Proportional Counters, CCDs and Polarimeters

Joe Hill
USRA/CRESST
NASA Goddard Spaceflight Center

Outline

- The Ideal Detector
- X-ray Astronomy Early History
- Proportional Counters
- CCDs
- Polarimeters

What characteristics would an ideal X-ray detector have?

- High spatial resolution
- Large (effective) area
- Good temporal resolution
- Good energy resolution
- Unit quantum efficiency (QE)
- Large Bandwidth
  - (typically around 0.1-15 keV)

Fraser, X-ray Detectors in Astronomy

What characteristics would an ideal X-ray detector have?

- Stable on timescales of years
- Negligible internal background
- Immune to radiation damage
- Requires no consumables
- Simple, rugged and cheap
- Light weight
- Low power
- Low output data rate
- No moving parts

Fraser, X-ray Detectors in Astronomy

The battle of signal versus noise…

- Detectable signal is always limited by the statistical variation in the background
  - Intrinsic detector background
    - Interactions between the detector and space environment
  - Diffuse X-ray Background=Q.Ω.j_d

J_d=diffuse background flux (ph/cm^2/s/keV/sr)
Q=quantum efficiency (counts/photon)
Ω=Field of view

The battle of signal versus noise..

If a source is observed for time, t, and a required confidence level, S, is required then,

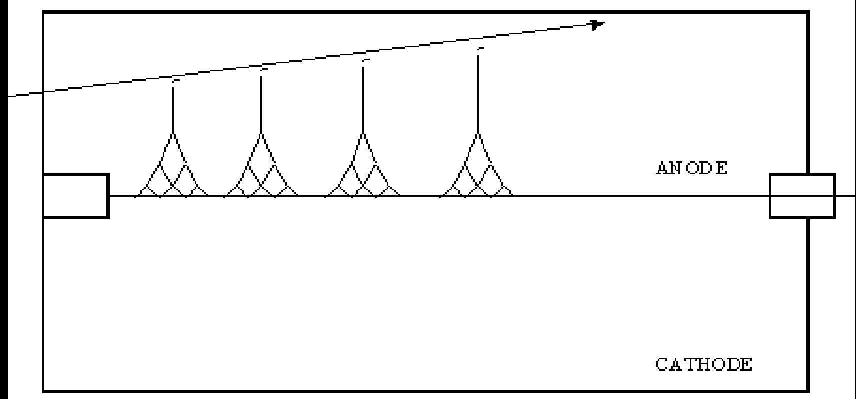
- Minimum Detectable Flux:

$$F_{\min} = \left(\frac{S}{Q.A_s}\right)\left(B_i.A_b + \frac{Q.\Omega.j_d.A_s}{t.\delta E}\right)^{1/2}$$

Proportional Counters

- Workhorses of X-ray astronomy for >10 years
- 1962-1970: Rockets and Balloons
  - 1962 Sco X-1 and diffuse X-ray sky background discovered by Giacconi sounding rocket
  - Limited by atmosphere (balloons) and duration (rockets)
- 1970-> Satellite era
  - Uhuru: First dedicated X-ray Satellite
  - e.g. Ariel V, EXOSAT
  - e.g. Ginga
  - e.g. XTE

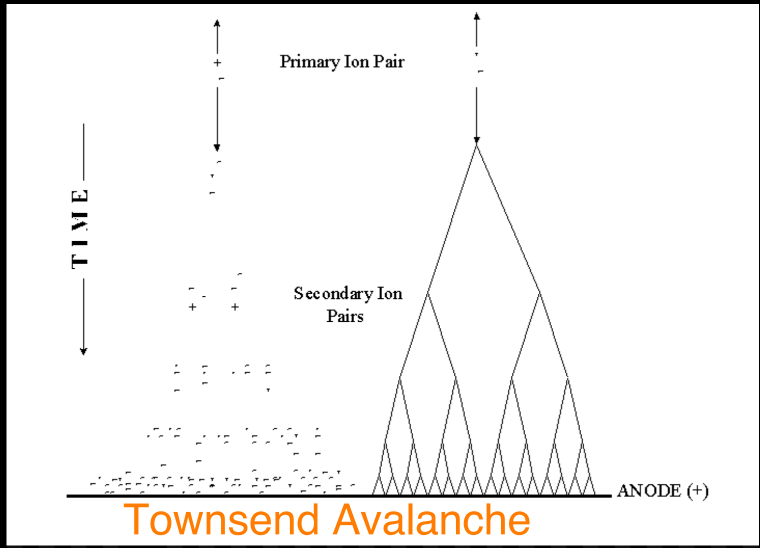
How do they work?



Typical wire proportional counter

- Gas Detectors (Ar, Xe)
- Incident X-ray interacts with a gas atom and a photoelectron is ejected
- Photoelectron travels through the gas making an ionisation trail
- Trail drifts in low electric field to high E-field
- In high E-field multiplication occurs (avalanche)
- Charge detected on an anode

Typical Characteristics



$$\frac{\Delta E}{E} = \frac{0.4}{\sqrt{E}}$$

- Energy Resolution is limited by:
  - The statistical generation of the charge by the photoelectron
  - By the multiplication process
- Quantum Efficiency:
  - Low E defined by window type and thickness
  - High E defined by gas type and pressure

