The Polarization Frontier

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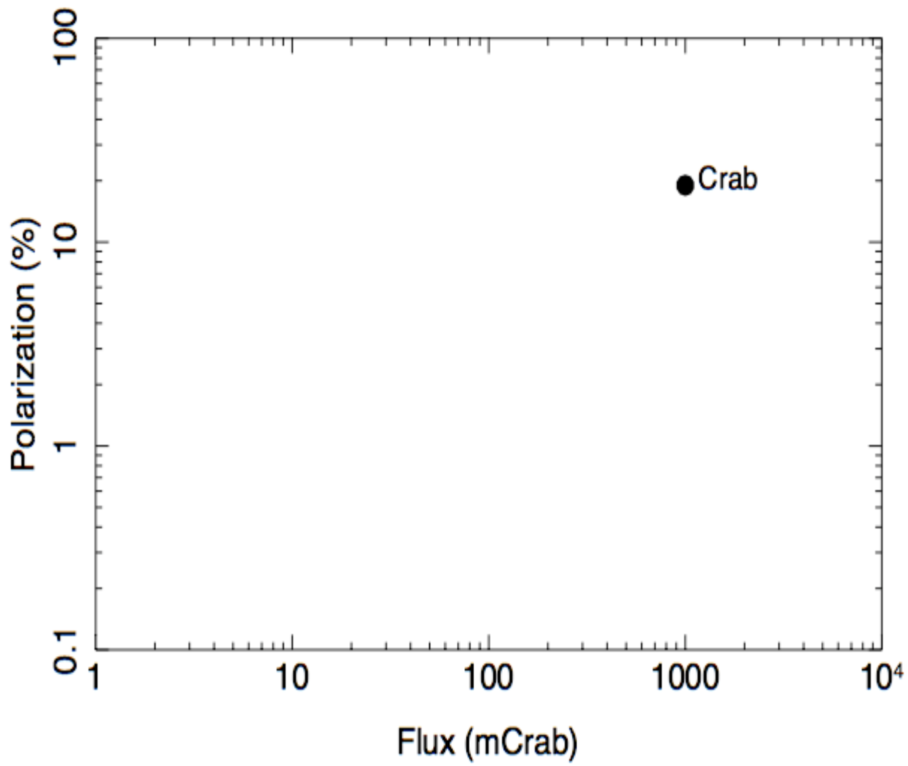
Elihu Boldt Memorial Symposium

6 November 2009



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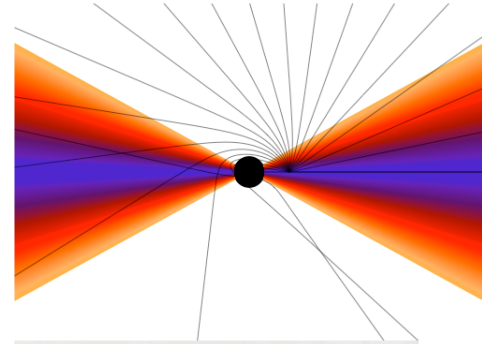
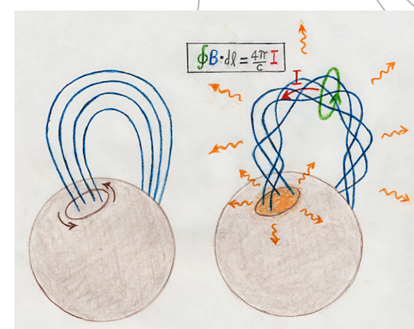
From an observational point of view, X-ray polarimetry starts with a nearly completely blank slate

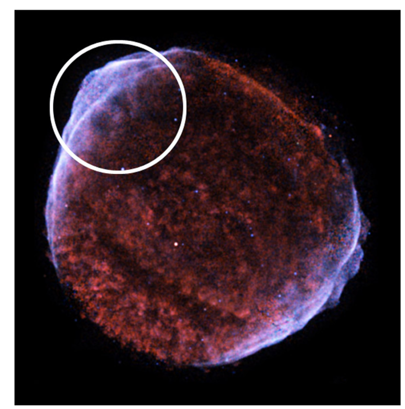
Theory predicts that X-ray polarimetry will



