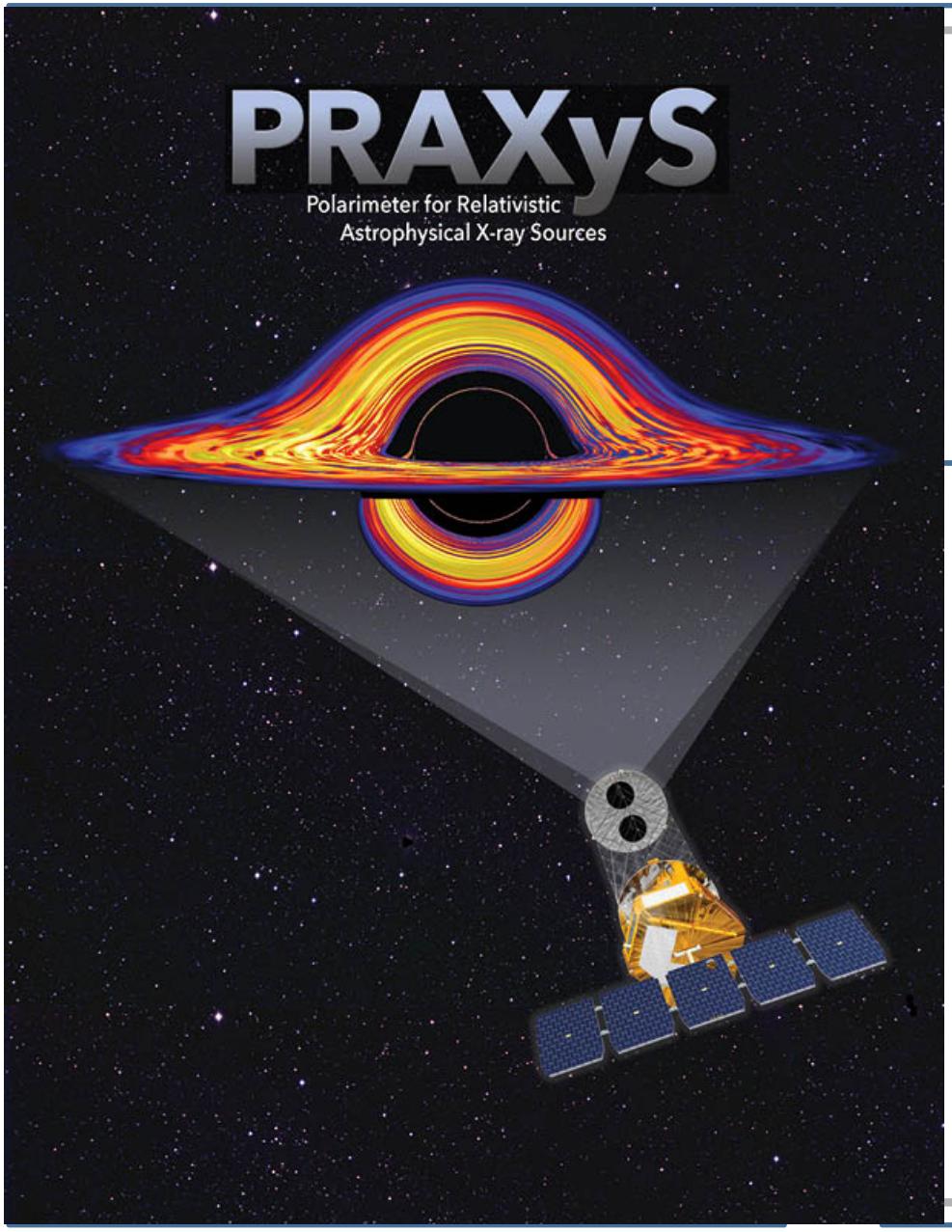



# PRAXyS

## Astrophysics Subcommittee
## Oct 23, 2015

**Principal Investigator: Keith Jahoda**
**Project Scientist: Tim Kallman**
**Science Team Lead: Chryssa Kouveliotou**

**Spacecraft Provider: Orbital ATK**
**Instrument Developer: GSFC**

# PRAXyS Team

**Science Leadership:** Jahoda (PI), Kallman (PS) Kouveliotou (Science Team lead)

**Co-I Organizations:** University of Iowa, APL, JAXA

**Science Team:** Arizona, CfA, Clemson, Copernicus Ctr, Cornell, GWU, Iowa, JHU, Maryland, Nagoya, NASA's ARC, NASA's GSFC, NC State, Rice, RIKEN, Stanford

# Polarization

- Of all the observables for any photon, only the ***E***-field orientation is asymmetric with respect to photon trajectory.
  - No surprise that polarization measures geometry
  - Very few celestial sources are truly round, but few can be imaged directly: polarization provides a means to see geometry on length scales orders of magnitude smaller than imaging can probe

- Polarization is a probe of exotic physics: strong fields
  - GR predicts bending of light – and thus alters the polarization vector
  - Bending dependent on potential, so energy dependent effects are expected
    - Radius, distance of Cyg X-1: $r \sim 20\ R_{sun}$, $d \sim 2000$ pc, $\theta \sim 50$ micro arcsec; ($\theta_{\text{event horizon}} < 1$ nano arcsec)

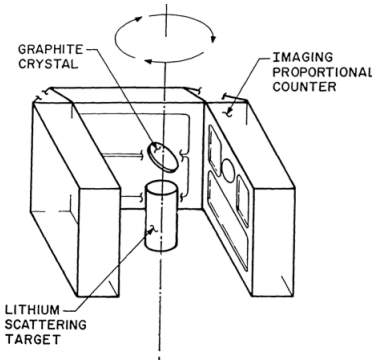
  - QED predicts birefringent opacity for large fields
    - observed polarization measures affect of magnetic field along line of sight
    - For hot spot on the surface of a NS, phase resolved intensity probes the surface while phase resolved polarization probes the atmosphere.
    - For emission generated above the surface (rotation powered pulsars), phase resolved polarization probes height of emission
    - Crab: $r \sim 10$ km, $d \sim 2000$ pc, $\theta \sim 30$ pico arcsec

- Polarization is also affected by interactions with matter
  - Large angle scattering has polarization dependence

