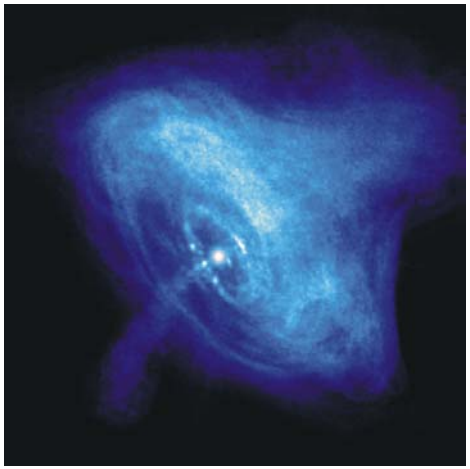
# PRIZE
# PolaRIZation Explorer

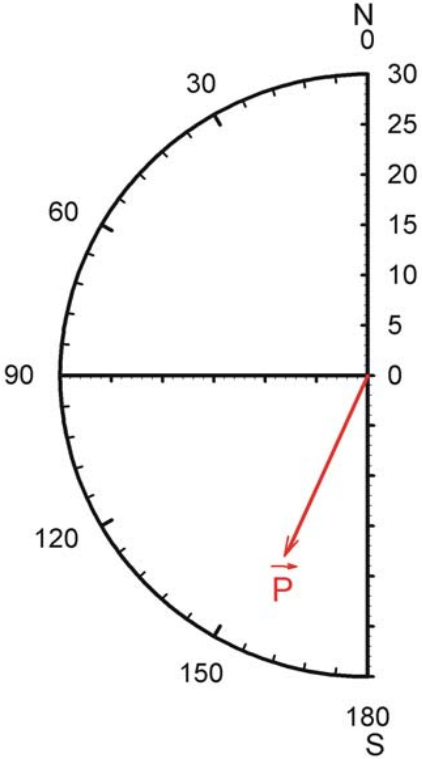
SAO

**Principal Investigator:** Eric Silver, The Smithsonian Astrophysical Observatory

**Industrial Partner:** Ball Aerospace & Technologies Corp.

**Science Team:**
Smithsonian Astrophysical Observatory
Massachusetts Institute of Technology
Danish Space Research Institite
Russian Space Research Institute
Ball Aerospace & Technologies Corp.
Sonoma State University
Lawrence Livermore National Laboratory
Max-planck-institute For Astrophysics
Cambridge University
University of Illinois At Urbana-Champaign
Instituto Nazionali Di Astrofisica, Palermo
Harvard College Observatory
University of California at Berkeley
Gettysburg College
McGill University
University of California at San Diego
Florida Institute of Technology






SAO MIT DSRI ИКИ Ball

## Science Payload

The Two SODART Flight Mirrors
and
The SXRP Polarimeter Flight Unit
from the
Spectrum X-Gamma Payload

A Replica of the Bragg Crystal Polarimeter
in SXRP

## Mission Overview

*A Unique Combination of Features*
Two 8 m, High Throughput Telescopes for
Sensitive X-Ray Polarimetry

Energy-Resolved X-Ray Polarization
Measurements
in the 2 - 16 keV Energy Band

Accurate Photon Timing for Pulsar Studies

## Key Mission Characteristics

Two SODART mirror assemblies and SXRP polarimeter are built, calibrated and qualified for flight.

The Bragg crystal polarimeter for the second telescope is a streamlined replica of the one in SXRP.

A small, lightweight, selectively redundant spacecraft enables highly stable operation in low earth orbit.

Spacecraft components are flight proven, have low cost, and minimal schedule risk.

In addition, significant margins for schedule (10 weeks), cost (25%), and technology have been established.

## Launch Vehicle

The Taurus 2210 launcher provides high reliability to orbit.

# Science Objectives

*Explore the Ultimate Limits of Gravity and Energy*

Test General Relativity predictions of strong field gravity near black holes *

Measure the spin of a black hole*

Explore mechanisms for jet propagation in microquasars

Test if jets from black holes power the X-ray emission

Measure the accretion disk geometry around neutron stars*

Determine whether accretion-powered pulsars have pencil or fan-beam geometries*

Test the source geometry for rotation-powered pulsars*

Measure the extreme field strengths of magnetars

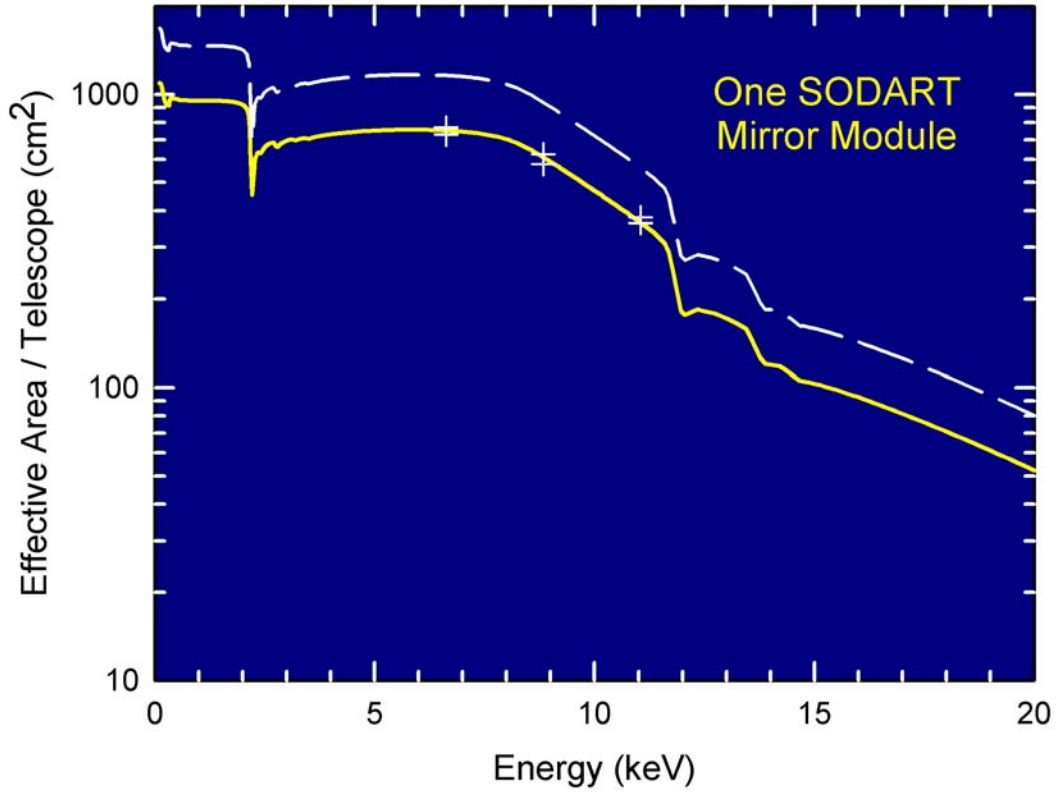
Confirm that supernova remnants are sites for cosmic ray acceleration