- Probe black hole spin and accretion disk geometry
    - direct radiation is polarized parallel to the disk and dominates at lower energies
    - return radiation is polarized perpendicular to the disk
    - polarization magnitude and orientation is diagnostic



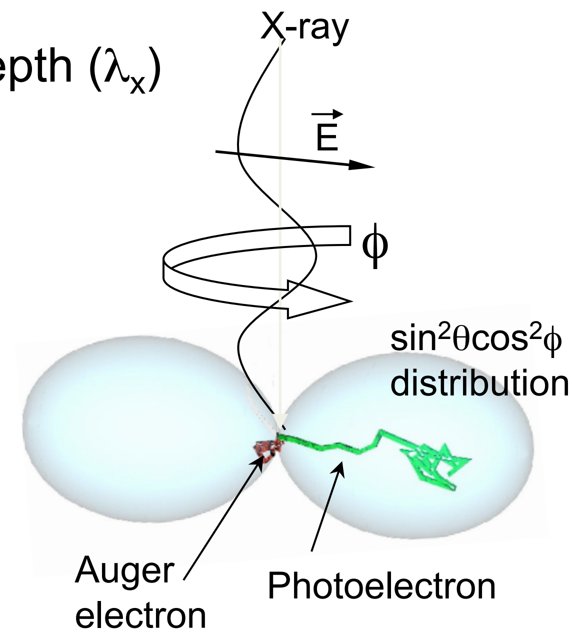
- Probe the high magnetic fields near the surface of neutron stars
    - X-rays are highly polarized perpendicular to k-B plane
    - Propagation in high fields probes GR effects



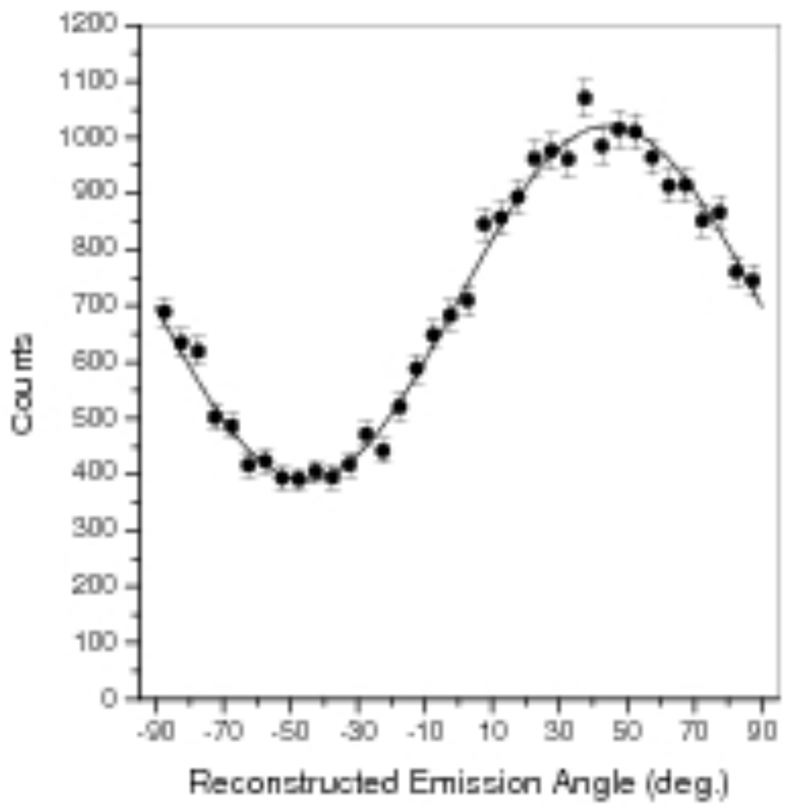
- Characterize the magnetic fields in supernova remnants