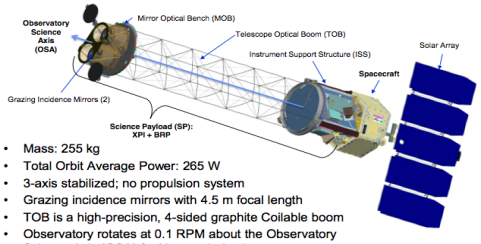
# History

MCW (center) at Wallops Island in 1971

SXRP geometry




GEMS at PDR




- 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)

- Observations of astrophysical X-ray polarization began with sounding rockets in 1971; continued with OSO-8 (mid 1970s), obtaining measurements of the Crab Nebula and upper limits
- Interest remains high, observations/results unavailable
- SXRP built in 1990s but not flown
- GEMS reached PDR (2012), but not confirmed

# PRAXyS – Relationship to GEMS

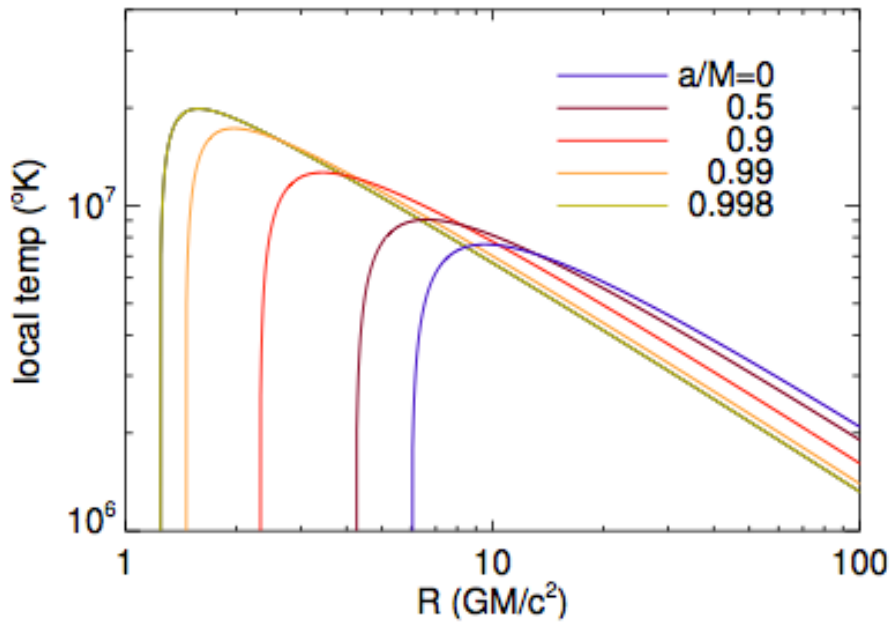
- GEMS
  - Proposed January 2008
  - Selected June 2009
  - Polarimeter TRL-6 review in Oct 2011
  - Technically Successful PDR Feb 2012
  - Not confirmed at KDP-C in May 2012
    - Concern over adequacy of project budget/schedule relative to independent estimates and cost-cap
    - GEMS team directed to capture polarimeter development for possible future opportunities (Explorer or otherwise) *without prejudice or benefit*

- PRAXyS
  - Builds on the GEMS design and experience
  - Payload development is advanced; procurement and assembly durations are known from GEMS engineering and protoflight units
  - Many lessons learned – and applied – about doing small missions at a large NASA center

  - Expanded Science Team
  - Expanded opportunities for community participation
    - Data will be made public upon validation

# Black Hole – Thermal state

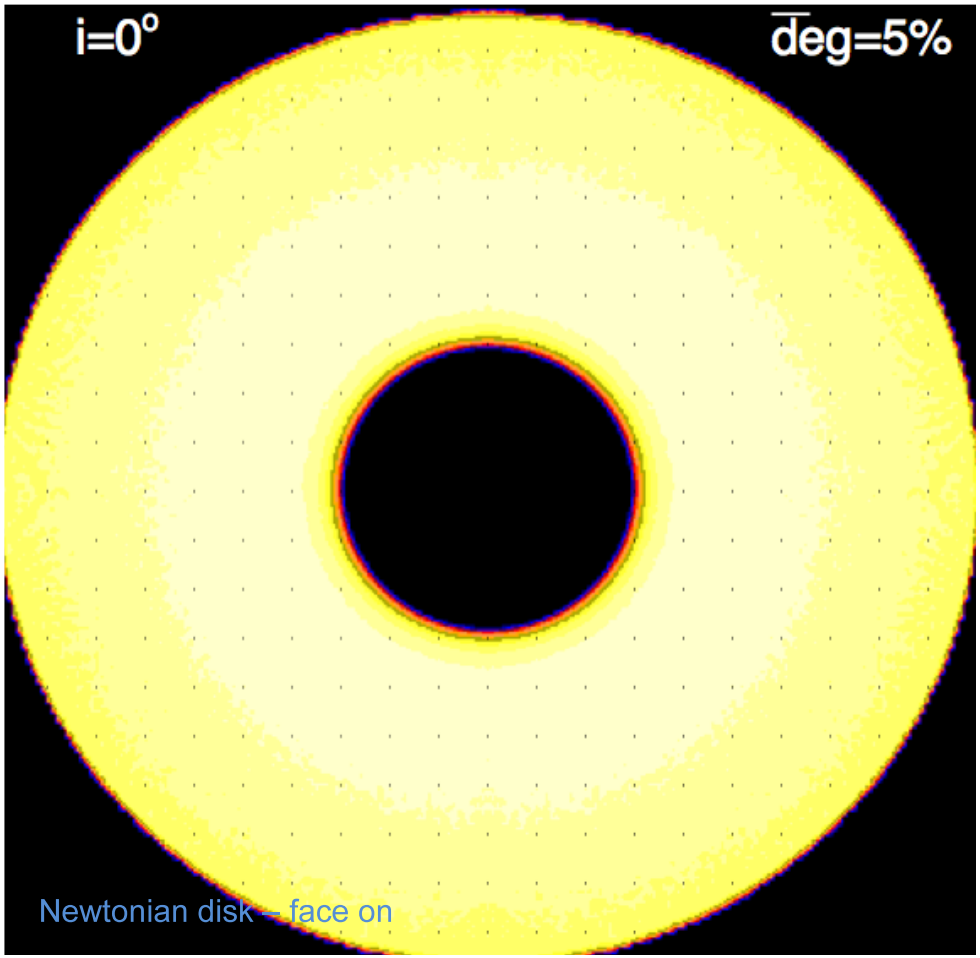
- $T(R)$ increases towards BH
- $T(R) \sim M^{-1/2}\dot{M}^{1/4}$
- most of the flux from $R \lesssim 10R_S$
- GR $\rightarrow$ last stable orbit (ISCO)
- position of ISCO function of BH mass, spin