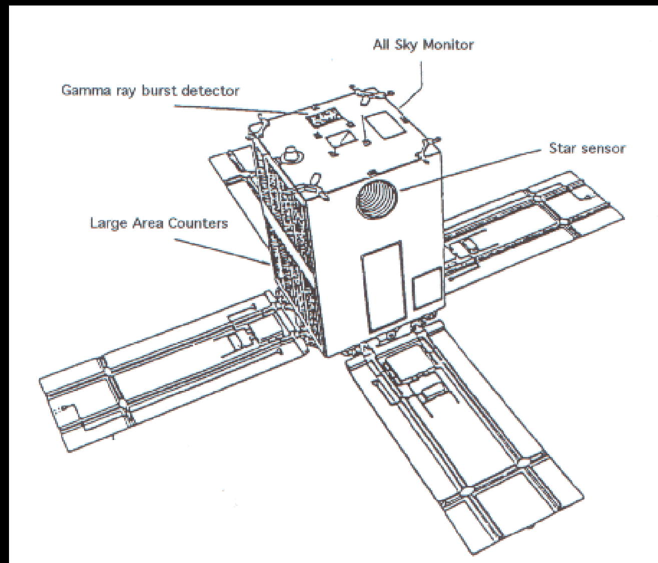
Typical Characteristics

- Position sensitivity
  - Non-imaging case: $Sensitivity \propto \sqrt{Area}$
  - Limited by source confusion to 1/1000 Crab
  - Imaging case: track length, diffusion, detector depth, readout elements
- Timing Resolution
  - Limited by the anode-cathode spacing and the ion mobility: ~ μsec
  - Timing variations: $Sensitivity \propto Area$

Background rejection techniques

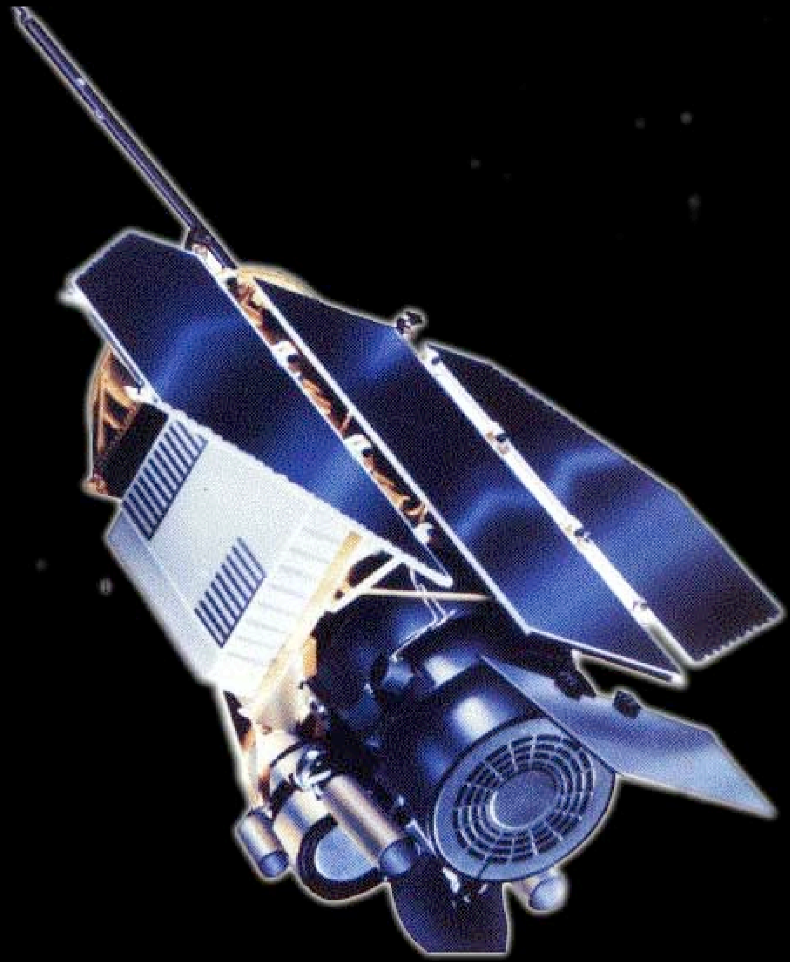
- Energy Selection
  - Reject events with E outside of band pass
- Rise-time discrimination
  - Rise time of an X-ray event can be characterised. The rise-time of a charged particle interactions have a different characteristic.
- Anti-coincidence
  - Use a sub-divided gas cell with a shield of plastic scintillator
  - Co-incident pulses indicate extended source of ionisation

Ginga
1987-1991



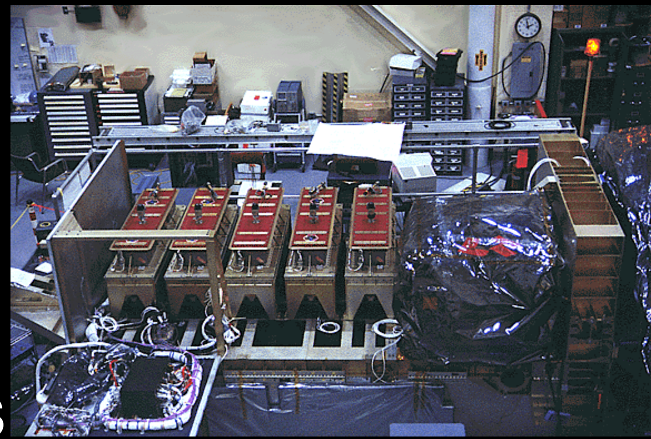
- LAC large area prop counter
  - Energy Range 1.5-30 keV
  - QE >10% over E range
  - Eff Area 4000cm^2
  - FoV 0.8x1.7 sq deg
  - Ar:Xe:CO_2 @ 2Atm
  - Energy Res: <20% @ 6 keV
  - Sensitivity (2-10 keV) 0.1 mC
- ASM (1-20 keV)
  - 2 prop counters 1''x45'' FoV
- GBD (1.5-500 keV, 31.1 msec)

ROSAT: 1990-1999



- 2 Position Sensitive Proportional Counters
  - 5 arcsec pos res
  - 0.1-2 keV
  - FoV 2 degrees
  - Eff area 240 cm^2 @ 1keV
  - Energy resn: 17% @ 6 keV
- Soft X-ray Imaging: >150 000 sources
- Low Resolution Spectroscopy

RXTE (1995--)



- Detectors: 5 proportional counters
- Collecting area: 6500 cm^2
- Energy range: 2 - 60 keV
- Energy resolution: < 18% at 6 keV
- Time resolution: 1 microsec
- Spatial resolution: collimator with 1 degree FWHM
- Layers: 1 Propane veto; 3 Xenon, each split into two; 1 Xenon veto layer
- Sensitivity: 0.1 mCrab Background: 90 mCrab