Photoelectric X-ray Polarimetry

- Exploits: strong correlation between the X-ray electric field vector and the photoelectron emission direction
- Advantages: dominates interaction cross section below 100keV
- Challenge:
  - Photoelectron range < 1% X-ray absorption depth (λ_x)
  - Photoelectron scattering mfp < e^- range
- Requirements:
  - Accurate emission direction measurement
  - Good quantum efficiency
- Ideal polarimeter: 2d imager with:
  - resolution elements $\sigma_{x,y} < e^-$ mfp
  - Active depth ~ λ_x
  - => $\sigma_{x,y} <$ depth/10^3



Modulation and sensitivity



In practice, the distribution of estimated track directions, even for purely polarized input, is more complicated than a projection of the $\sin^2\theta\cos^2\phi$ probability distribution.

$$N = A + B \cos^2 (\phi - \phi_0)$$

$$\mu = \frac{N_{max} - N_{min}}{N_{max} + N_{min}}$$

$$\mu = B / (2A + B)$$

Elihu's Polarimeter

E. Boldt 11-23-65

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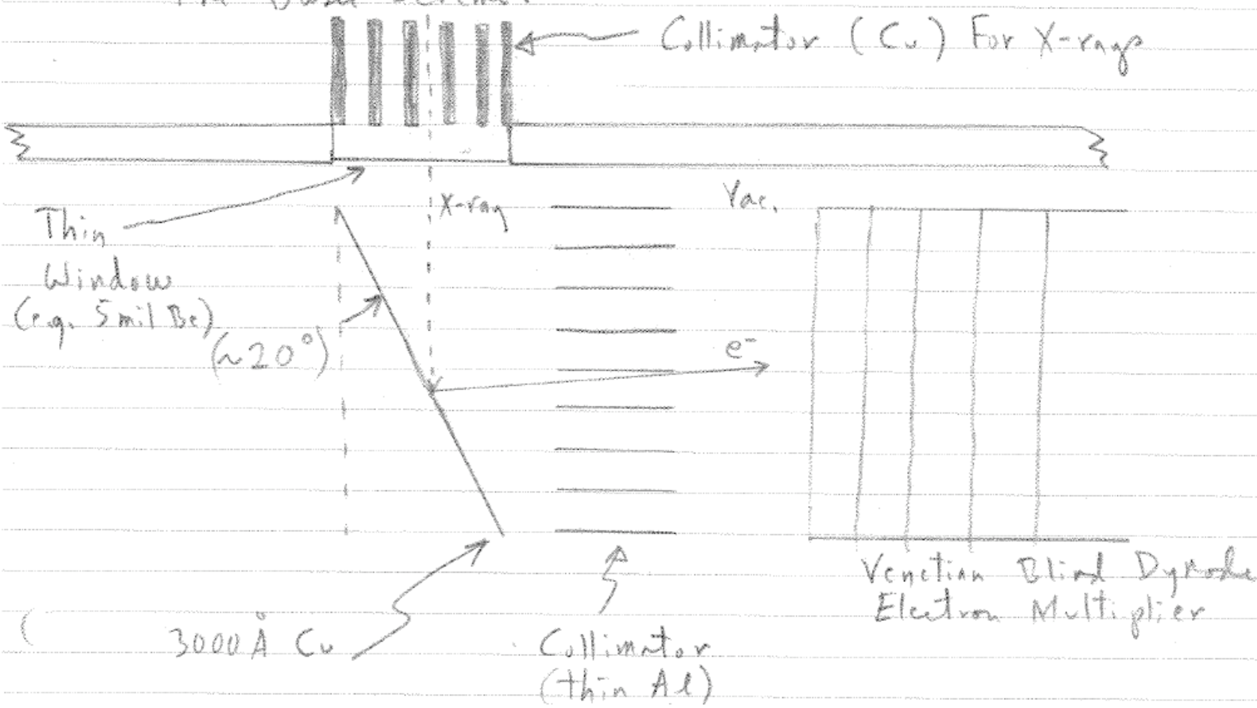
Electron Optics For X-ray Photon Polarization Measurement