Novikov & Thorne (1973)

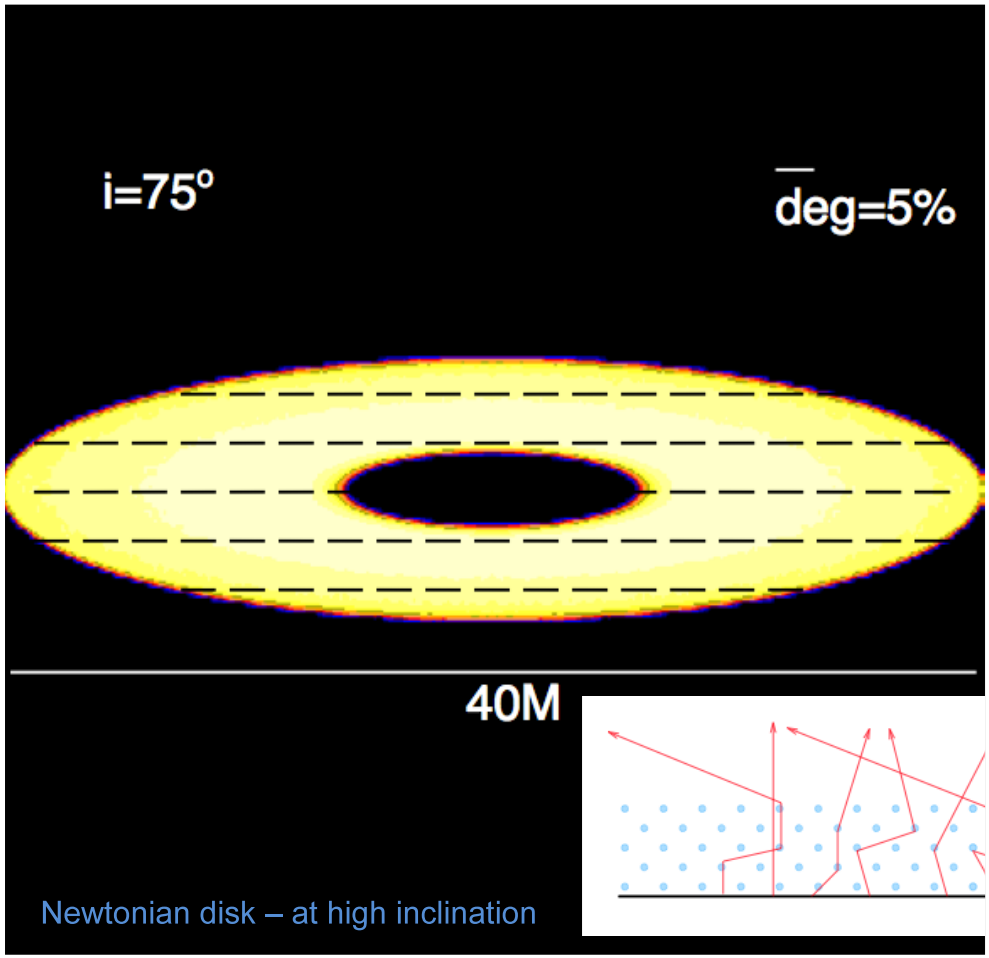
Emission characteristics depend on Environment (M-dot), Black Hole (Spin), and geometry (inclination). Special/General Relativity are important.