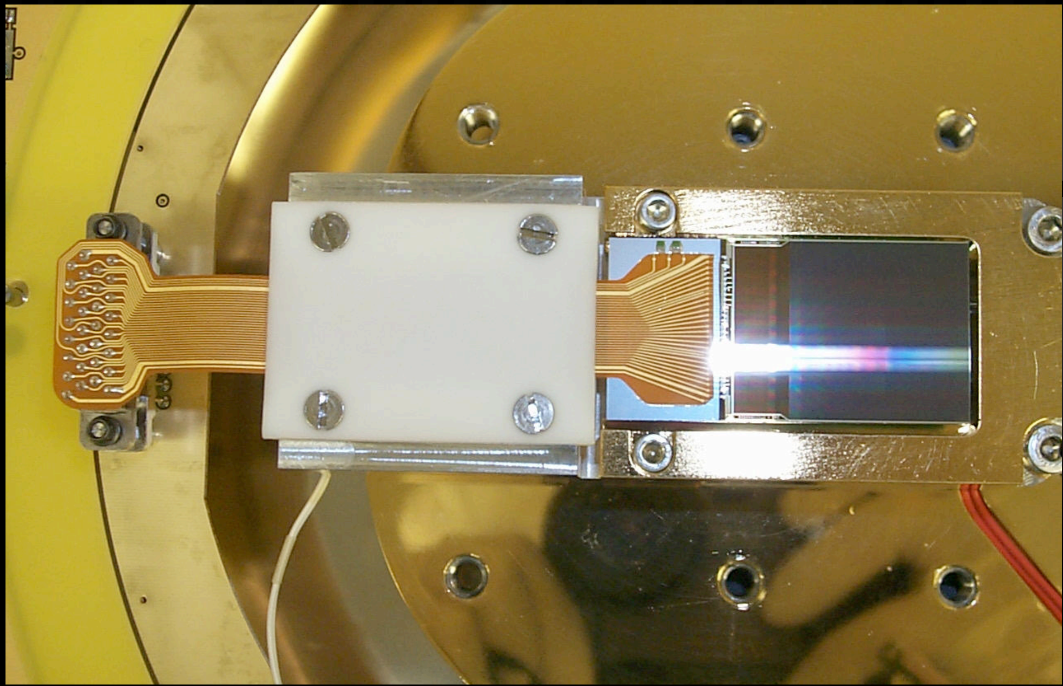
Calibration and Analysis Issues

- Gain drift
  - Gas contamination
  - Gas leak
  - Cracking
- Loss of counter e.g. micrometeoroid
  - Permanent change in instrument sensitivity
- Background veto
  - Variation in sensitivity
- Insufficient energy resolution for detailed studies of source spectra

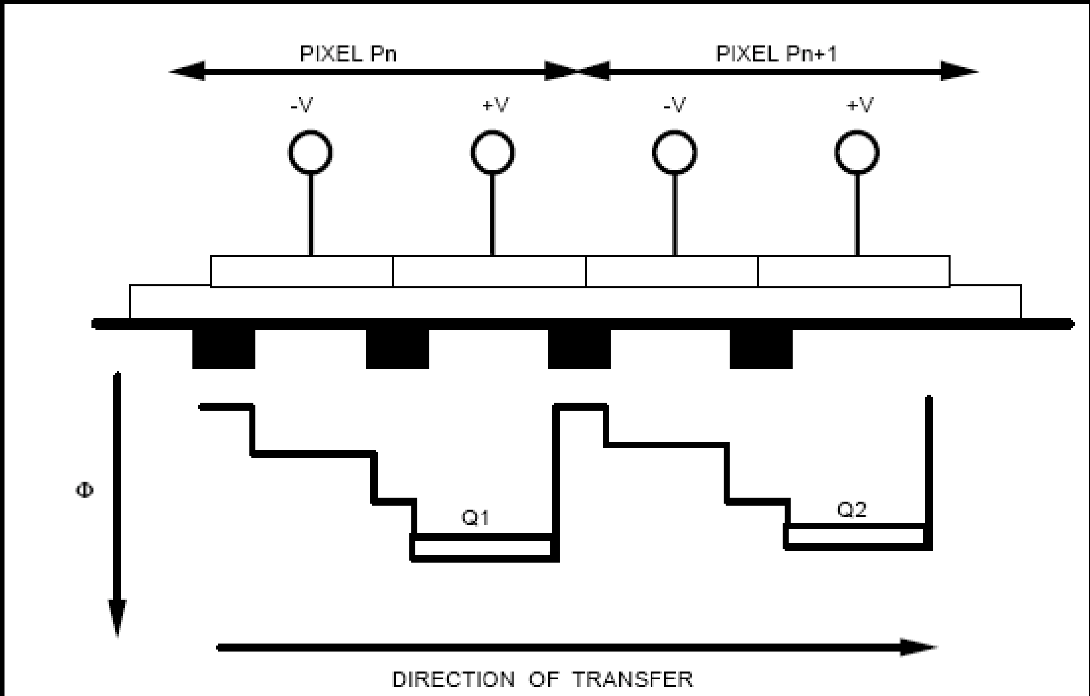
X-ray CCDs 1977 --

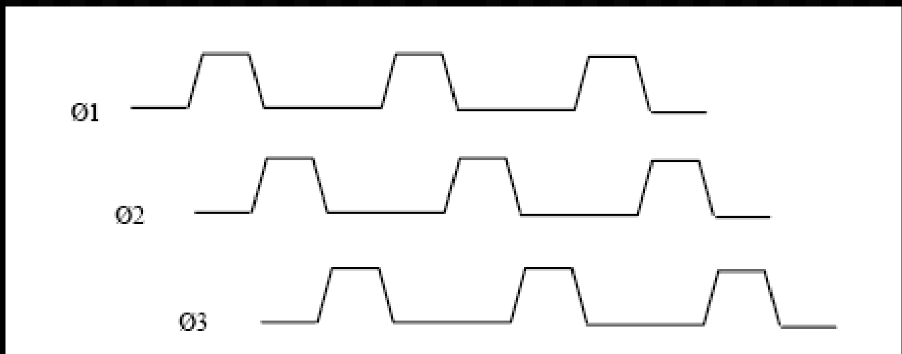
- ASCA
- XMM
- Chandra
- *Swift*
- Suzaku