The Basic Scheme:

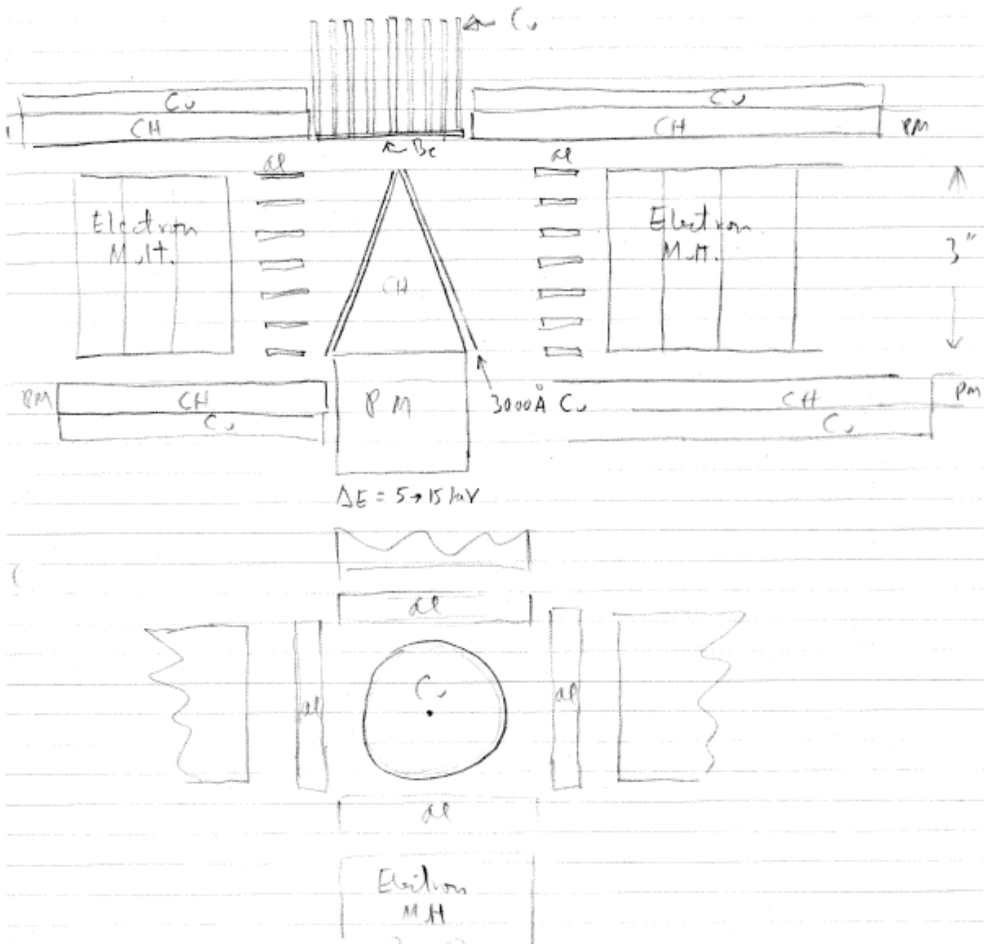


$$\frac{dI}{d\Omega} \propto (\vec{k} \cdot \vec{p})^2$$

Elihu's Polarimeter – Physical effects

- Photoelectric absorption
  - – Efficiency ~0.03 at 20 keV
- Scattering in the detector
  - – Energy loss and angle change via multiple scatters
- Tagging the signal
  - Scintillator tags 9 keV Cu-K photon
- Distribution of tracks $\frac{dI}{d\Omega} \propto (\vec{k}\cdot\vec{P})^2$
  - – Angular resolution provided by an electron collimator

