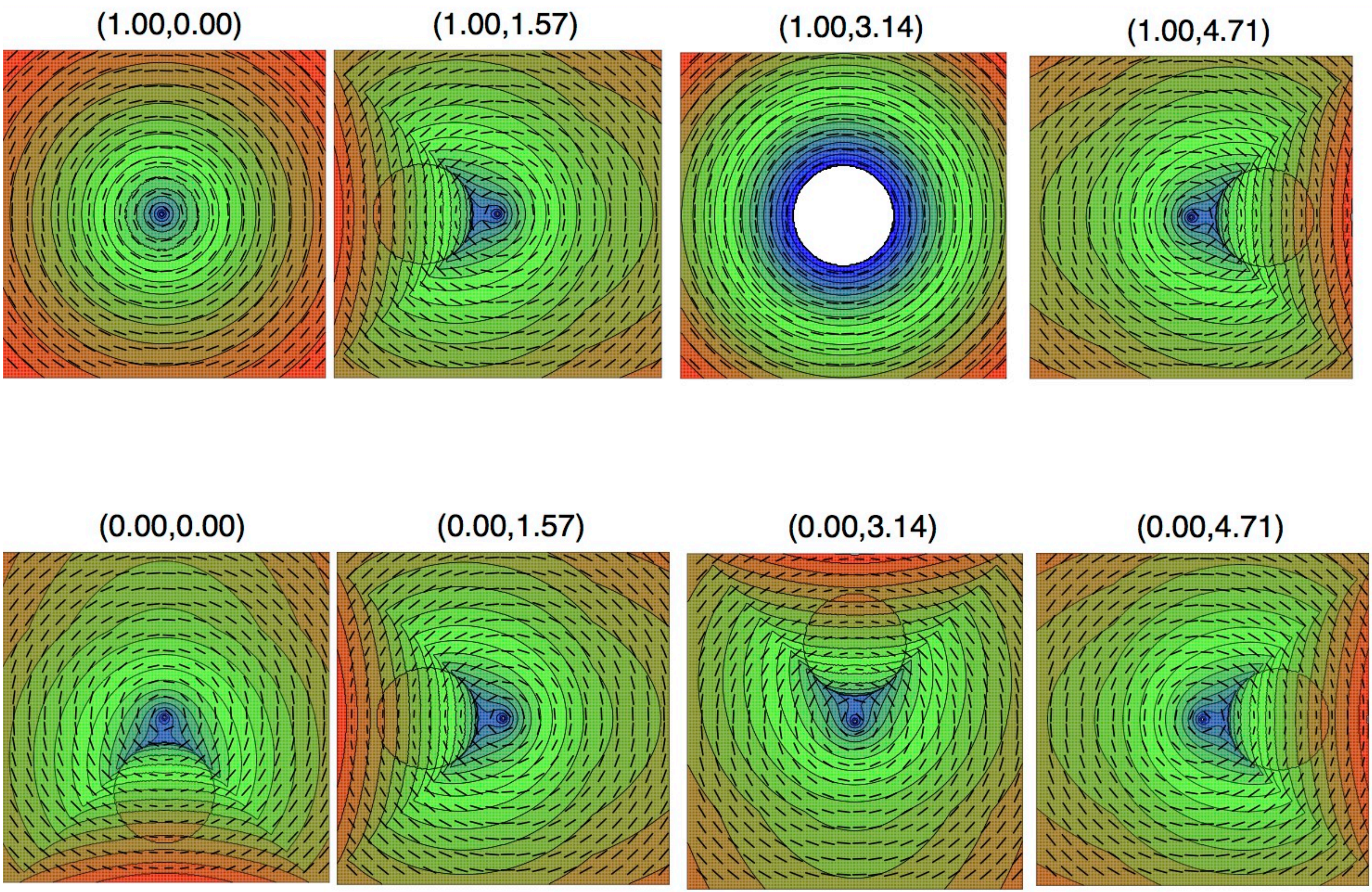


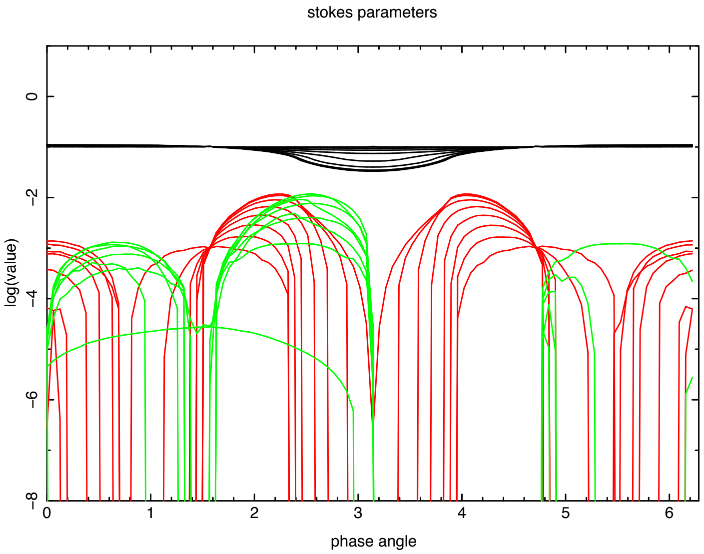
Fig. 7. Relationship of the properties of all envelopes with material concentrated in or symmetric about the orbital plane to the eccentricity, size and orientation of the resulting elliptical Q, U locus (executed twice per orbit)