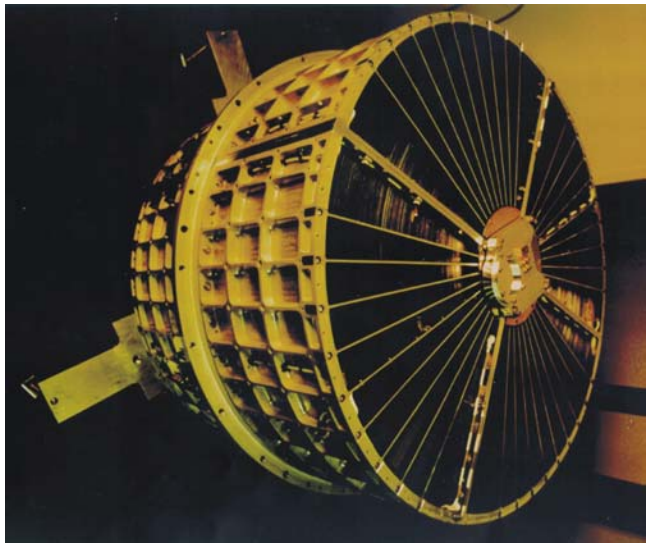
Constrain models for extragalactic jet propagation

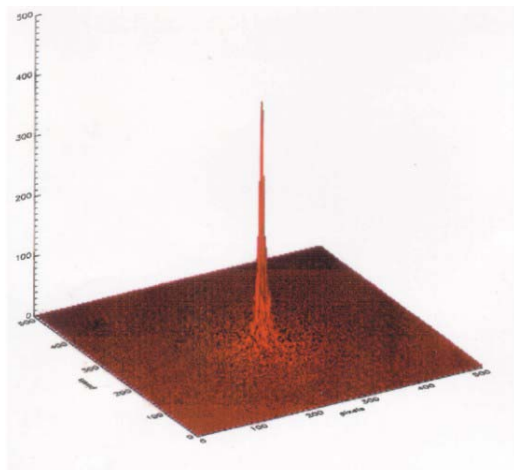
Test the standard unified model for AGN

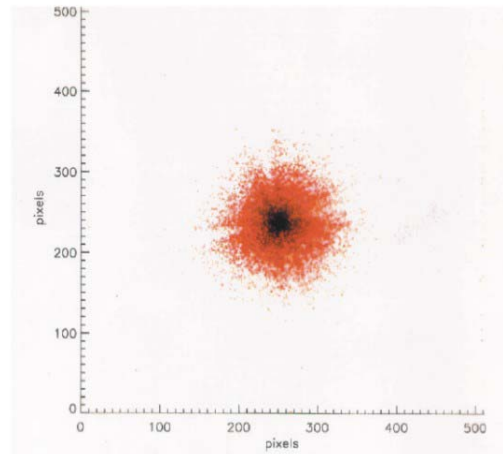
Determine the origin of the X-ray emission from radio galaxies and quasars

| SODART Mirror Module Parameters | |
|---|---|
| Field of View | 60 arc min |
| Half Power Width | 2.8 arc min |
| Focal Length | 8 m |
| Inner Shell Diameter | 16 cm |
| Outer Shell Diameter | 60 cm |
| Coating | Au - 400 |
| Effective Area at 2keV | 949 $cm^2$ |
| Effective Area at 8keV | 728 cm2 |
| Effective Area at 20keV | 61 $cm^2$ |
| Shell Material | Al |
| Shell thickness | 0.400 mm |
| Shell Length | 200 mm |
| Number of Shells | 143 |
| Mass/Mirror Module | 101 kgm |
| Total Mirrored Surface | 62 $m^2$ |