Elihu’s sensitivity



Elihu’s estimated detector rate is ~0.3 ct/sec for 1 Crab source. (assumes 5 cm aperture)

If

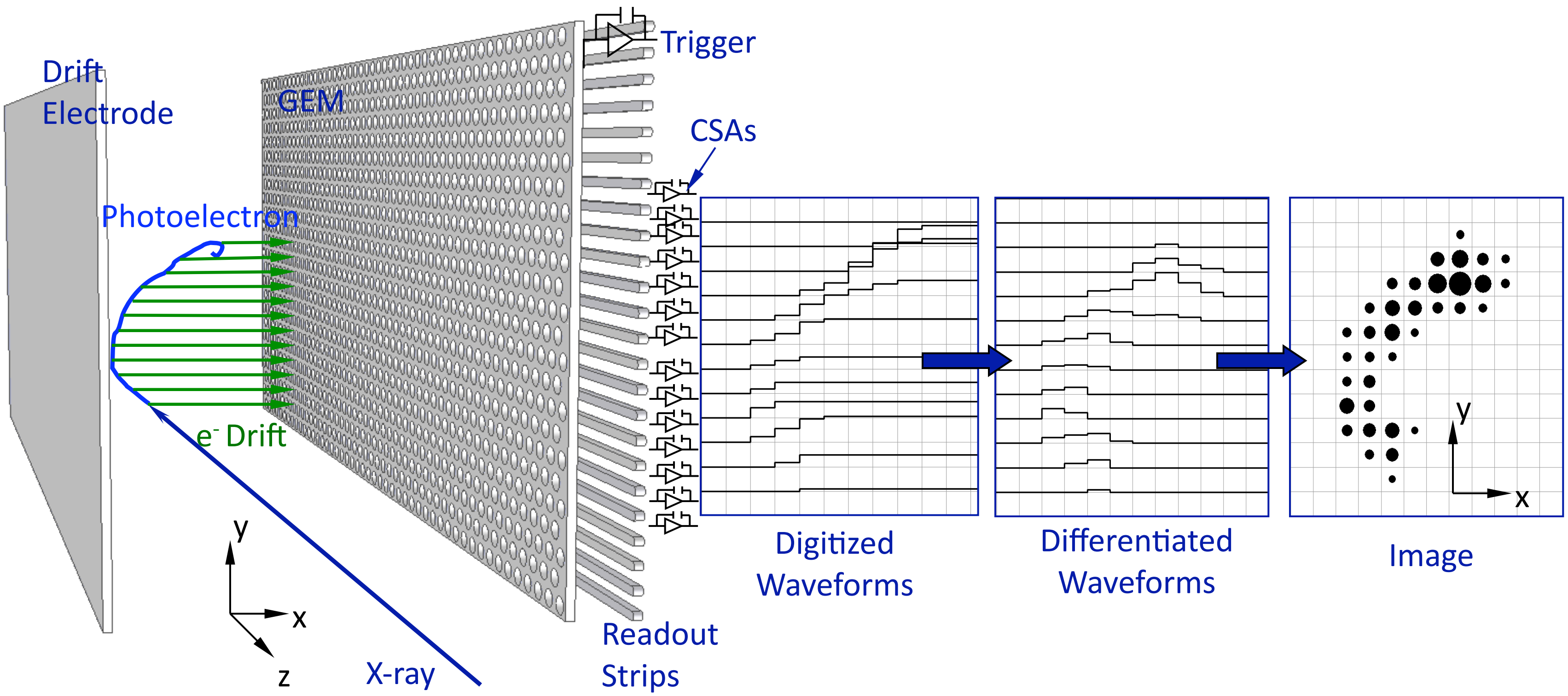
$S > B$,

$\mu > 0.1$

Polarization of the Crab nebula could have been detected in a few hours

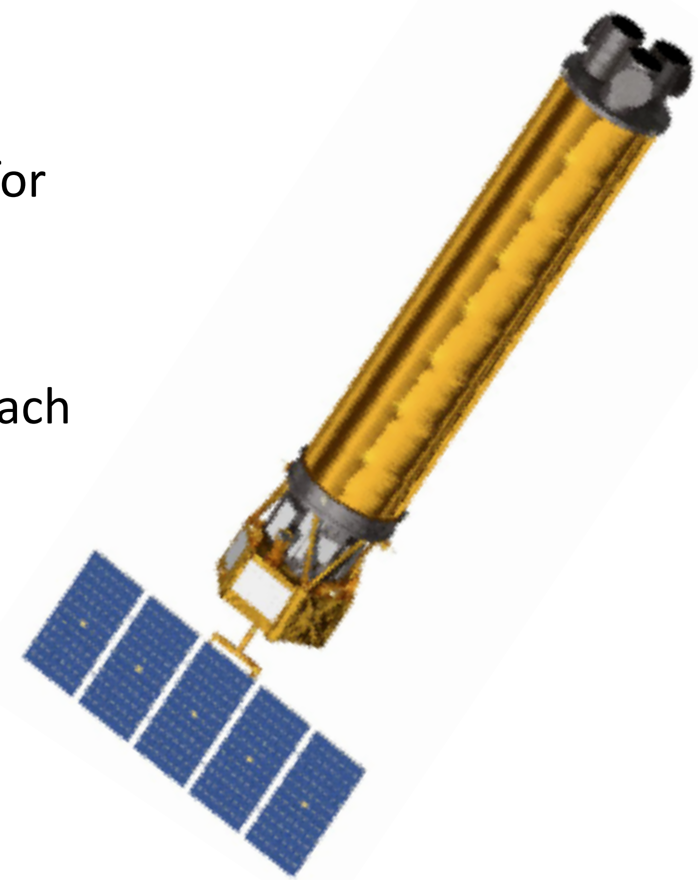
TPC Polarimeter Concept