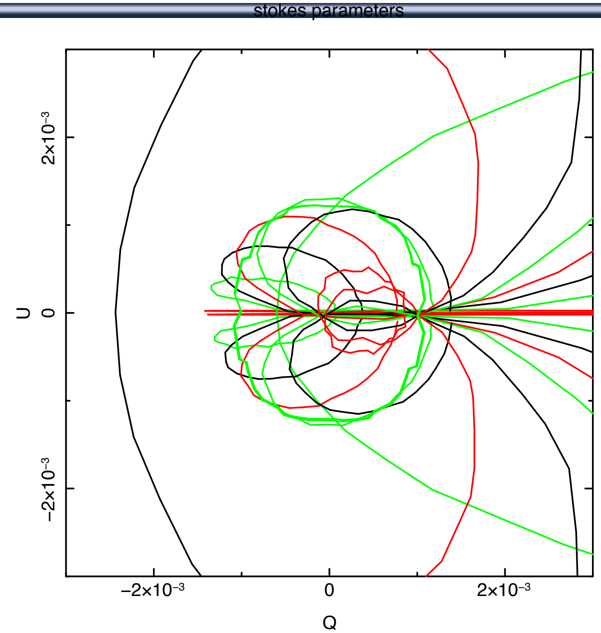


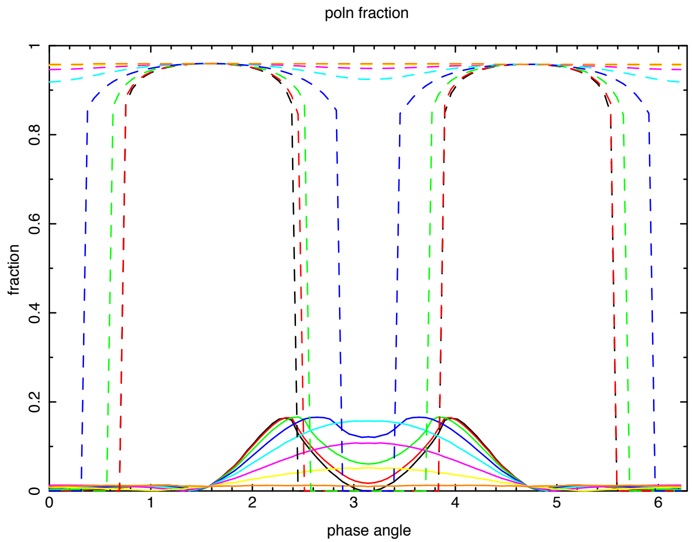
Polarization maps vs (sin i, phase angle) for binary with spherical wind from primary

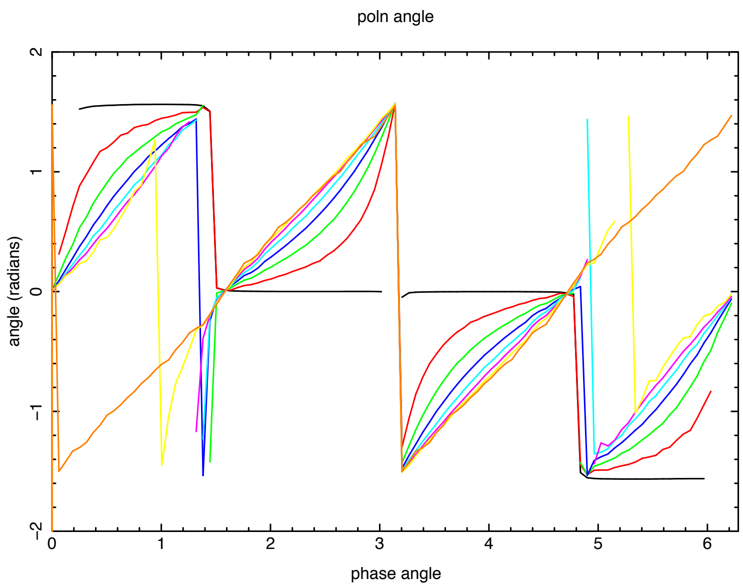


Stokes parameters and polarization vs phase angle for X-ray binary with spherical wind