# Polarized Image of black hole accretion disk



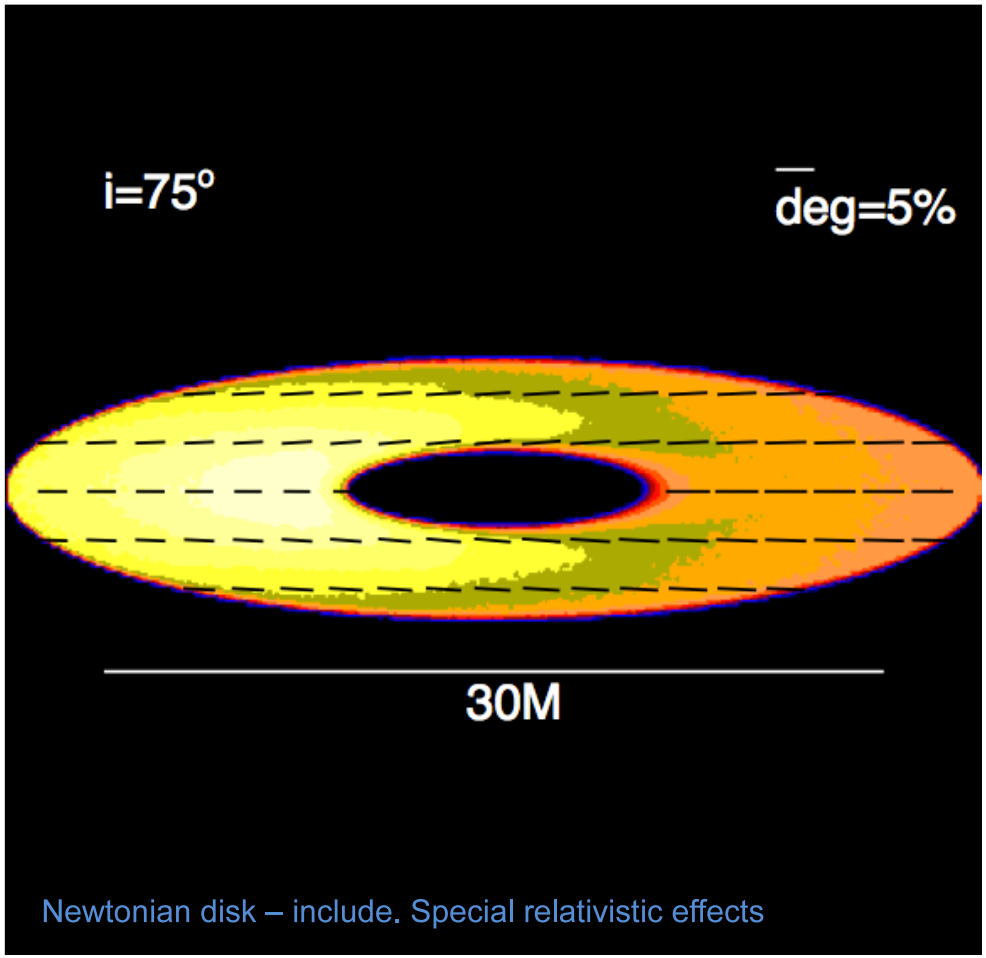

Newtonian disk – face on

# Polarized Image of black hole accretion disk



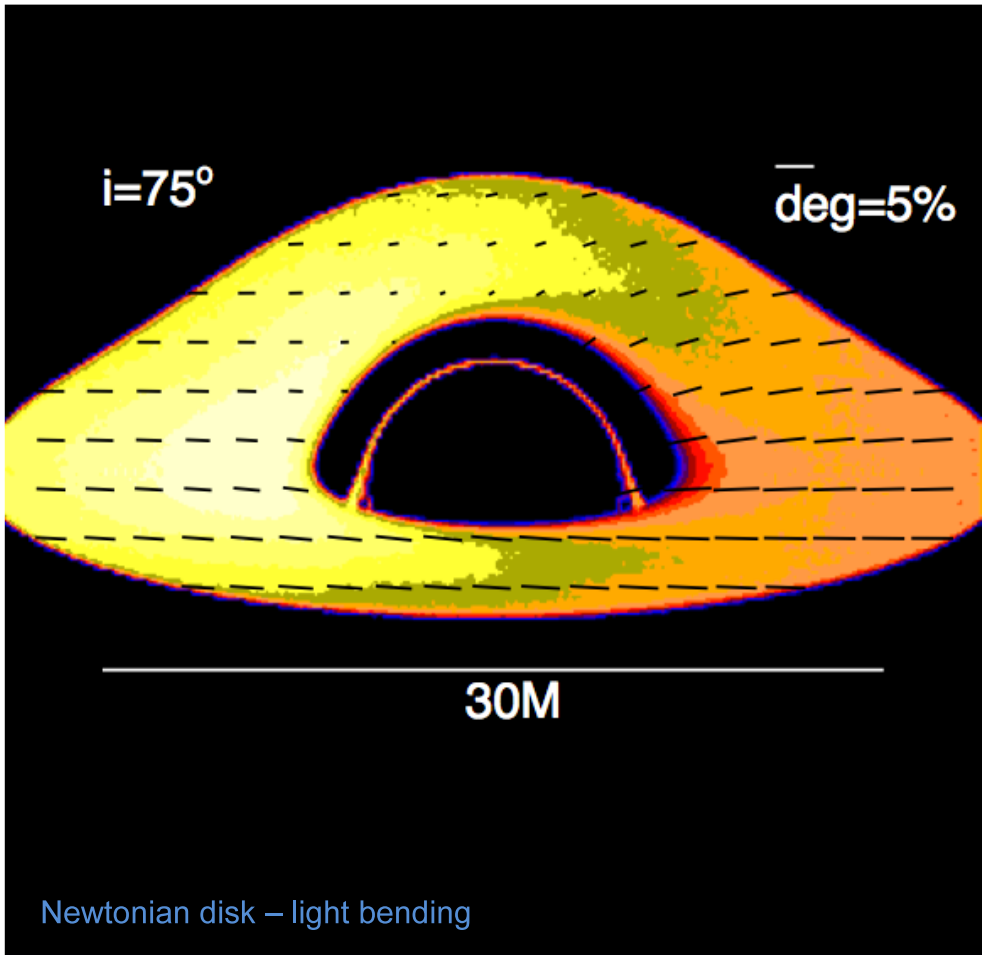

Newtonian disk – High Inclination

# Polarized Image of black hole accretion disk



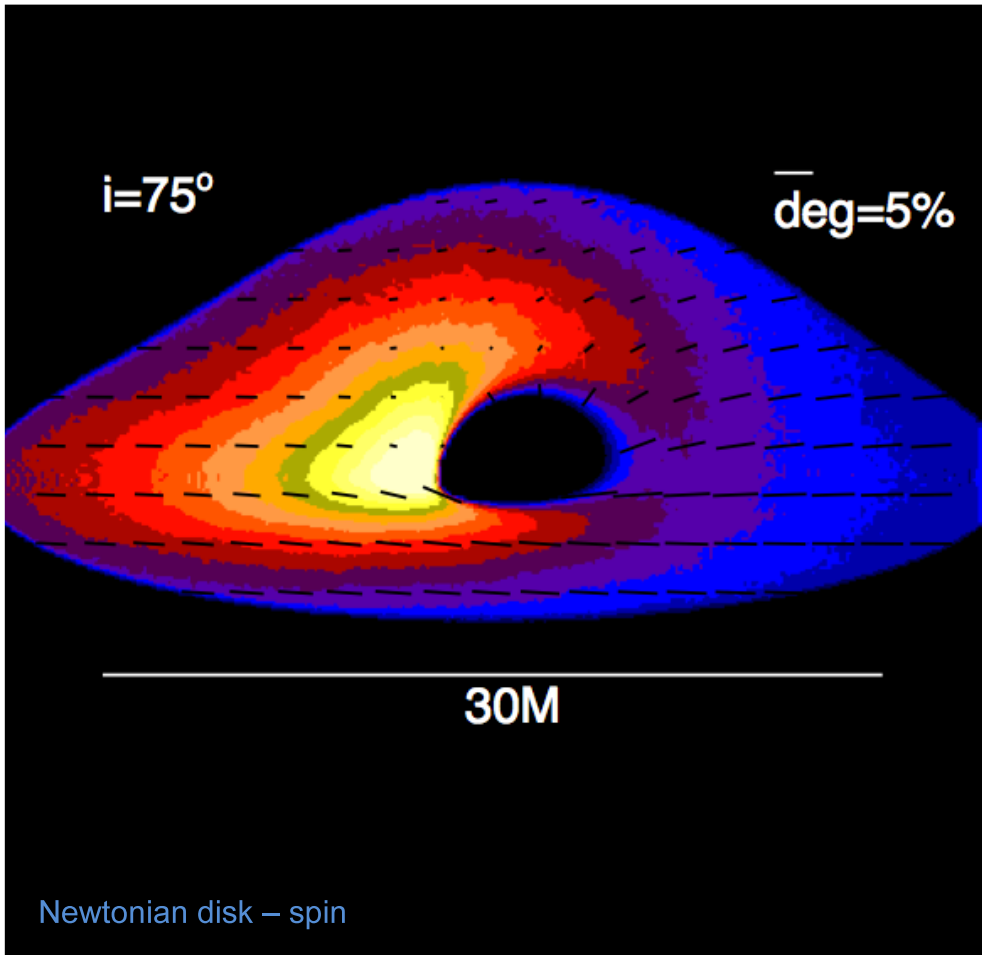

Newtonian disk – include special relativity