- Drift direction is perpendicular to X-ray propagation so efficiency is decoupled from other considerations
- One dimensional images using strip readout
- Pixels are formed by time projection, coordinates [arrival time,strip location]
- Drift height determined by collimation of beam



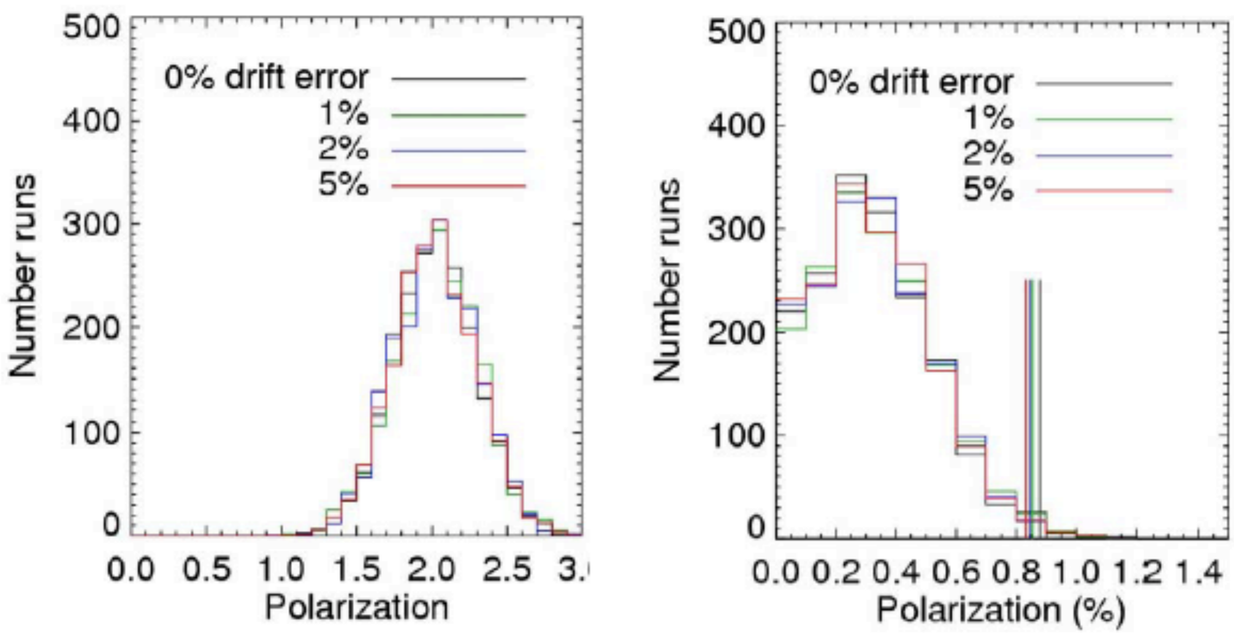
Gravity and Extreme Magnetism Small Explorer Concept