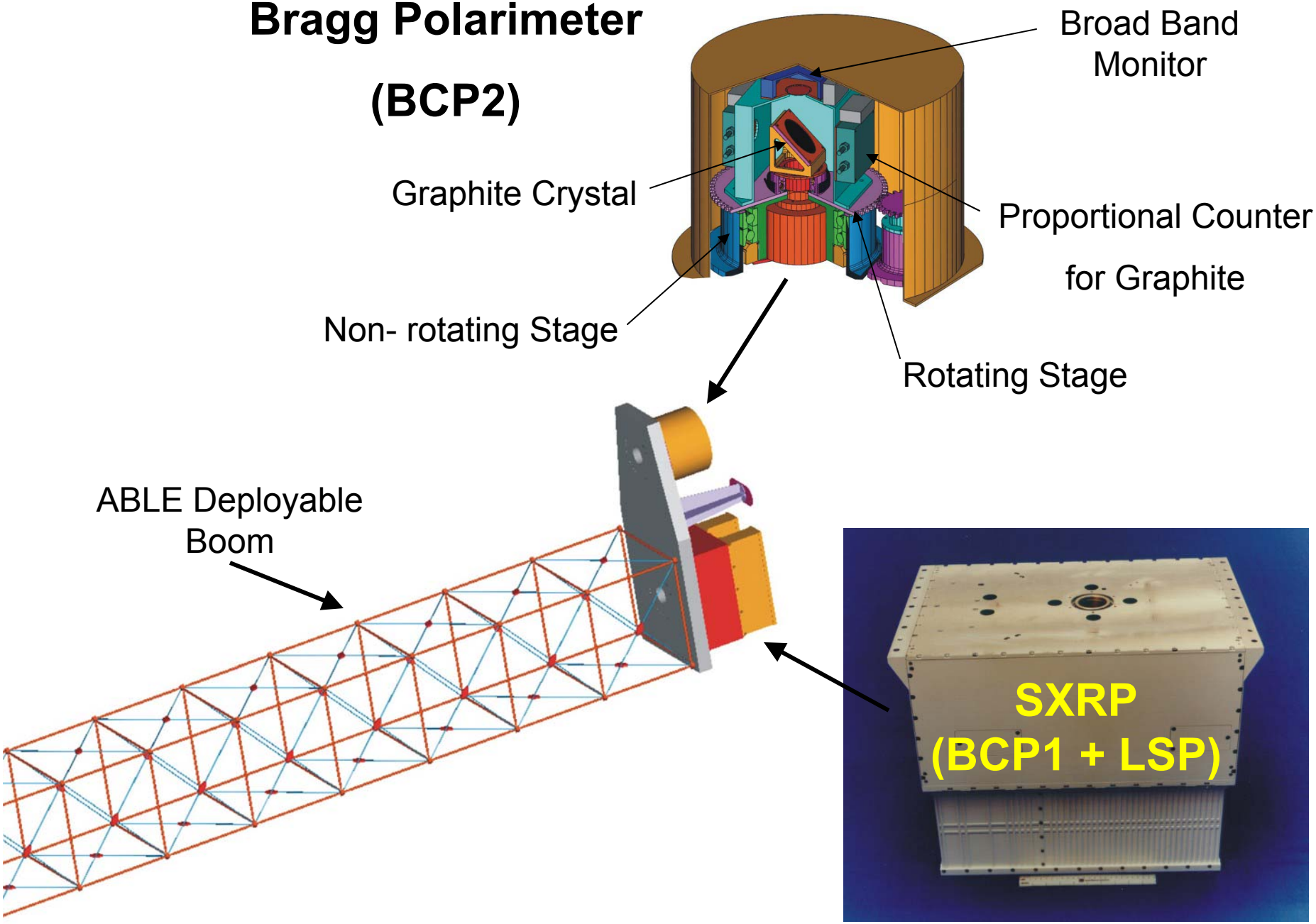


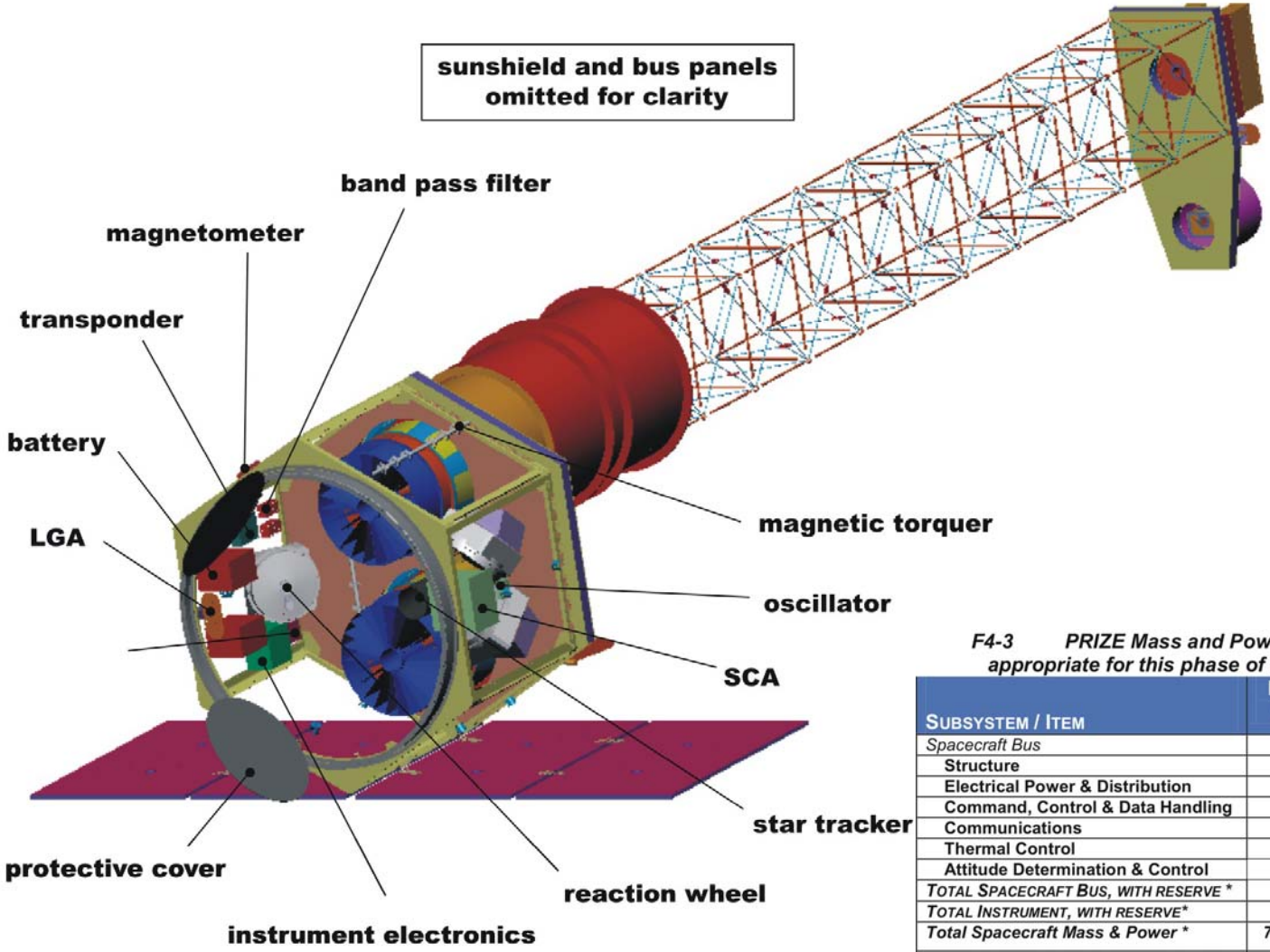







# Bragg Polarimeter (BCP2)

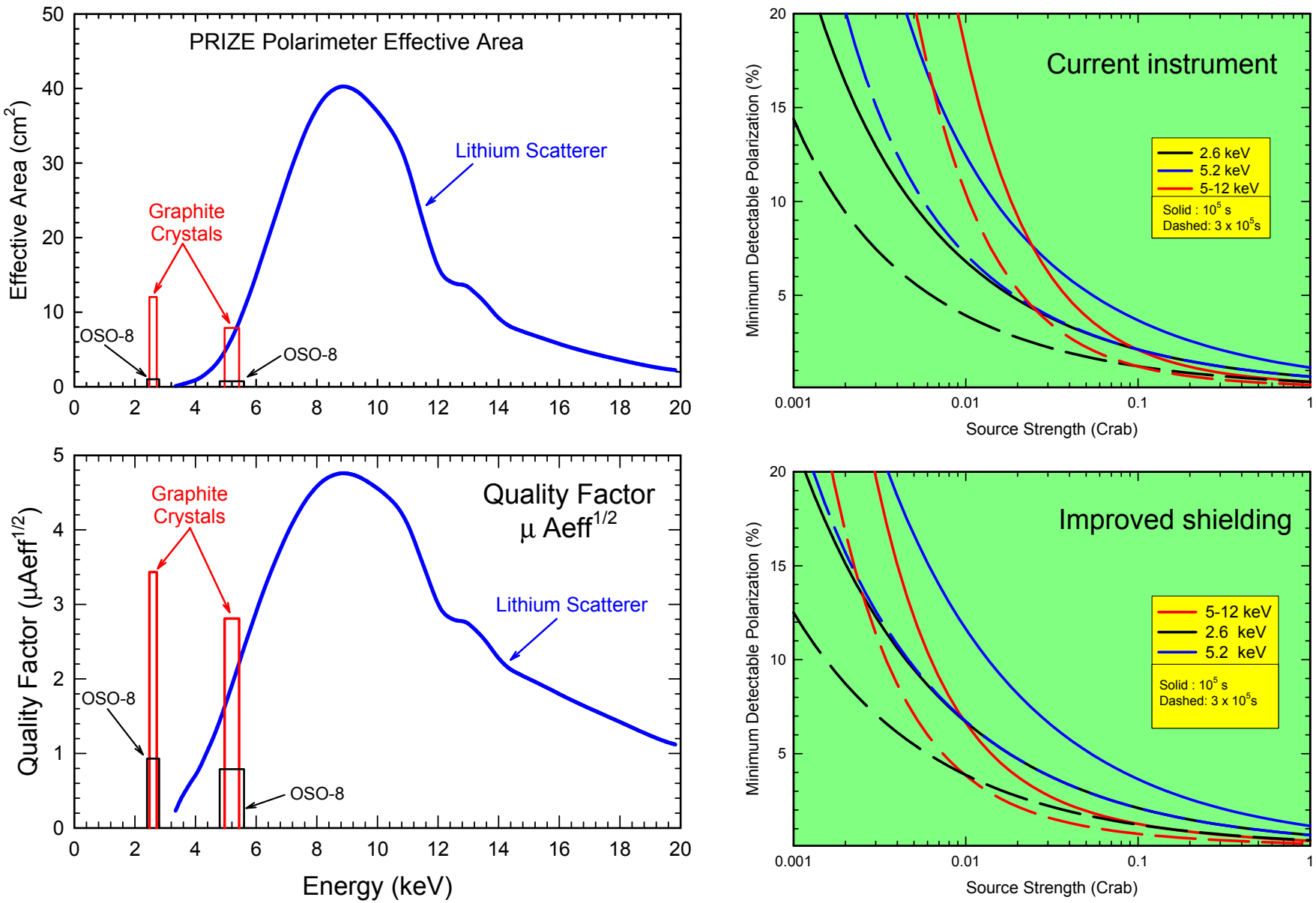




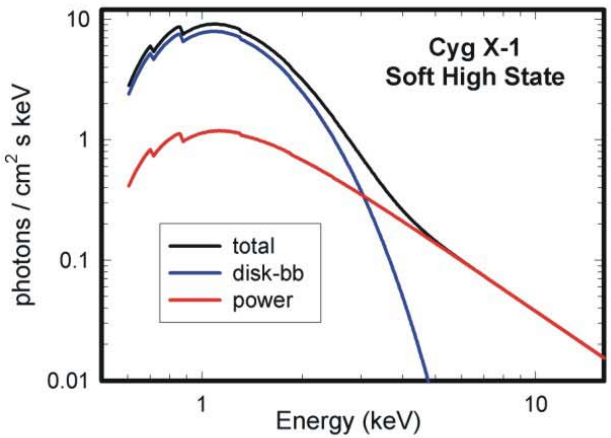

*F4-3 PRIZE Mass and Power Margins are appropriate for this phase of the program.*

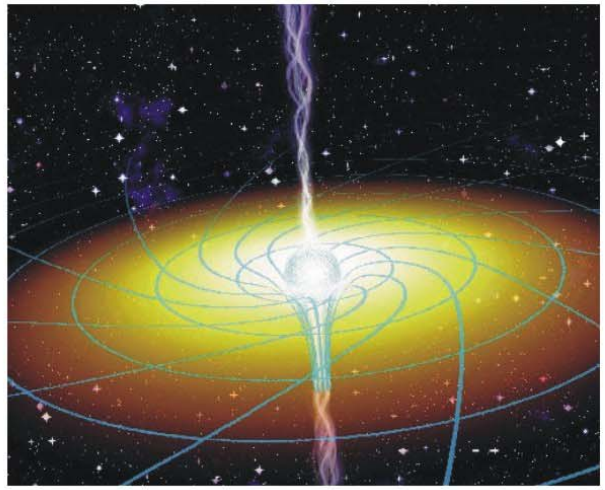
| Subsystem / Item | Mass (kg) | OAP (Watts) |
|---|---|---|
| *Spacecraft Bus* | | |
| **Structure** | 121.4 | N/A |
| **Electrical Power & Distribution** | 82.3 | 22.7 |
| **Command, Control & Data Handling** | 19.3 | 64.0 |
| **Communications** | 6.9 | 12.2 |
| **Thermal Control** | 7.1 | 36.3 |
| **Attitude Determination & Control** | 84.3 | 139.9 |
| ***Total Spacecraft Bus, with reserve **** | ***321.3*** | ***275.1*** |
| ***Total Instrument, with reserve**** | ***458.3*** | ***247.0*** |