# Polarized Image of black hole accretion disk



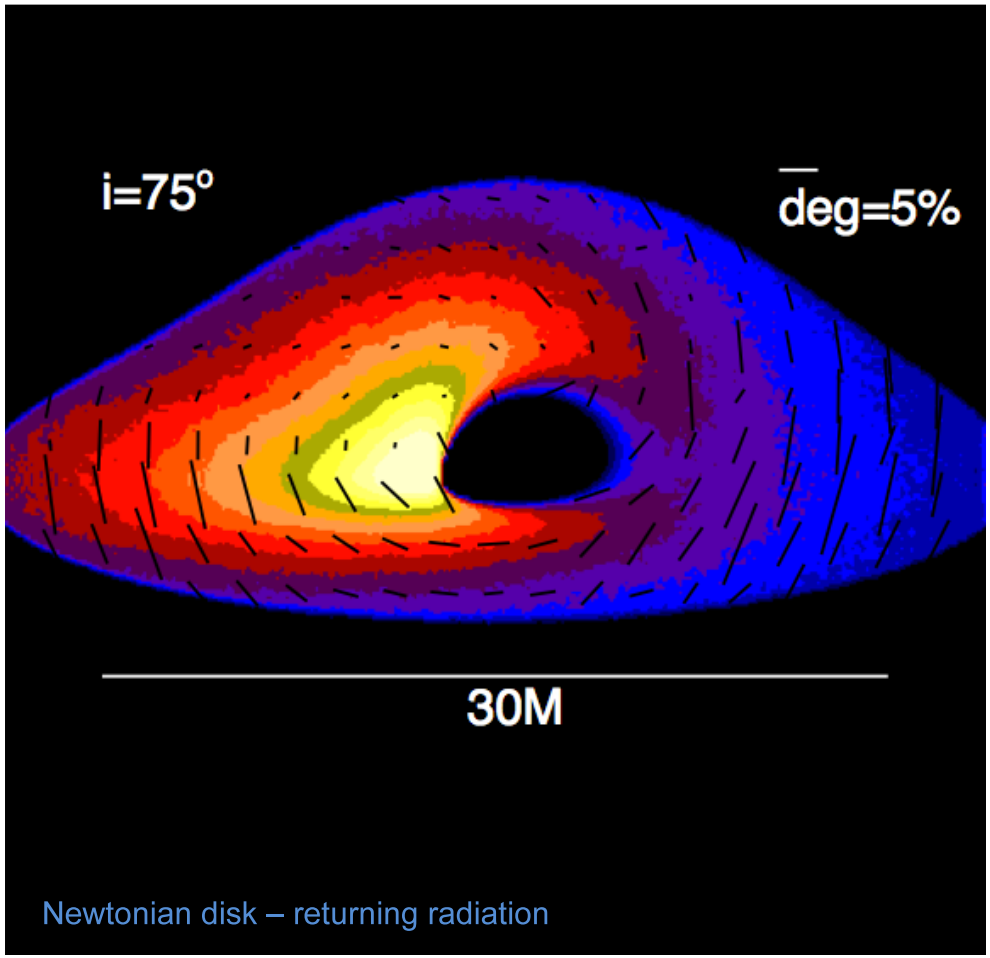

Newtonian disk – and light bending

# Polarized Image of black hole accretion disk



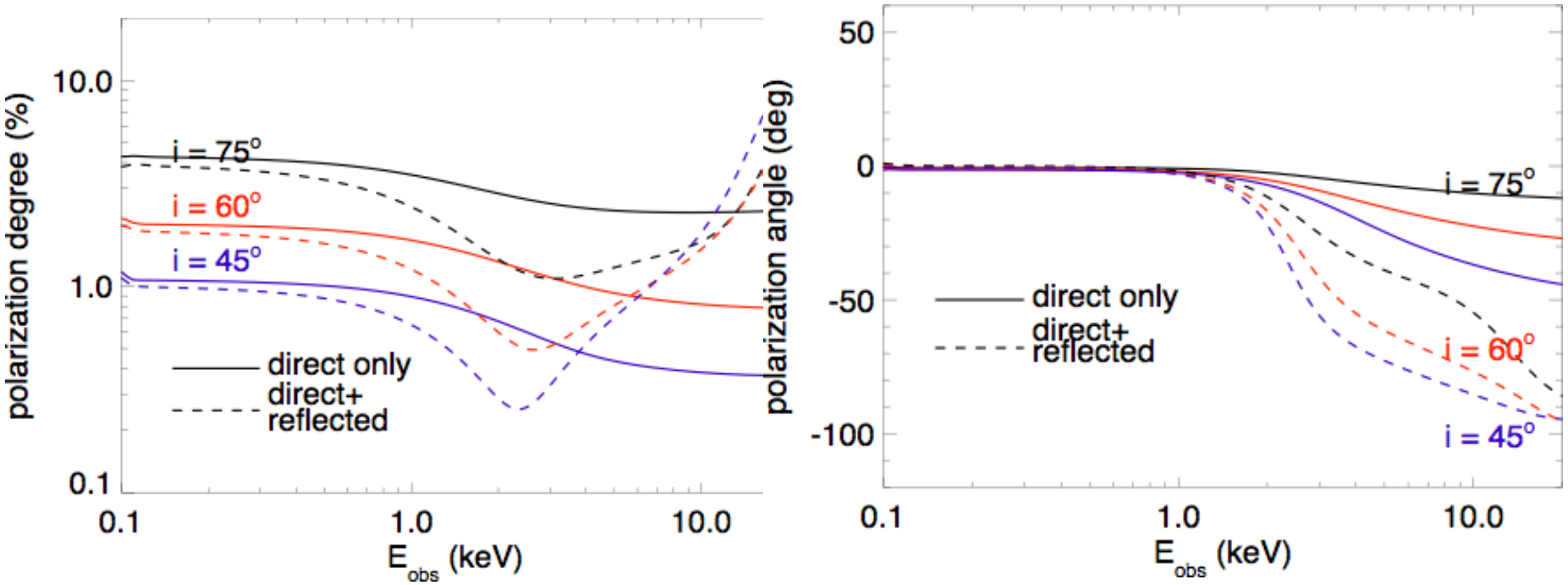

Newtonian disk – spin

# Polarized Image of black hole accretion disk




Newtonian disk – returning radiation

# Two regimes in black hole polarization behavior -

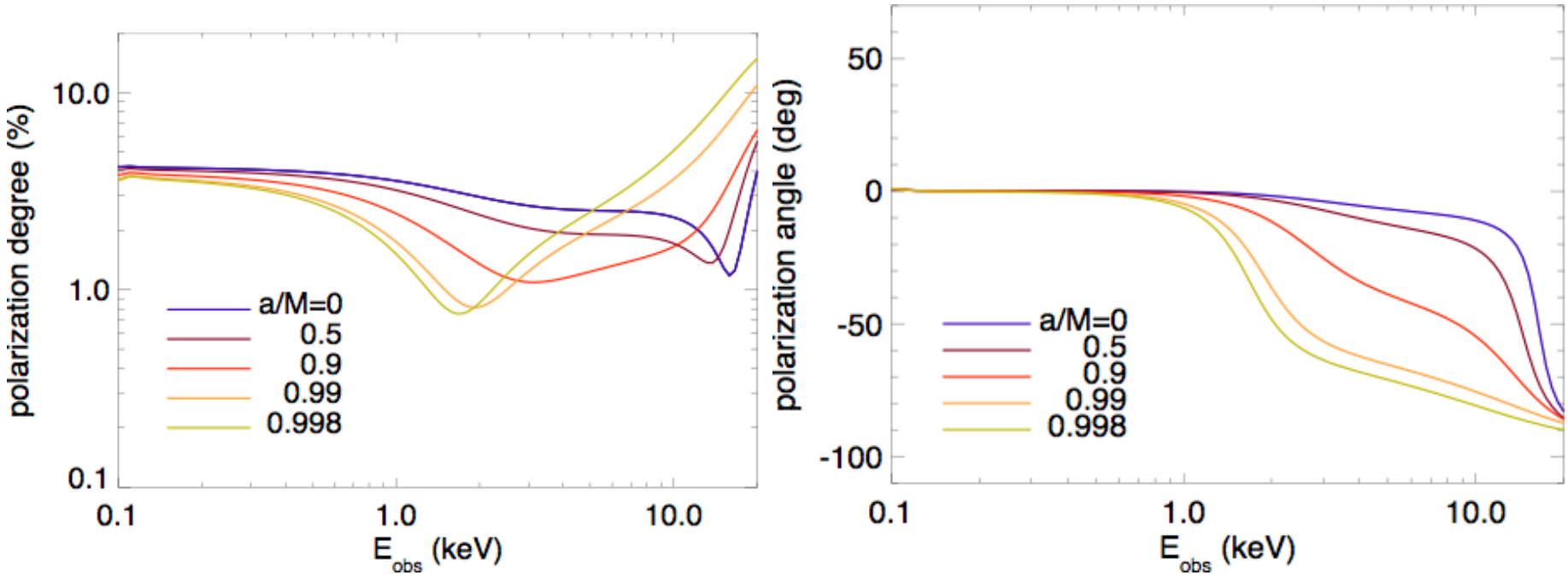