Swift XRT CCD



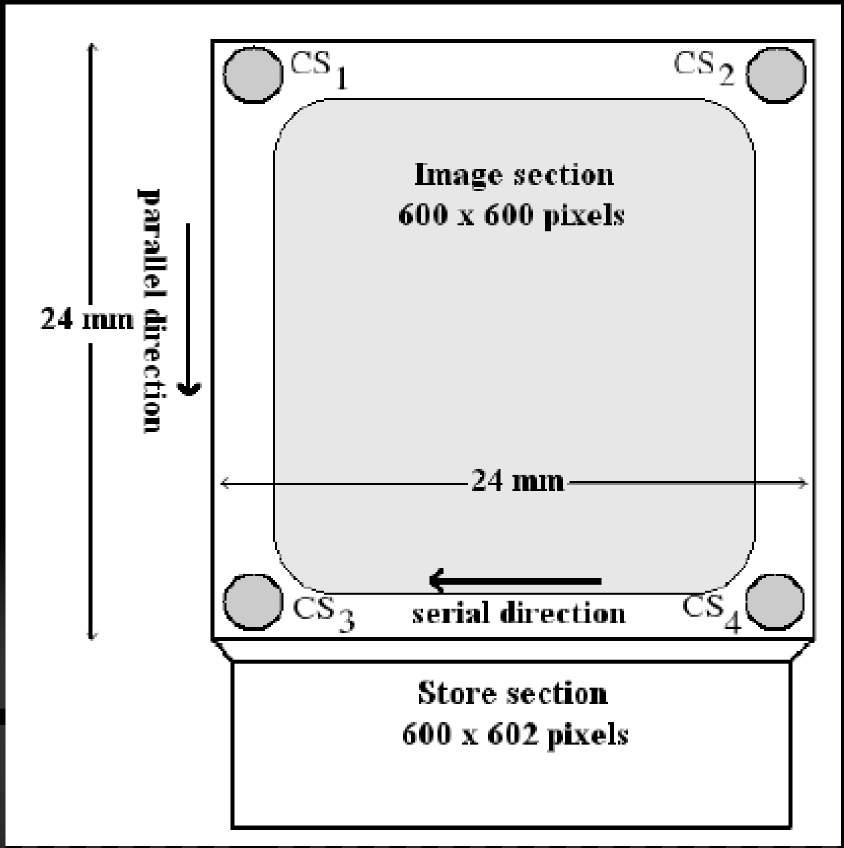
CCD Operation - charge transfer





- 2-phase CCD
- 3 Phase CCD

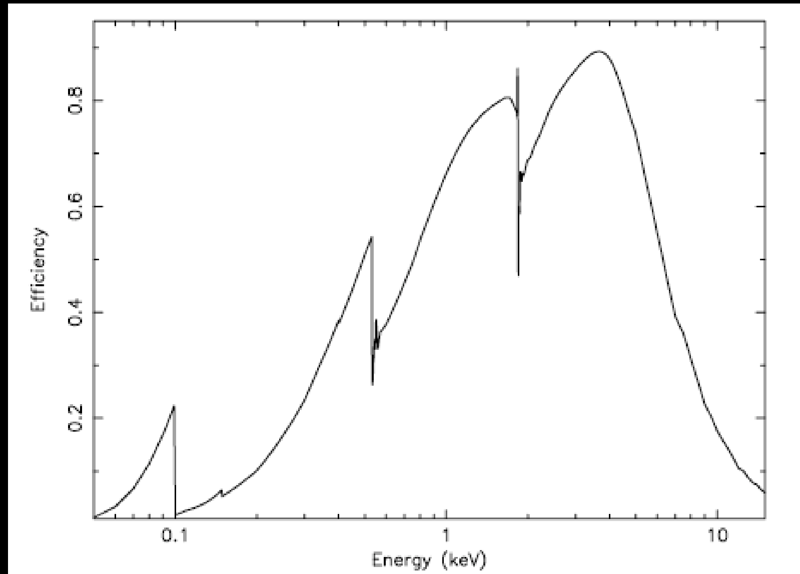
CCD Operation

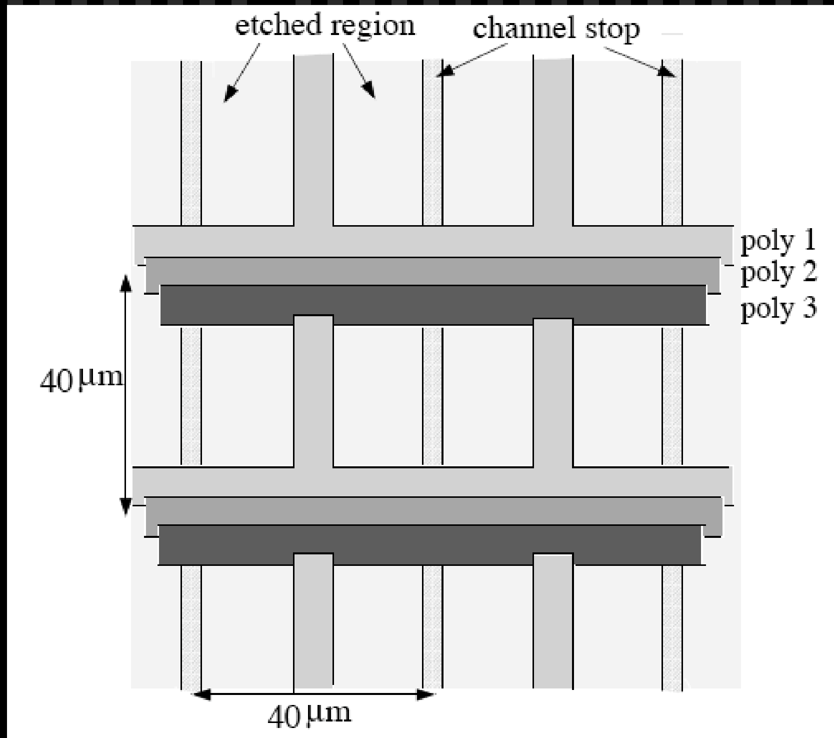


- Cooling (<-90 ºC)
  - To prevent dark current
  - To freeze traps
- Bias Maps
  - To minimise variations in background over the detector
- Hot Pixel Maps
  - To account for damage in the detector