| ***Total Spacecraft Mass & Power **** | ***779.6 kg*** | ***522.1 W*** |
| ***Taurus 2210 (with 63 inch PAF) capability to 28.5°, 600 km*** | ***939 kg*** | ***N/A*** |
| ***Total Power Generated (EOL, orbit avg)*** | ***N/A*** | ***679 W*** |
| **Mission Mass and Power Margins** | **159 kg (20%)** | **157 W (30%)** |

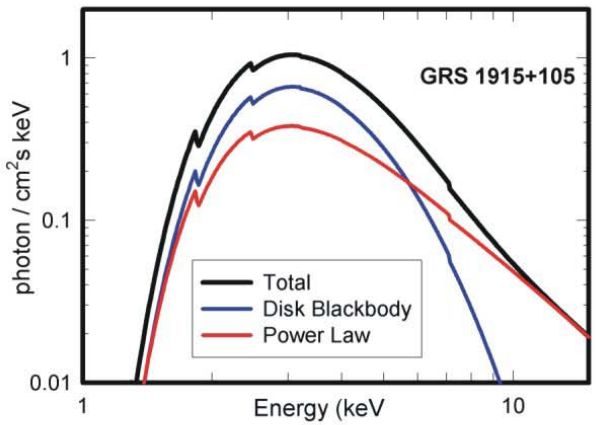
** Note: Spacecraft Bus (mass / power) include (15 / 21)% reserve*
*Instrument (mass / power) include ( 9 / 25) % reserve* ***(See Master Equipment List )***

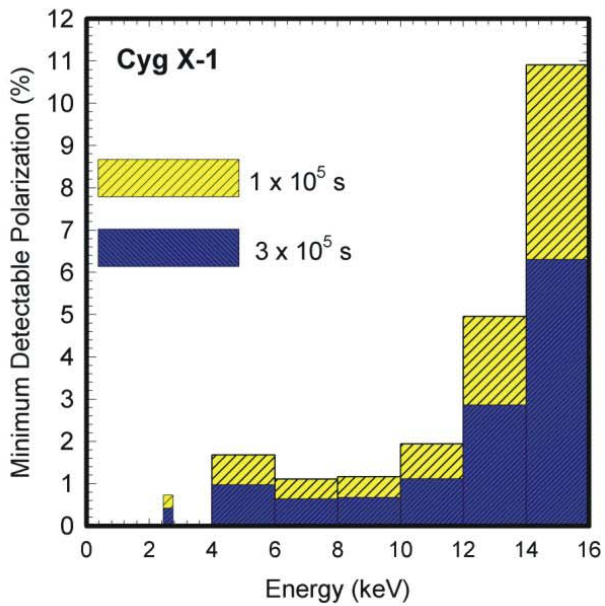

PRIZE Polarimeter Effective Area
Effective Area (cm$^2$)
Lithium Scatterer
Graphite Crystals
OSO-8
OSO-8
Current instrument
Minimum Detectable Polarization (%)
Source Strength (Crab)
2.6 keV
5.2 keV
5-12 keV
Solid : $10^5$ s
Dashed: 3 x $10^5$s
Quality Factor
μ Aeff$^{1/2}$
Quality Factor (μAeff$^{1/2}$)
Energy (keV)
Improved shielding