(Schnittman and Krolik 2009)

- 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

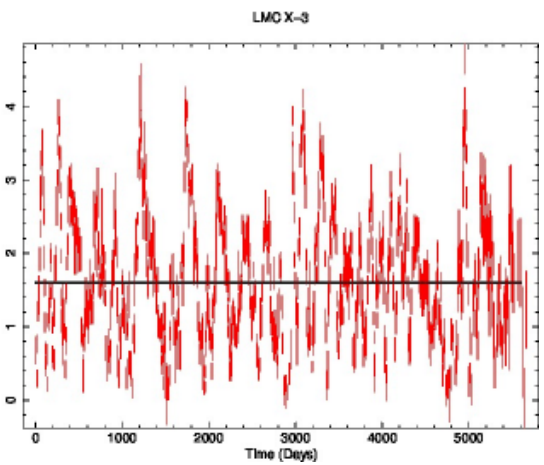



(Schnittman and Krolik 2009a)

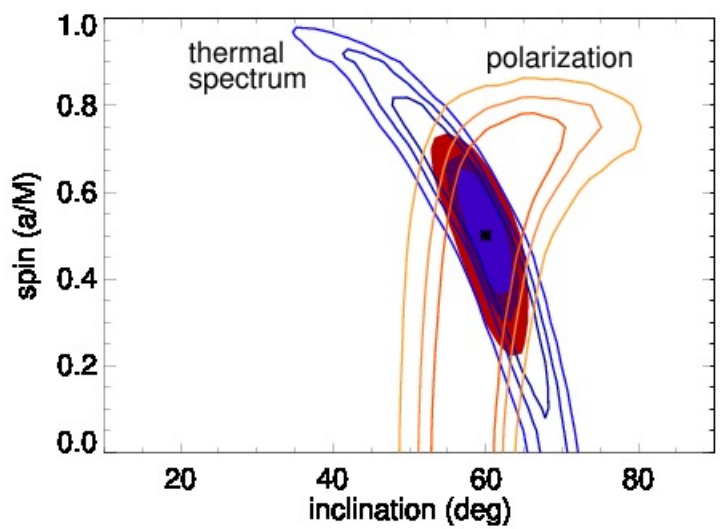
- Strength of return radiation depends on spin
- Therefore, transition energy between the direct and return-dominated regimes, and strength of high energy polarization, depend on spin