- The Time Projection Polarimeter is the heart of the Gravity and Extreme Magnetism Small Explorer
    - Currently in Phase B
    - Launch in 2014
- Rotation of three-axis stabilized spacecraft for low false modulation due to instrumental systematic error
- Full sky visibility; ~300 sources accessible, each for ~ 8 weeks every 6 months
- Straightforward operations concept
- 9 month program of 35 targets
- No consumables, lifetime ≥ 2 yr



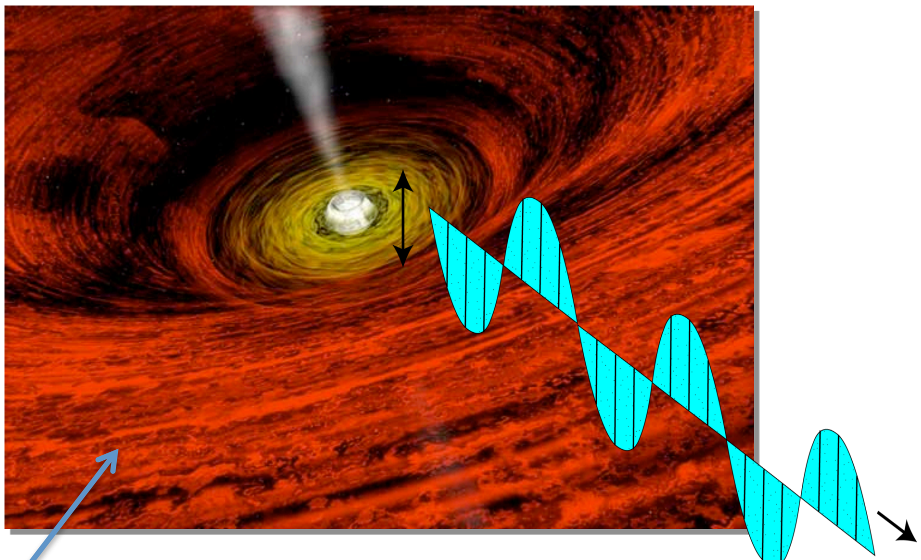
Benefits of Rotation

- Simulations with 10^6 photons/run (μ~ 0.5, MDP < 0.01) show the power of spacecraft rotation
- PROCEDURE
  - Generate photons
  - Move photon E-field into detector frame
  - Generate photoelectron direction with $\cos^2(\phi)$ distribution
  - Distort (by stretching) one axis
  - Measure the distorted direction
  - Map the photoelectron direction back onto the sky