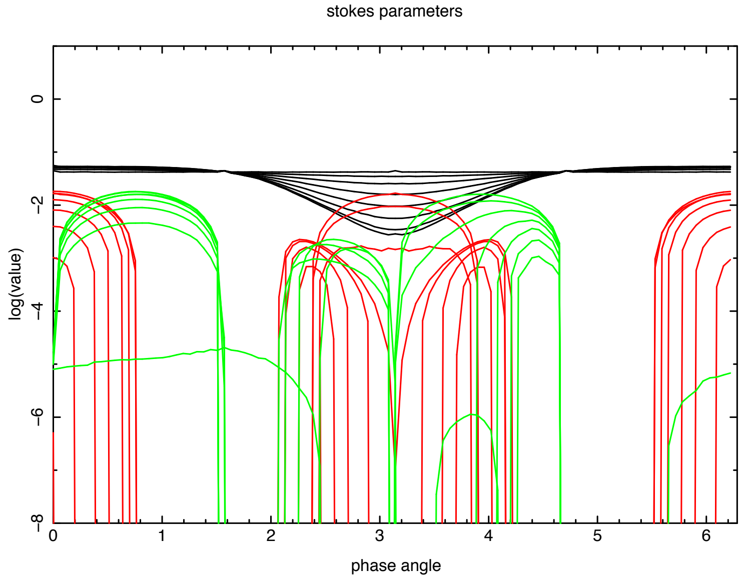


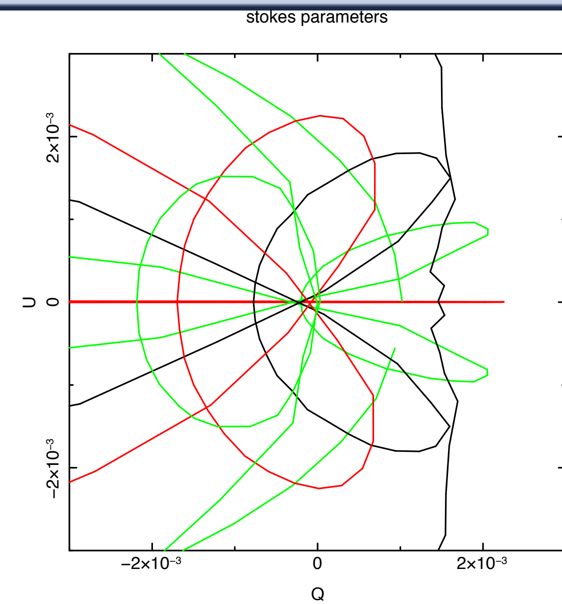


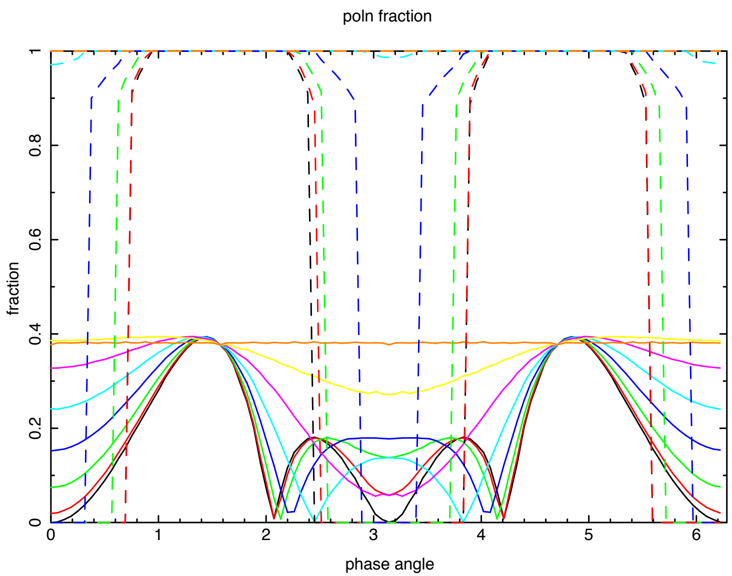


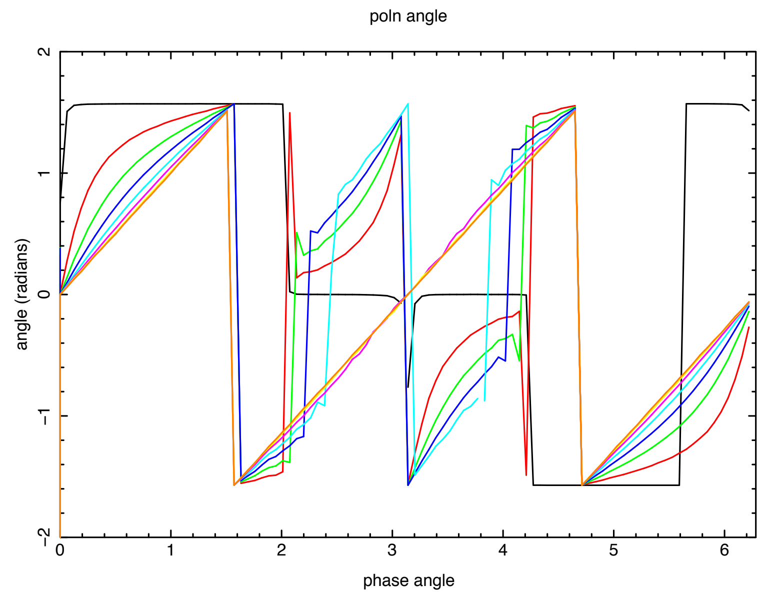


Stokes parameters and polarization vs phase angle for X-ray binary with reflection from companion star