# 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 (2-4 keV, 4-8 keV) show that spin and inclination determination is robust against changes in black hole intensity state
  - Low energy polarization fraction separates inclination
  - Low vs high polarization angle separates spin




ASM decade long light curve for LMC X-3;



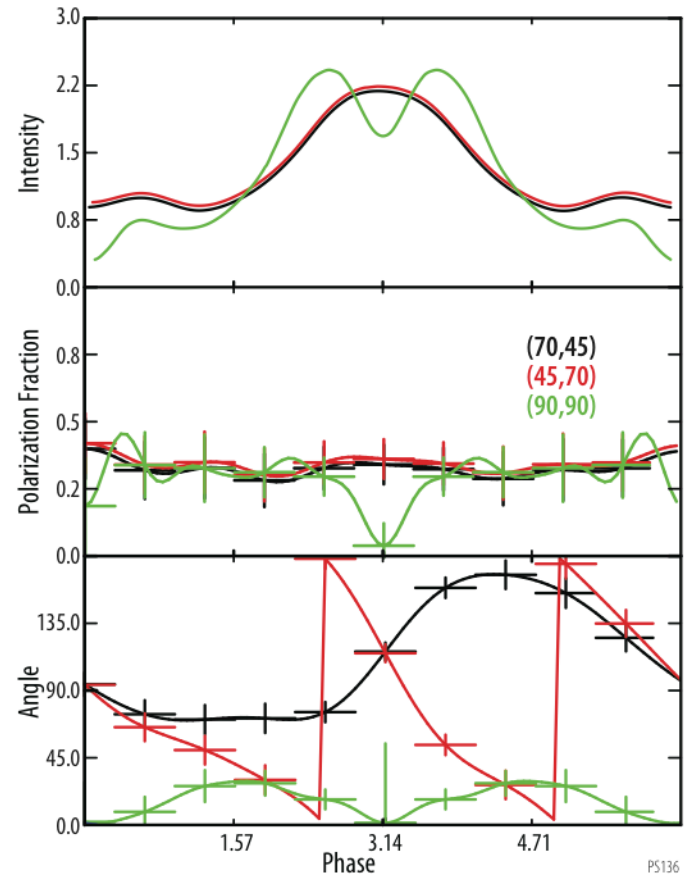

Schnittman and Krolik (ApJ, submitted)

# Neutron Stars and Magnetic Fields

- In the ultrahigh fields of *magnetars,* birefringence leads to measurements of ***B.***
- For synchrotron emission from electrons and positrons travelling along field of *Rotation powered pulsars*, polarization is diagnostic of emission location
- In *Accretion Powered pulsars*, energy resolved polarization probes ***B*** and $\rho$, constrains shock conditions and geometry