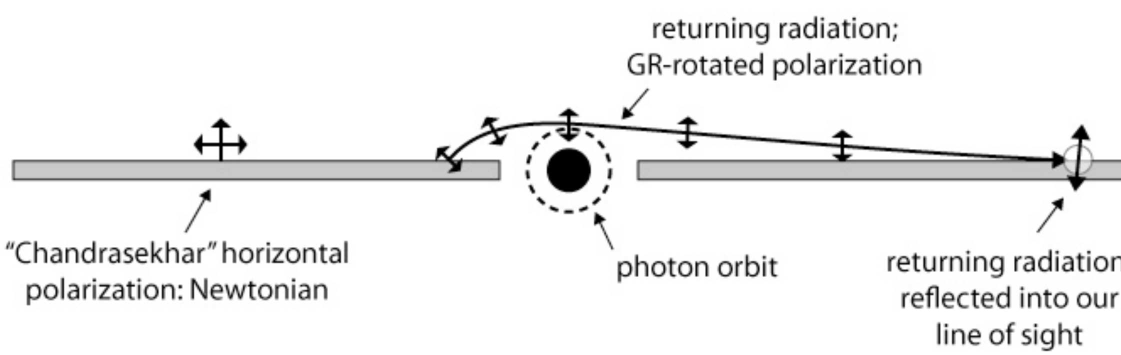


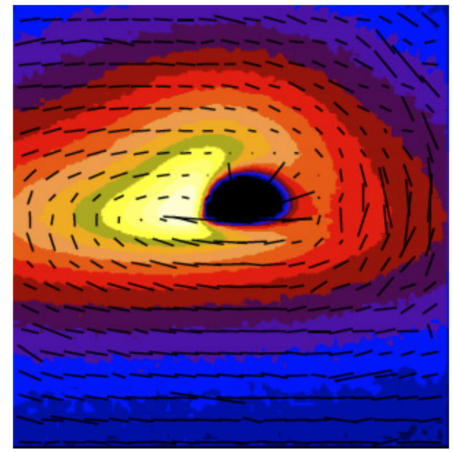
- RESULTS: Spacecraft rotation removes the effects of detector asymmetries

Black holes bend x-rays and rotate the polarization according to their spin



Accretion disk





How the image of the disk would look if we could resolve the image for a black hole with high spin

GEMS will open the frontier of X-ray polarimetry

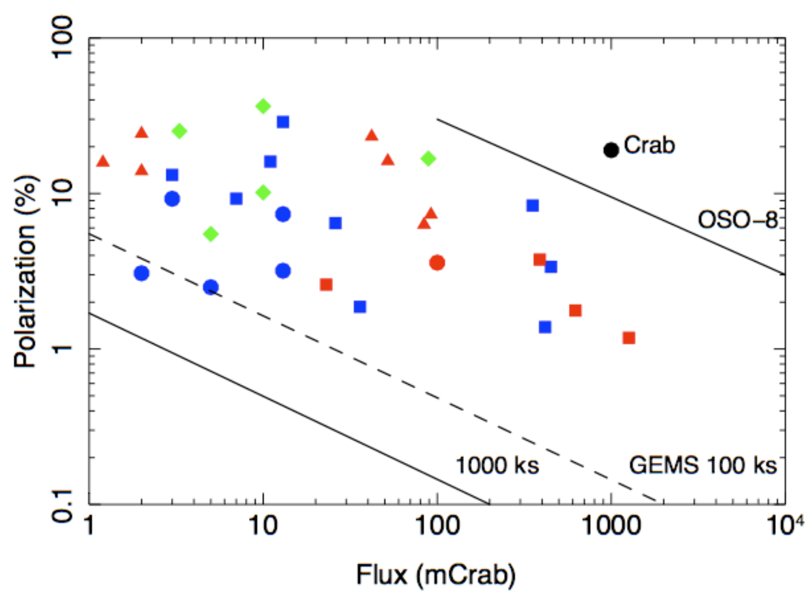
- GEMS will open a brand-new window on the sky.
- Polarization in the X-ray band is essentially unexplored: the polarization of only *one* object outside the solar system has been previously detected.
- GEMS will be ~100x more sensitive than any previous instrument and will be able to study well *dozens* of objects.
- *Discoveries* are expected from black holes, neutron stars, supernova remnants.

Targets with known fluxes and polarization estimates

Black holes

Neutron stars

Supernova remnants



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NEW TERRITORY