CCD Bandpass

- Low E response
  - Electrodes
  - Optical blocking
- High E response
  - Si thickness





CCD Modes

Photodiode Mode

- Provides highest resolution timing - ~usec
- Spectroscopy - Fluxes < pile-up

Windowed Timing Mode

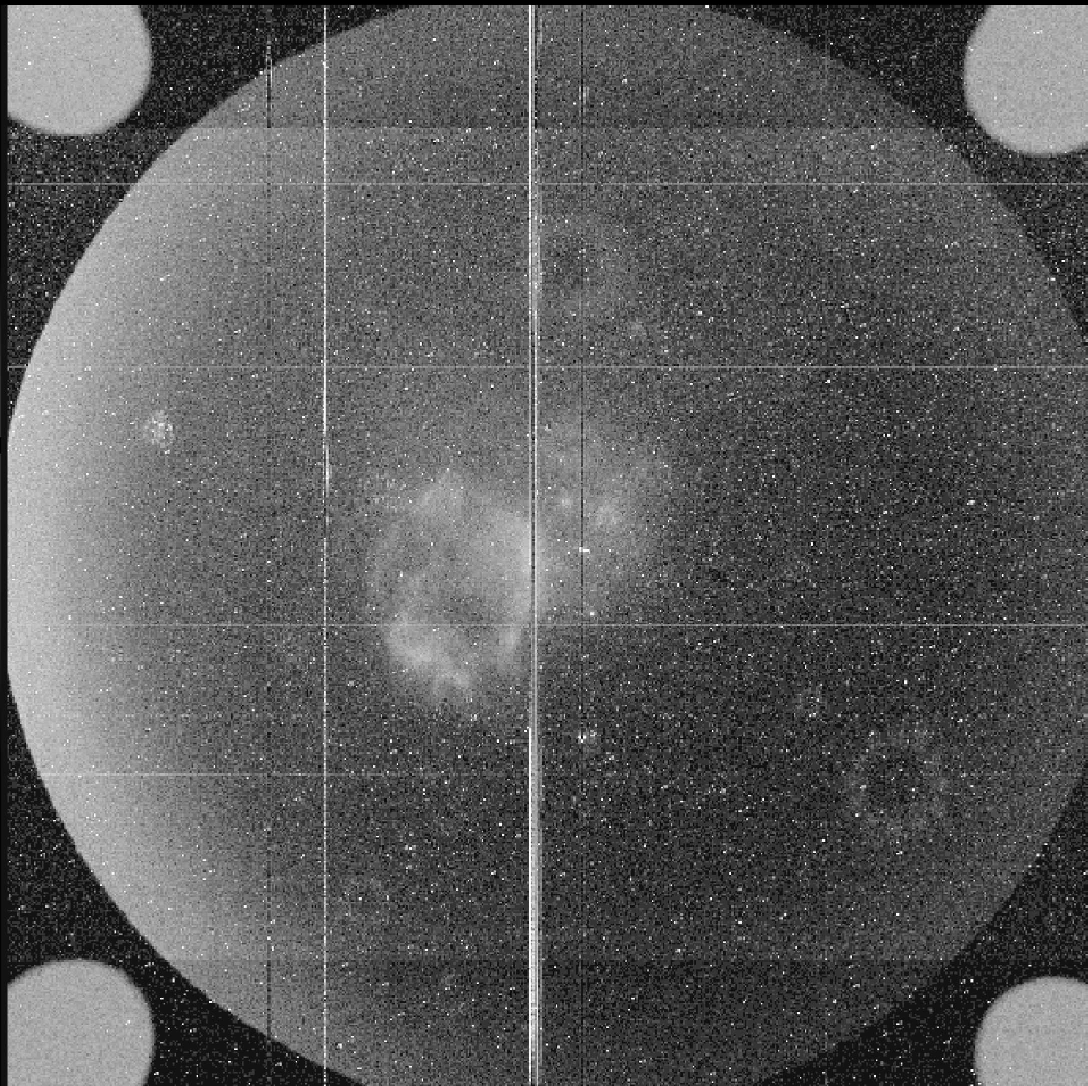
- Timing Resolution - ~ msec
- Spectroscopy
- 1-d position

Photon-counting Mode (Nominal)