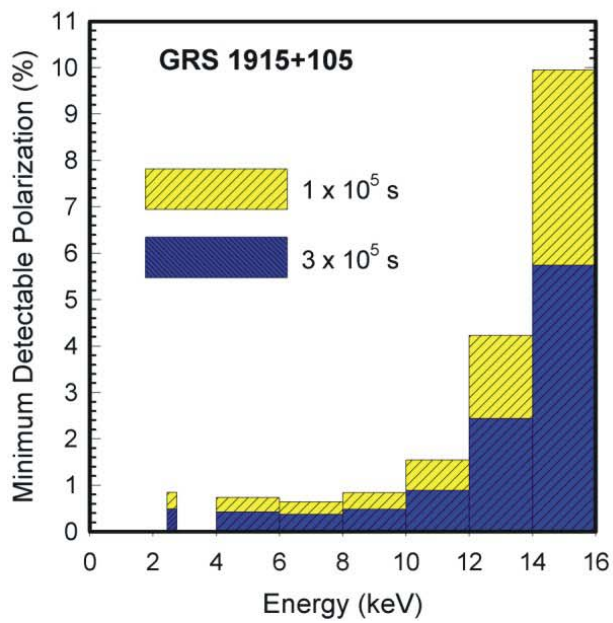
# Observe how black holes influence space, time and matter





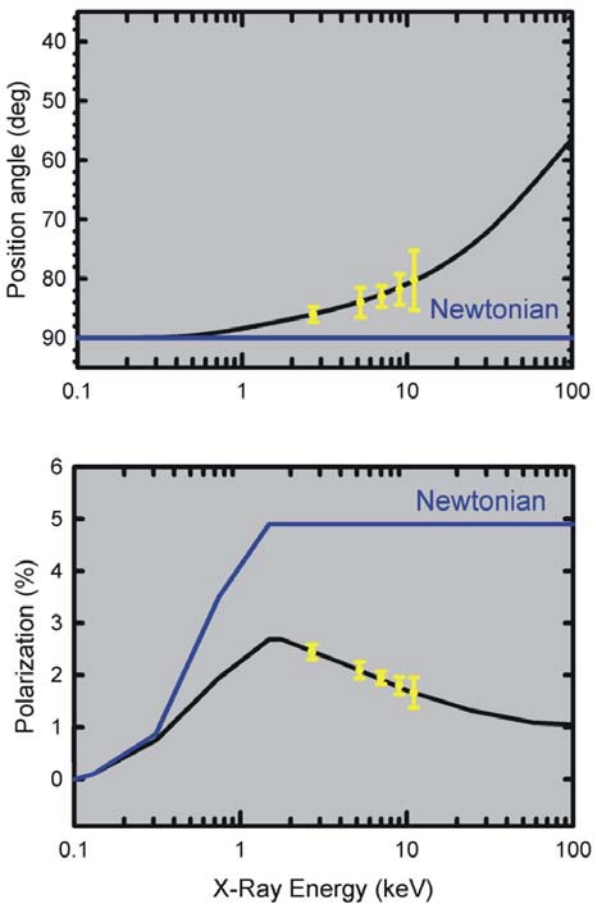



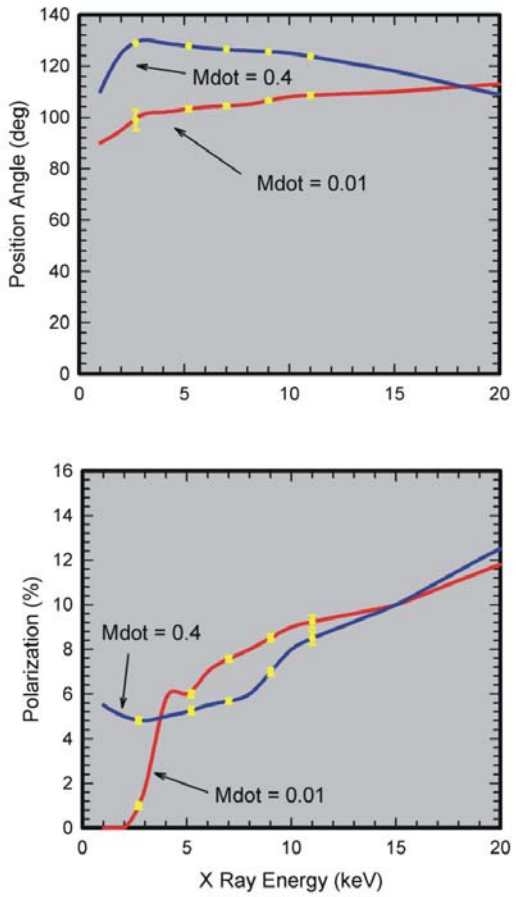

Energy resolved polarimetry for black holes Cyg X-1(high state) and GRS 1915+$10^5$ for $10^5$ s and 3 x $10^5$ s. Spectra from Cui et al. 1998 for Cyg X-1; Muno et al.1999 for GRS 1915+105).Estimated inclination angles are 30° for Cyg X-1 and 70° for GRS 1915+105.

# Test the theory of general relativity near black holes
# Determine the spin of a black hole

**Predicted polarization fractions and position angles as a function of energy for disk models near a black hole.**



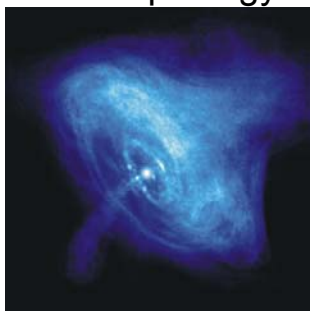

Disk with 75.5° inclination
(Conners, Piran and Stark,1980)

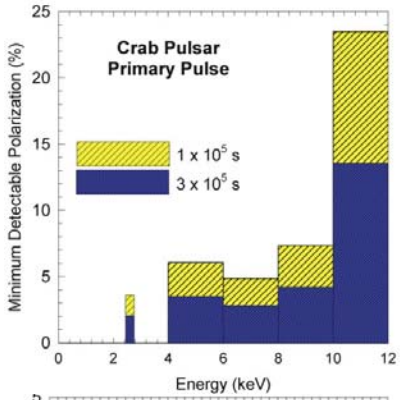


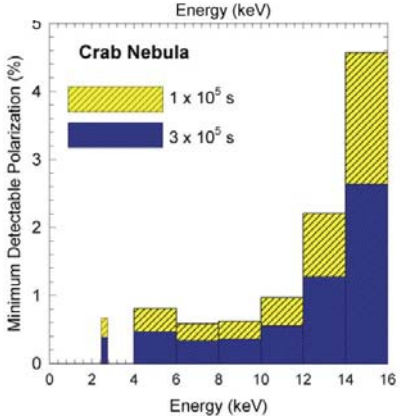

Effects of mass accretion rate for a 10 solar mass black hole (Matt, Fabian and Ross, 1993)