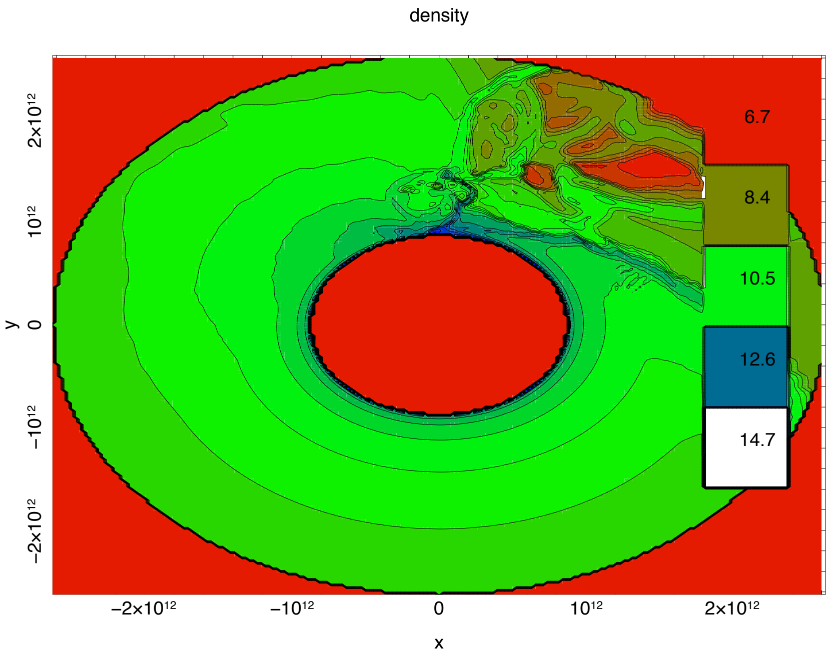


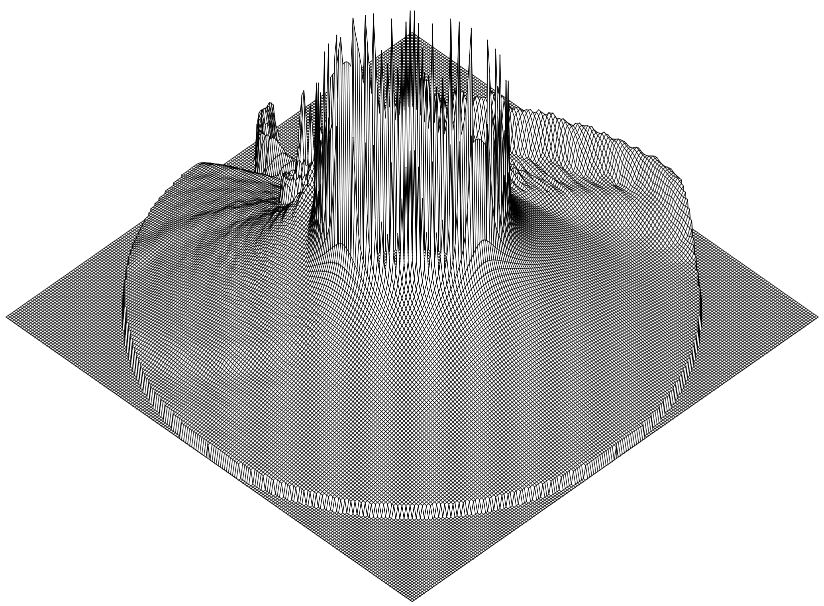






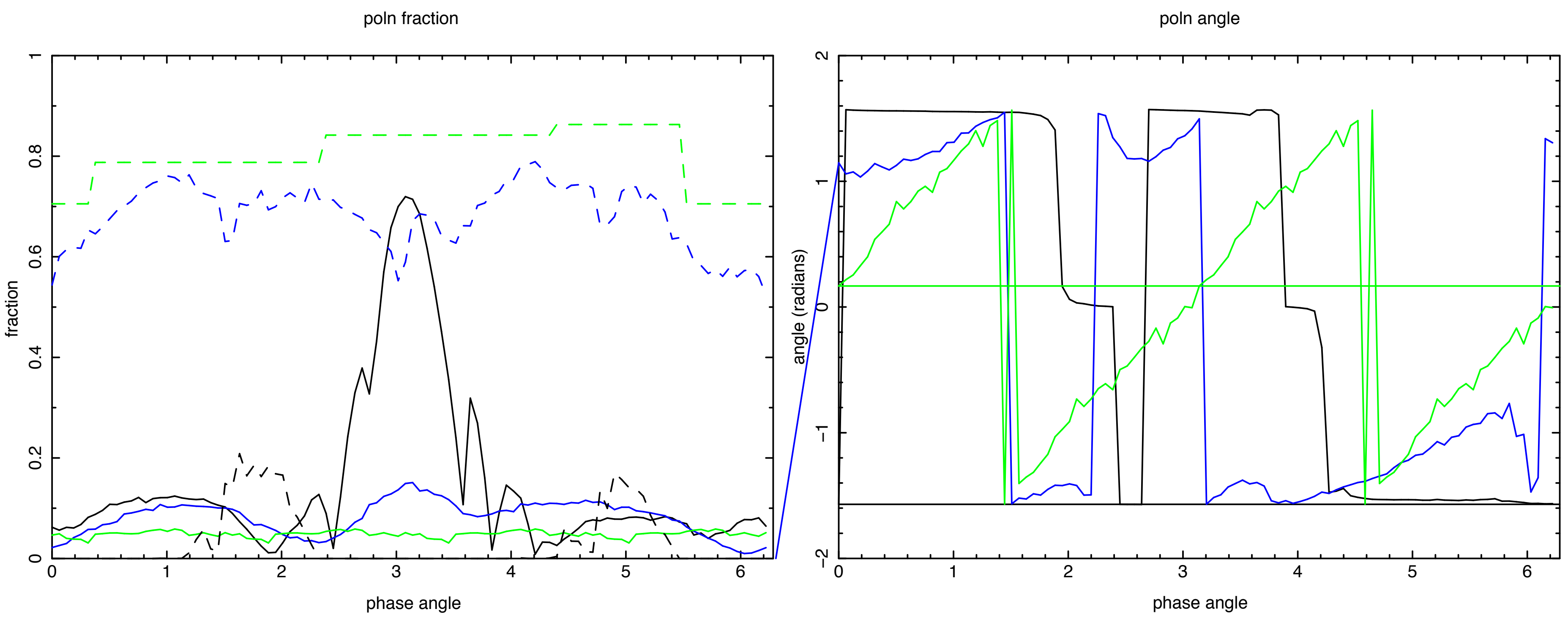
Hydrodynamic interaction between wind and compact object





results in density distribution with asymmetry relative to line of centers

Stokes parameters and polarization vs phase angle for X-ray binary with hydrodynamic wind



In spite of asymmetry, qualitative features of spherical case are preserved

GEMS can measure polarization from a variety of X-ray sources

- Targets include black holes, neutron stars, X-ray binaries, PWNs and SNRs
- Polarization is measure of geometry, more direct than any other technique
- X-ray sources are (often) more compact and difficult to image directly than sources which are studied in other wavelengths
- X-ray polarization probes inner regions of sources which cannot be studied using other techniques
- Gems strengths: effective area/mass, technical maturity and heritage

backup