- Low resolution timing – ~ sec
- Spectroscopy
- 2-D position

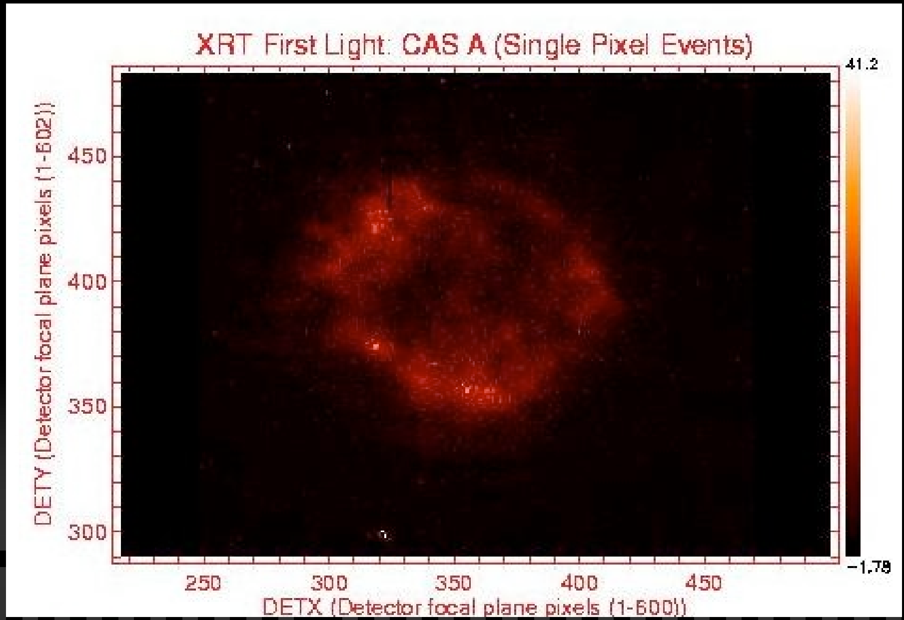
CCD Characteristics for Data Analysis

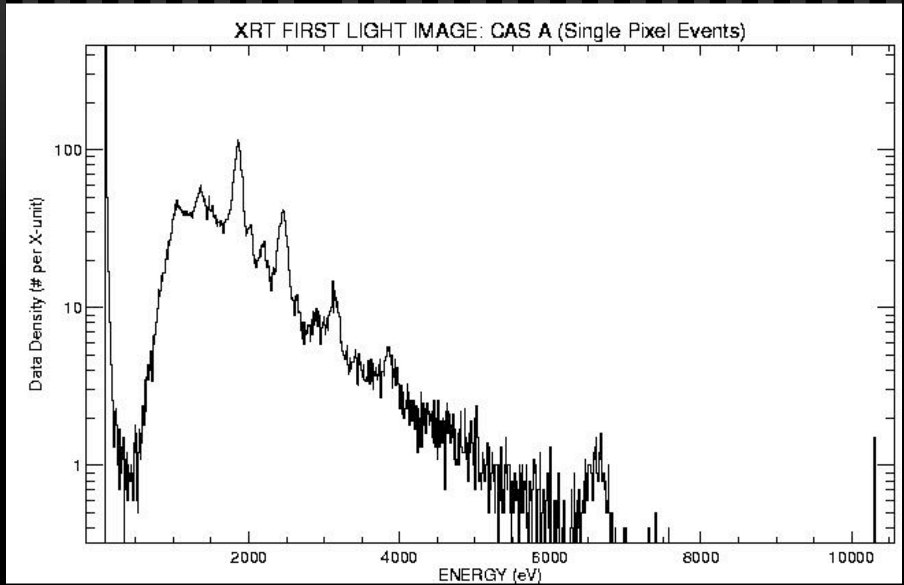
- Quantum Efficiency
- Background
- Energy resolution
- CTI
- Hotpixels



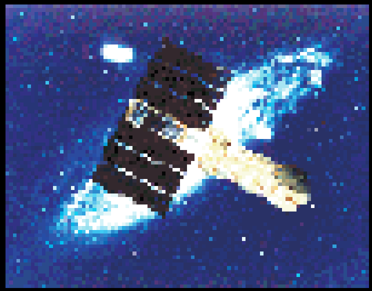
CCD Cas-A

- Cas-A image and spectrum
- HPD 15”
- 2.36”/pixel





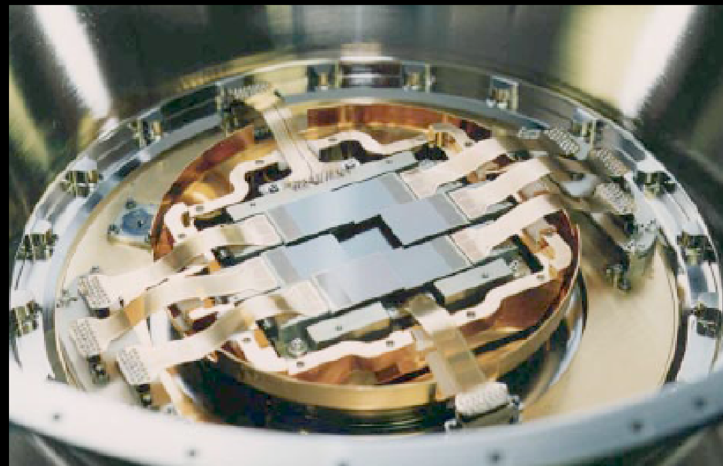
ASCA 1993-2001



- First Obs to use X-ray CCDs
  - i.e. Imaging+broad bandpass+good spectral resolution+large eff. area
- 0.4-10 keV
- 4 telescopes w/ 120 nested mirrors, 3' HPD
  - 2 proportional counters
  - 2 CCDs
- Effective Area: 1300 cm^2 @ 1 keV
- Energy resolution 2% at 6 keV

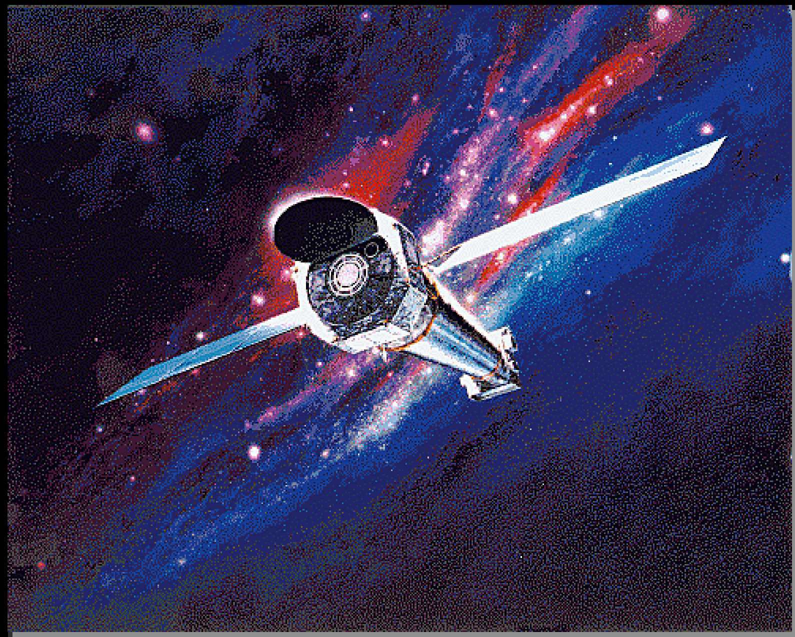
XMM - EPIC MOS
1999 --

- 3 Telescopes
- Pos Res 15''
- 2 EPIC 1 PN camaras
  - 0.1-15 keV
  - ~1000 cm^2 @ 1 keV
  - E resn: 2-5 %
  - FoV 33'