# Neutron Stars and Supernova Remnants

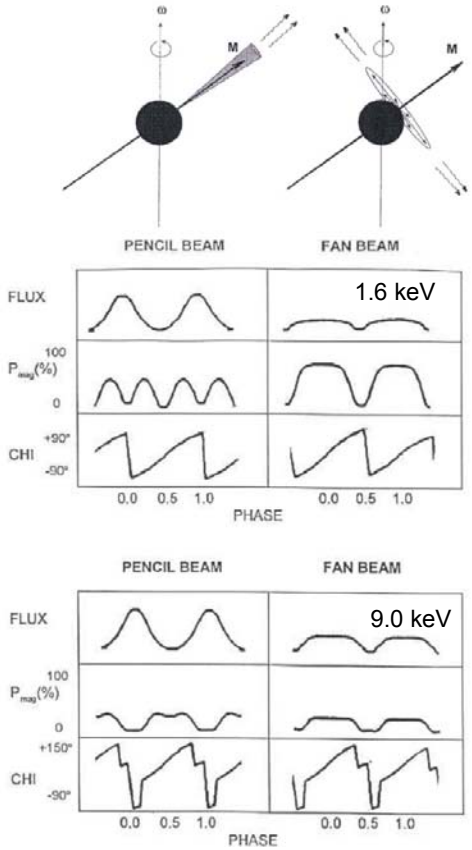
Compare polarization data with pulsar wind nebula morphology





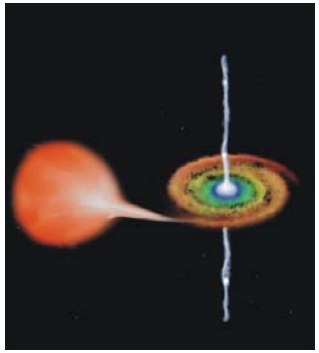

Determine pulsar beaming mechanisms

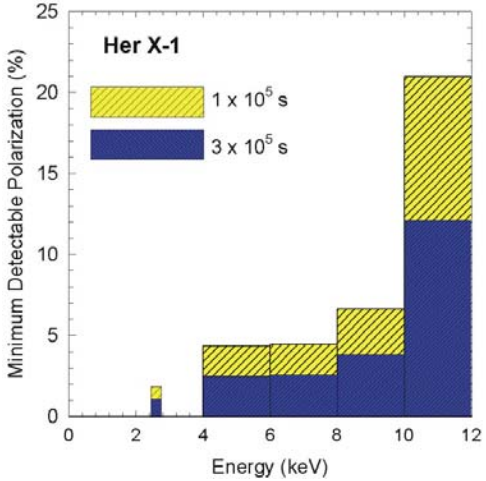



Schematic of pencil and fan beam geometries.

Predictions for pulse phase dependent polarization at two x-ray energies (Meszaros et al.1988).

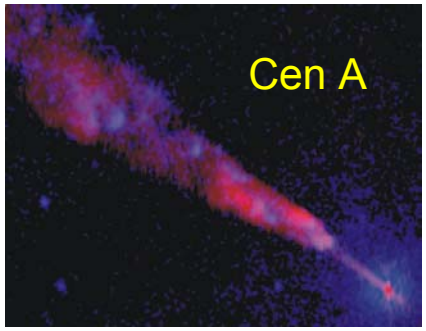
Study accretion disk dynamics



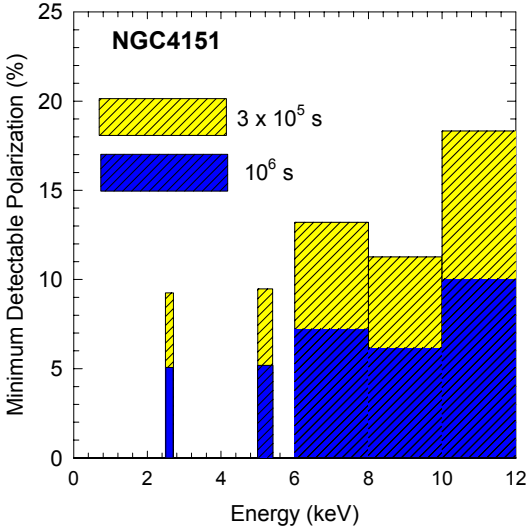



Energy resolved polarimetry of Her X-1 using PRIZE.

# Active Galacitc Nuclei Blazars, Quasars and Radio Galaxies




Reveal the nature of cosmic jets and relativistic flows
Test models of blazars and jets




| Minimum Detectable Polarization (MDP) (%) 3 sigma | | | | |
|---|---|---|---|---|
| **Source** | **2.6 keV** | **5.2 keV** | **5-12 keV** | **Flux 2-10 keV $10^{-11}$ ergs cm$^{-2}$ s$^{-1}$** |
| **Galactic Black Holes in $10^5$ s** | | | | |
| Cyg X-1 (high state) | 0.7 | 1.1 | 0.3 | 2800 |
| GRS 1915+105 | 0.8 | 1.3 | 0.4 | 1900 |
| Recurring BH Transients | 1 | 1.6 | 0.5 | 1700 |
| **Neutron Star Binaries in $10^5$ s** | | | | |
| Her X-1 | 2.2 | 3.9 | 2 | 240 |
| Cen X-3 | 1.4 | 2.5 | 0.9 | 480 |
| Cir X-1 | 0.9 | 1.5 | 0.5 | 1680 |
| GX 9 +9 | 1.5 | 2.5 | 1 | 576 |
| Vela X-1 | 1.4 | 2.5 | 0.9 | 600 |
| GX340+0 | 1.1 | 1.8 | 0.6 | 1080 |
| **Rotation Powered Pulsars in 5 x $10^5$ s** | | | | |
| Crab Pulsar primary pulse | 1.6 | 2.8 | 2.3 | 80 |
| Crab Pulsar leading edge | 2.2 | 4 | 4.5 | |
| Crab Pulsar trailing edge | 2.2 | 4 | 4.5 | |
| **Supernova Remnants 5 x $10^5$ s** | | | | |
| Crab Nebula | 0.3 | 0.51 | 0.17 | 2273 |
| Tycho | 2.9 | 5.4 | 7.7 | 21.3 |
| Cas A | 1.28 | 2.23 | 1.6 | 128 |
| **AGN - Supermassive Black Holes in 3 x$10^5$ s** | | | | |
| **Seyferts** | | | | |
| NGC4151 | 8.1 | 8.2 | 7.7 | 15 |
| IC4329A | 7.5 | 13.2 | 25 | 8 |
| **Radio Galaxies and Quazars** | | | | |
| Cen A | 5.7 | 3.22 | 2.1 | 15 |
| 3C273 | 5.9 | 9.8 | 13.9 | 15 |
| **Blazers** | | | | |
| Mrk 421 | 4.4 | 10.1 | 20.6 | 15 |
| Mrk 501 | 7.2 | 15 | 34.4 | 7 |
| PKS2155-304 | 6.3 | 16.6 | 50.8 | 7 |