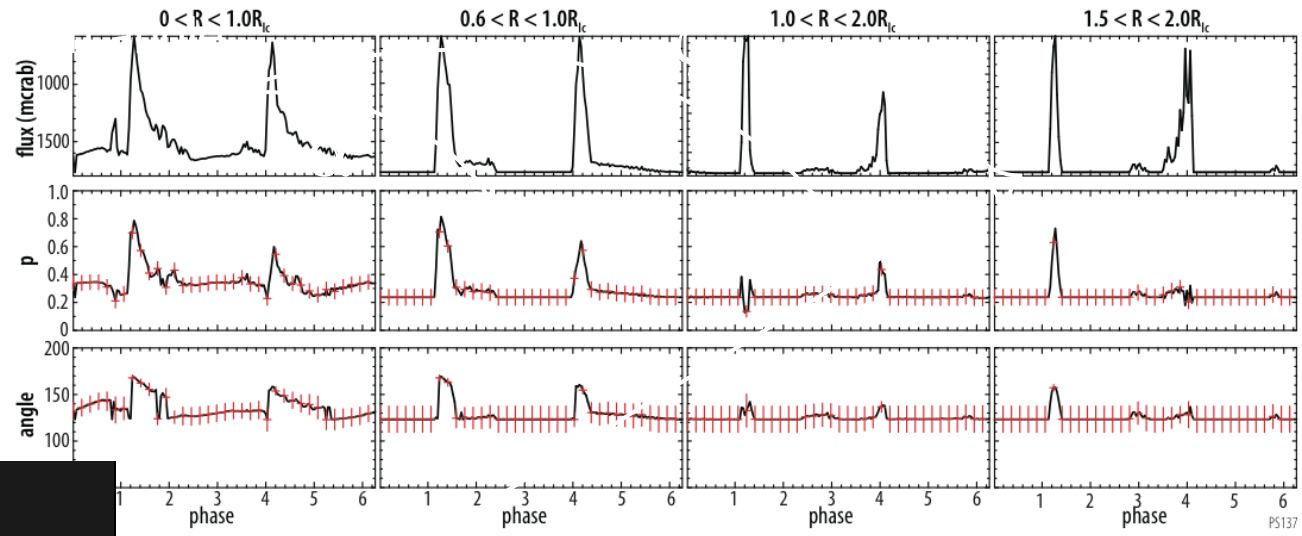
# Magnetars

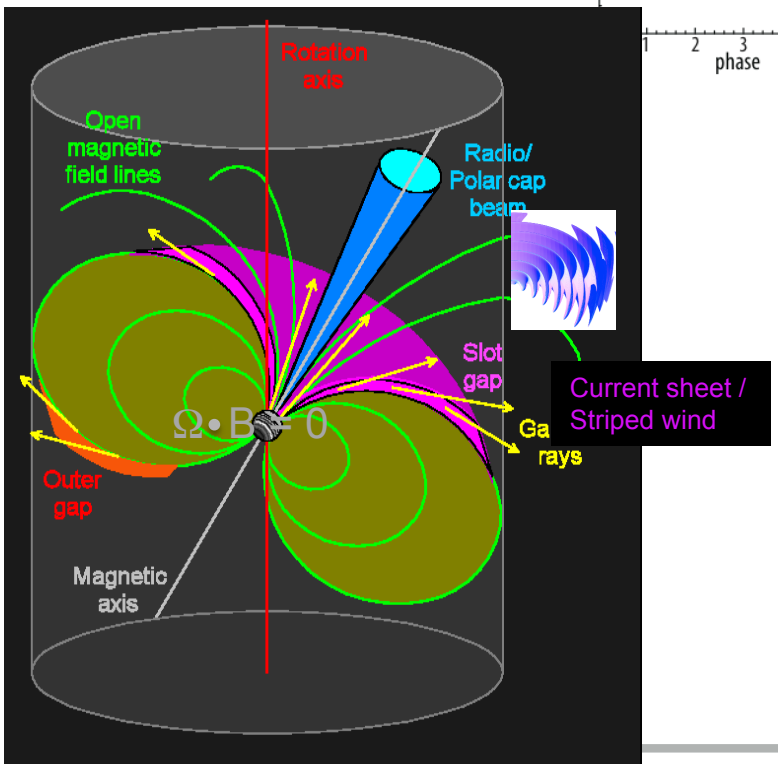
- Ultrahigh ***B*** fields of magnetars are birefringent
  - Polarization rotates as photon travels from surface to $r_{plr}$
  - Intensity probes surface; polarization probes field
  - Diagnostic of ***B*** and viewing angles




- Figure adapted from Fernandez and Davis 2011 (4-12 keV)

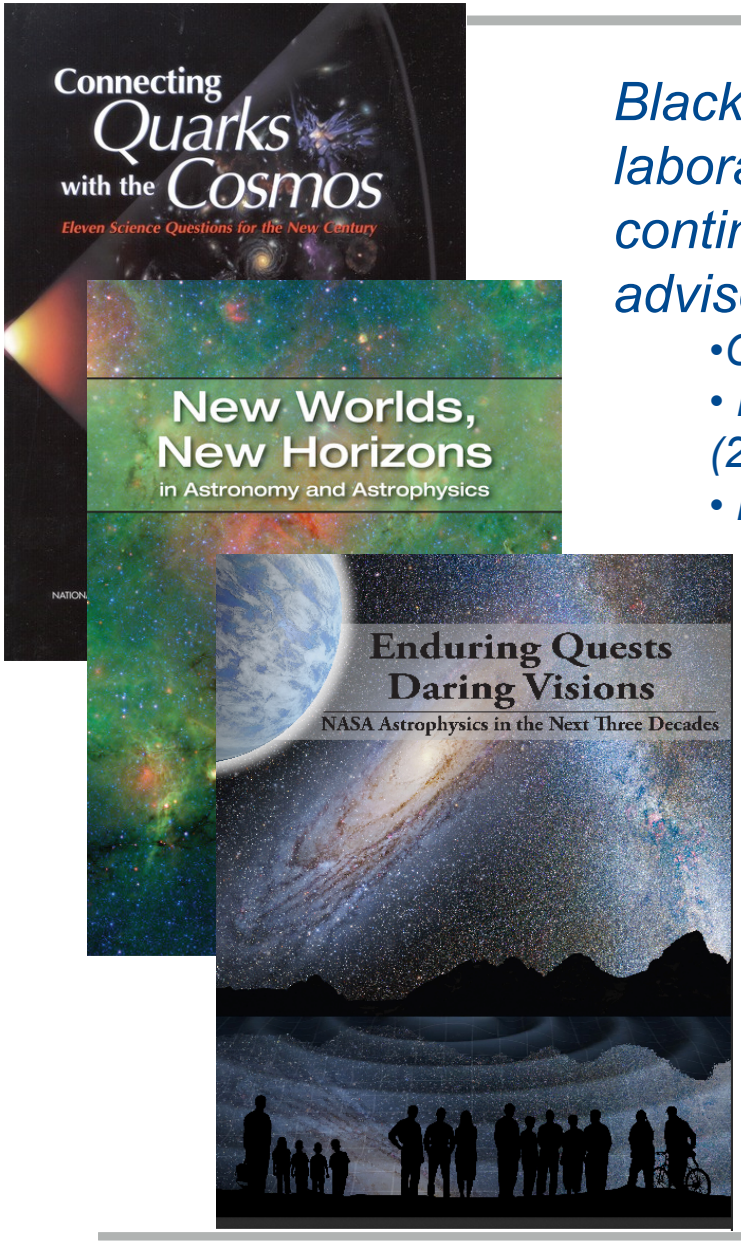
# Rotation powered Pulsars - Crab




- Polarization probes height of emission, within or beyond light cylinder.
- Depolarization of peaks and orientation outside of peaks are both diagnostic

# Traceability to Strategic Plans




*Black Holes and Neutron Stars are laboratories for Physics and Astrophysics, continually identified as priorities by National advisory committees:*

- *Connecting Quarks with the Cosmos; NRC (2003)*
- *New Worlds, New Horizons, NAS Decadal survey (2010)*
- *Enduring Quests, Daring Visions (2013)*

*X-ray Polarimetry addresses these questions, and provides some answers to the question:*
"How does the universe work?"

# Polarization measurements

- Measurements are demanding
  - Fractional polarization may be small
  - Photoelectric polarimeters require ~2 x $10^6$ photons to detect 1% signals (~2 x $10^4$ to detect 10%)
  - Instrumentalist claims about the value of simultaneous spectral, temporal, spatial resolution must be measured against number of expected counts and signal per energy band, phase bin, or image pixel

  - PRAXyS provides
    - Proportional counter energy resolution: $\Delta E/E \sim 20\% \, (E_{keV}/6)^{-0.5}$
      - Probes gravitational potential of accretion disks
    - Sub millisec timing resolution
      - Probes field structure and emission geometry of NS
    - Several arc minute spatial resolution (defined by field of view)

# SUMMARY: PRAXyS Breakthrough Capabilities

- Substantially greater sensitivity (2-10 keV) than the only previous X-ray polarimetry instrument, OSO-8.
- Energy range and sensitivity to measure general relativistic (GR) effects around black holes (BHs)
- Energy range, sensitivity and timing resolution to detect vacuum polarization in pulsars and magnetars
- Very low-risk implementation (based on work done for successful GEMS technical PDR and subsequent development)

All PRAXyS prime mission data will be made public as soon as they are validated.