- Large collecting area
- High resolution spectroscopy with RGS
  - 0.1-0.5% 0.35-2.5 keV

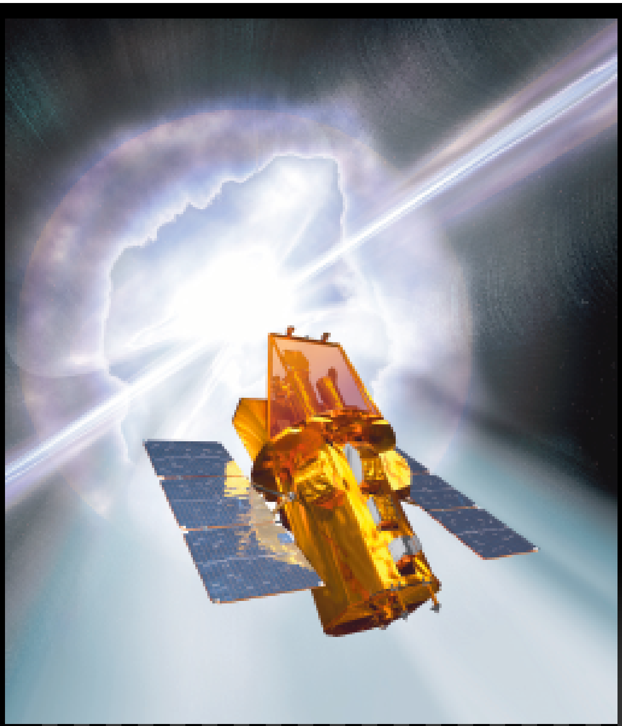
Chandra - ACIS 1999 --

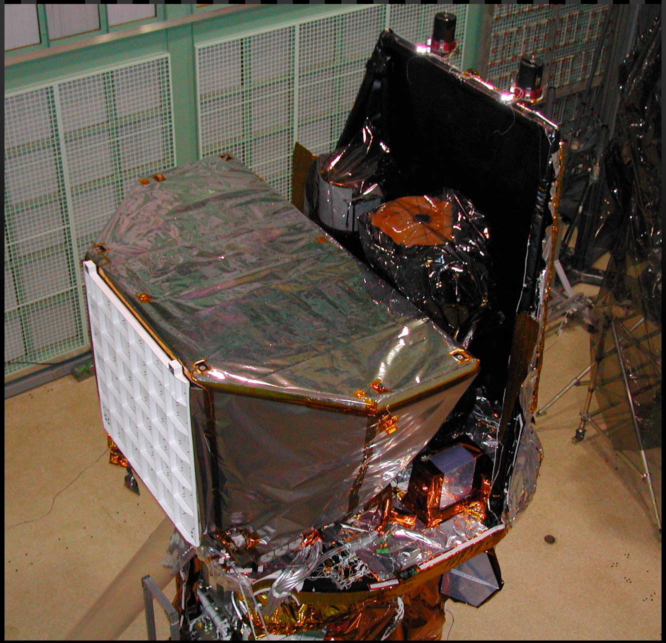


- Eff Area 340cm^2@1 keV
- 0.2 - 10 keV
- Pos Resn: <1 arcsec HPD
- Energy resolution
  - w/ grating ~0.1-1%
  - w/o 1-5%
- High resolution imaging & high resolution spectroscopy

Swift XRT
2004 --

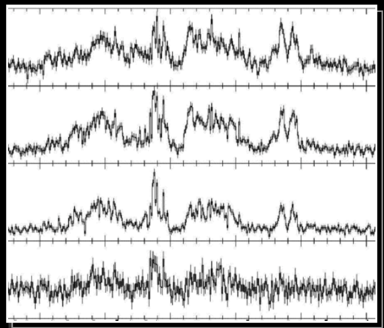
- Measure positions of GRBs to <5" in <100 seconds
- 0.3-10 keV
- 18" HPD
- 125 cm^2 @ 1.5 keV
- Automated operation