# Polarimeter Strawman Observing Plan including Minimum Detectable Polarization (MDP)

| Target Class | Target | Minimum Detectable Polarization (%) | | | T | Total Time |
|---|---|---|---|---|---|---|
| **Stellar Mass Compact Objects** | | 2.6 keV | 5.2 keV | 5-12 keV | (ks) | (ks) |
| BH binaries & Microquasars | Cyg X-1, GRS1915+105 (each twice) | 0.4,0.5 0 | 0.7,0.8 | 0.2,0.2 | 300 | 1200 |
| Recurrent/New Transients | ~ 5 sources (each twice) e.g., GX339-4, 4U1630-47 | <1 | <1 | <1 | 300 | 3000 |
| Neutron-star Binaries<br>Accretion Powered Pulsars | Cen X-3, Vela X-1 (in each of 5 pulse phases)<br>Her X-1 High State (in each of 10 pulse phases)<br>Her X-1 Low State (in each of 5 pulse phases) | 1.4<br>2.7<br>5.4 | 2.5<br>4.8<br>9.5 | 0.9<br>2.4<br>4.7 | 100<br>70<br>70 | 1000<br>700<br>350 |
| Low Magnetic Field | Sco X-1 GX 5-1, GX 349+2, GX 17+2, Cyg X-2, Cir X-1, GX 340+0, GX 9+9 | 0.2-1.8 | 0.3-3.3 | 0.1-1.5 | 100 | 800 |
| Rot ation Powered Pulsars<br>(Pulse Phased Polarimetry) | Vela in each of 5 pulse phase bins<br>Crab in each of 10 pulse phase bins | 4<br>3 | 6<br>5 | 5<br>4 | 200<br>100 | 1000<br>1000 |
| Magnetars | 4U0142+61, RXS1708-40, 1E2259+58 | 3-11 | 12-50 | 30- ... | 500 | 1500 |
| **Peculiar X-ray Binaries** | | | | | | |
| | Rapid Burster<br>Cyg X-3 ($P_{orb}$=4.8 hr) | 7<br>1.2 | 10<br>2.0 | 10<br>0.7 | 300<br>100 | 300<br>100 |
| **SNR's** | | | | | | |
| Plerion (pulsar wind nebulae) | (Crab, Vela)*e*, G21.5-0.9 7 10 18 500 500 | 7 | 10 | 18 | 500 | 500 |
| Shell | Tycho, Cas A, G347.5-05, RCW 86 | 1-7 | 2-11 | 2-40 | 500 | 2000 |
| **Supermassive Black Holes** | | | | | | |
| Seyfert 1 | NGC4151, IC4329A, NGC3783, NGC5548, MCG-6-30-15 | 7-11 | 7-23 | 3-55 | 300 | 1500 |
| Seyfert 2 | NGC4507, MCG-5-23-16, NGC5506 | 7-25 | 8-14 | 3-23 | 300 | 900 |
| Radio Galaxies | Cen A, 3C 273, 3C 120 | 6-20 | 3-20 | 2-30 | 500 | 1500 |
| Blazars | Mkn421, PKS2155-304, 3C279, Mkn501, 3C 390.3 | 4-13 | 9-20 | 18-44 | 400 | 2000 |
| ToO | X-ray transients (e.g. new novae), Blazars in outburst, GRBs | | | | 100-200 | 1000 |
| **Calibration** | Crab, Sco X-1 | 0.7, 0.2 | 1.2, 0.3 | 0.4, 0.1 | 100 | 1000 |
| Follow-up time | | | | | | 3450 |
| **GRAND TOTAL** | | | | | | **24800** |

About PRIZE, the NASA Peer Review glowingly said:

"Even if PRIZE were to achieve just 1/3 of its objectives, it would be a fantastic mission!"

BUT,

the Peer Review felt that PRIZE still has a major weakness:

"*The Crab might be just an anomaly.* Expected polarizations might be just at the detection limit. Many extragalactic sources may have polarization levels as low as 1% which would be difficult to measure."

NASA placed PRIZE in Category II

# Issues to Consider When Comparing Polarimeters

**Compatibility of Telescope HPD with Polarimeter Detector Area**

**Relative Sensitivity As a Function of Energy**

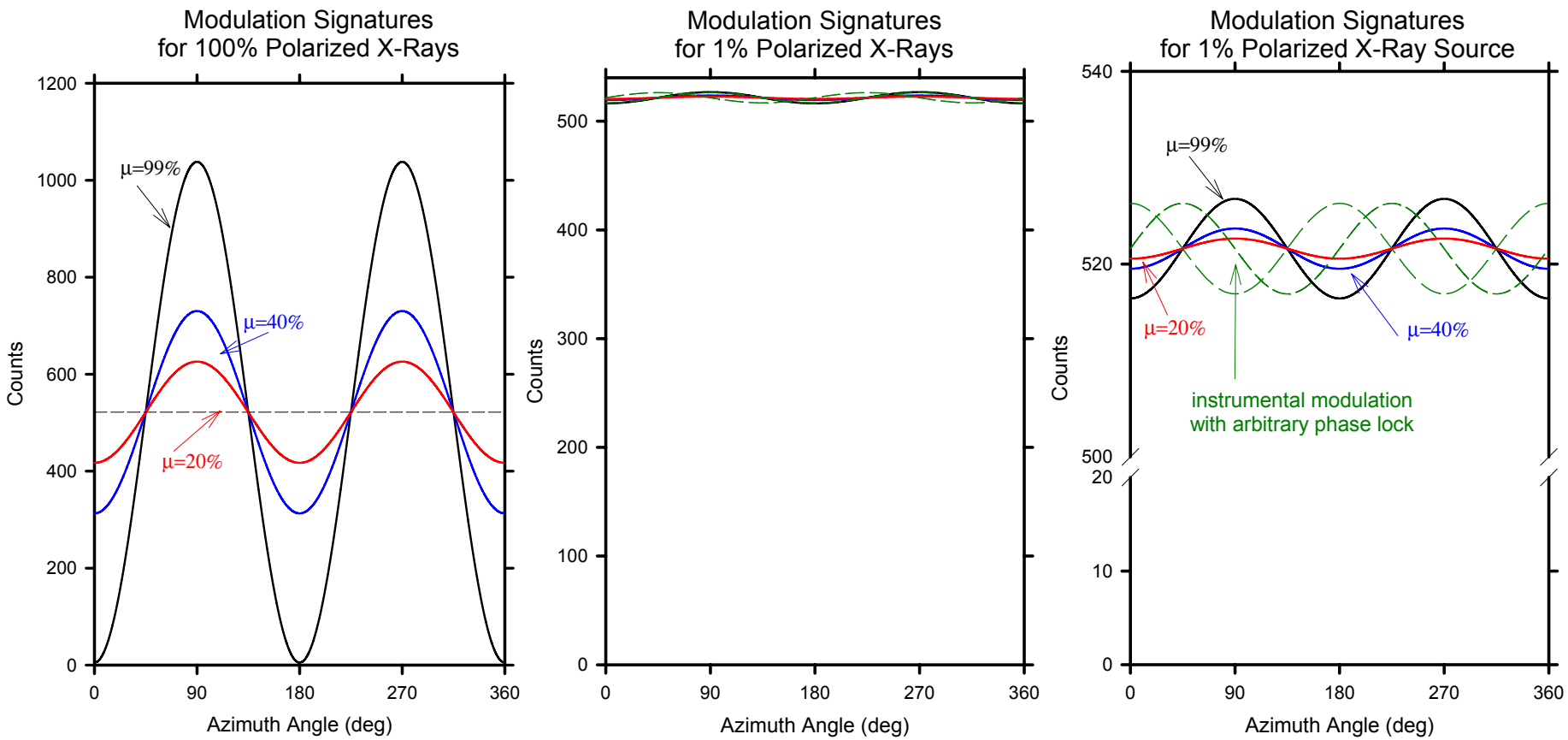
**Modulation Factor Plays a Dominant Role**

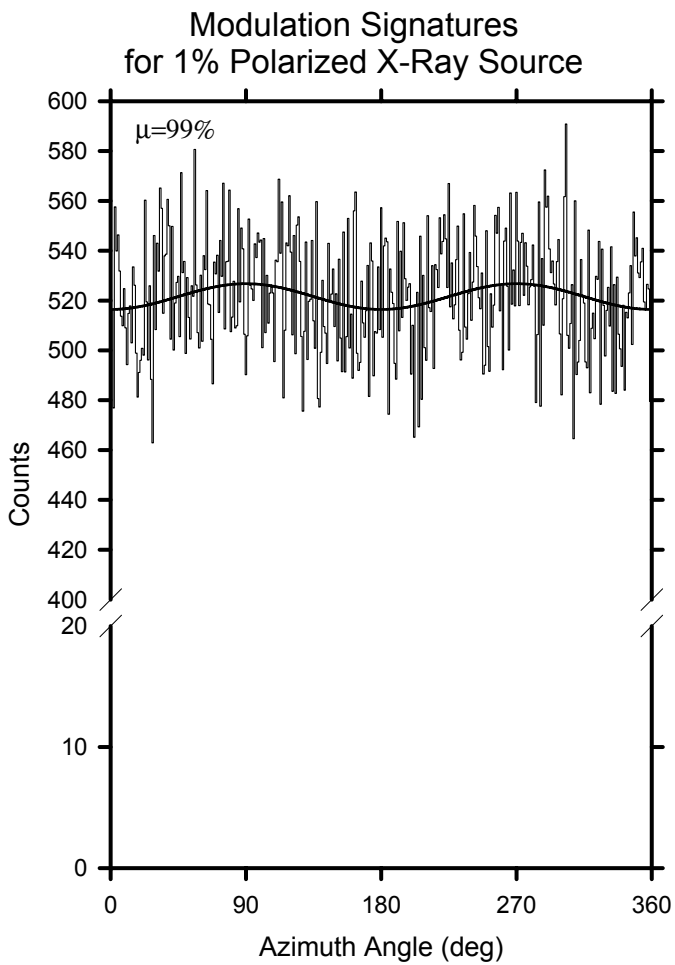
**in Measuring Polarization at 1% Level**

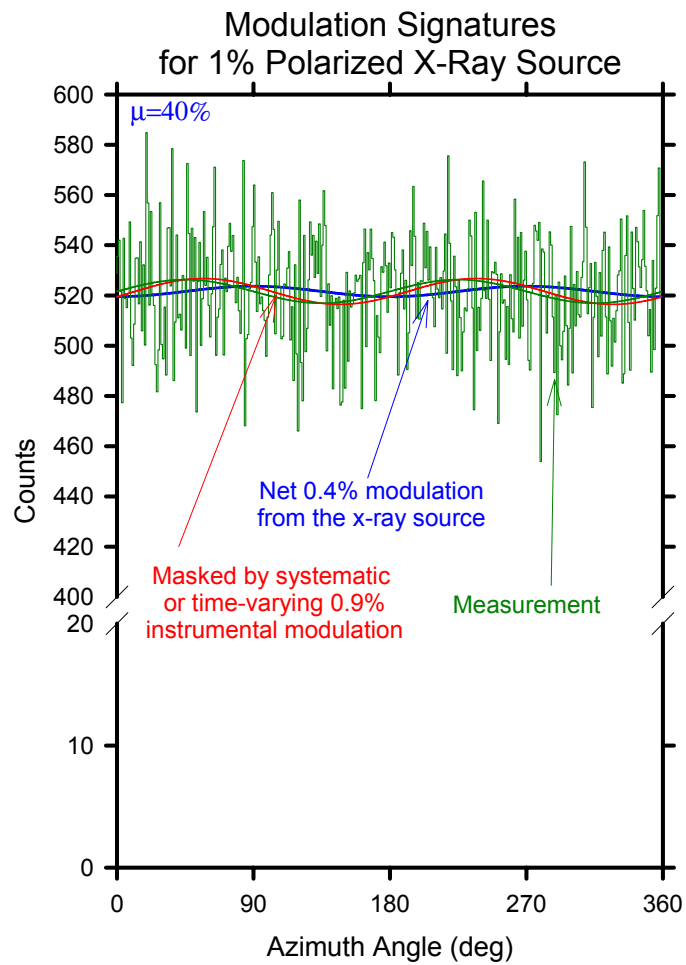
**Systematic Effects must be well understood**

**(Phase locked or not)**

Statistical Significance is not enough!


Modulation Signatures
for 100% Polarized X-Rays
Counts
Azimuth Angle (deg)
μ=99%
μ=40%
μ=20%
Modulation Signatures
for 1% Polarized X-Rays
Counts
Azimuth Angle (deg)
Modulation Signatures
for 1% Polarized X-Ray Source
Counts
Azimuth Angle (deg)
μ=99%
μ=20%
μ=40%
instrumental modulation
with arbitrary phase lock


Modulation Signatures
for 1% Polarized X-Ray Source
μ=99%
Counts
600
580
560
540
520
500
480
460
440
420
400
20
10
0
0
90
180
270
360
Azimuth Angle (deg)


Modulation Signatures
for 1% Polarized X-Ray Source
μ=40%
Net 0.4% modulation
from the x-ray source
Masked by systematic
or time-varying 0.9%
instrumental modulation
Measurement
Counts
600
580
560
540
520
500
480
460
440
420
400
20
10
0
0
90
180
270
360
Azimuth Angle (deg)

# To Measure Polarization at the 1% Level

**Highest Modulation Factor Possible**

**Systematic Effects Understood**

Sufficient Statistics