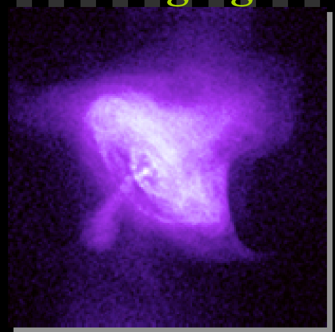


Polarimetry in X-ray Astronomy 1 keV-10 keV

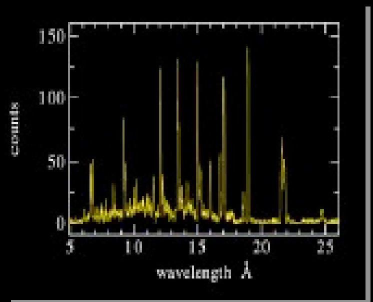
Timing



Imaging

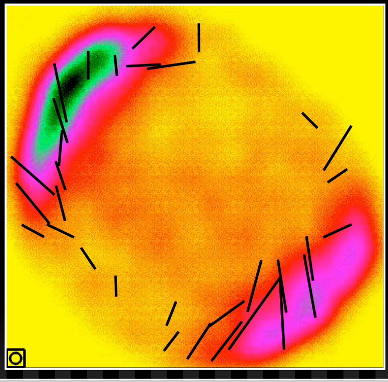


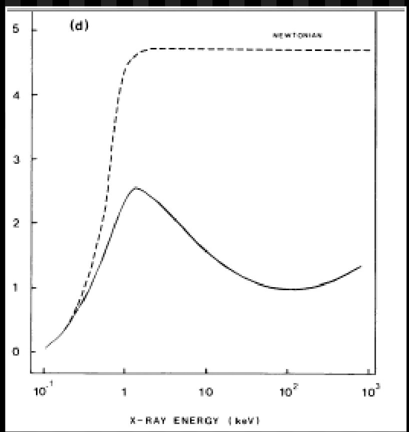
Spectroscopy



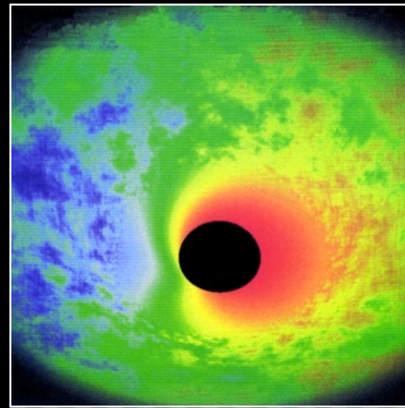
- Remains the only largely unexploited tool
  - Instruments have not been sensitive enough warrant investment
  - Two unambiguous measurements of one source (Crab nebula) at 2.6 and 5.2 keV
  - Best chance for pathfinder (SXRP on Spectrum-X Γ mission ~1993) never flew
- Interest and development efforts have exploded in the last 10 years
  - As other observational techniques have matured, need for polarimetry has become more apparent
  - Controversial polarization measurements for GRBs and solar flares
  - New techniques are lowering the technical barriers

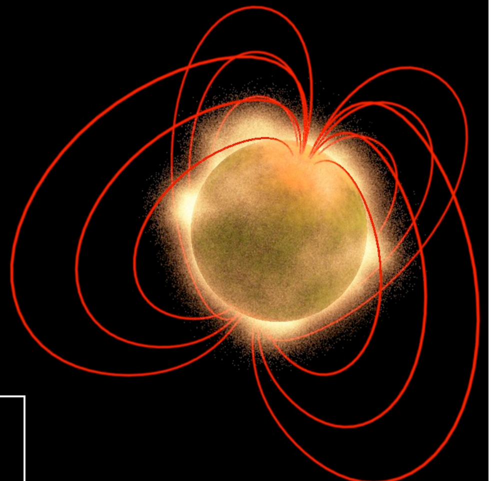
Polarization addresses fundamental physics and astrophysics



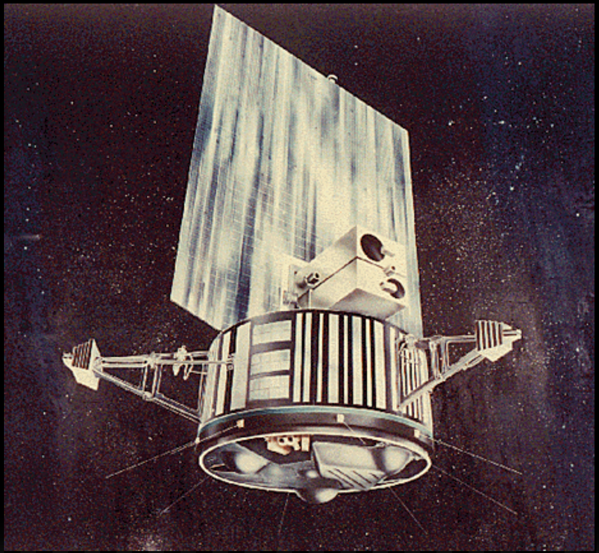


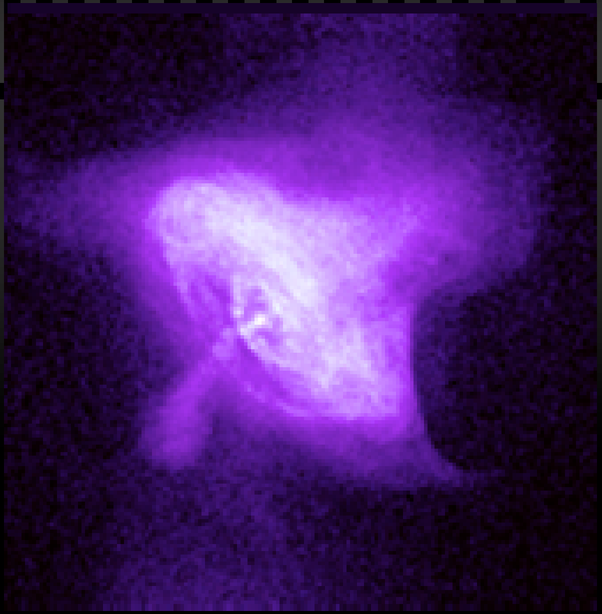
- How important is particle acceleration in supernova remnants?
- How is energy extracted from gas flowing into black holes?
- Does General Relativity predict gravity's effect on polarization ?





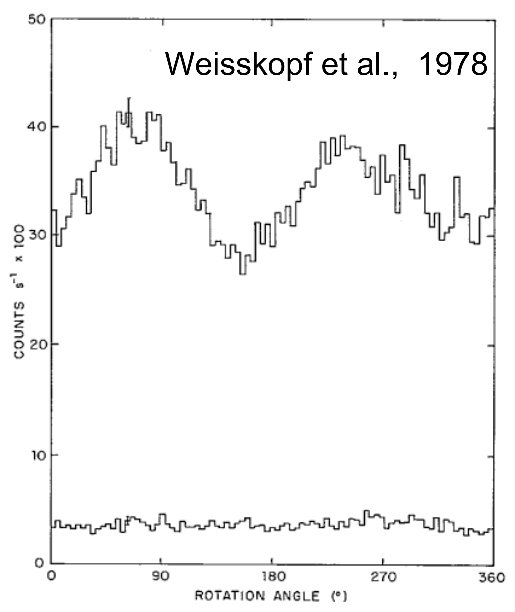
- What is the history of the black hole at the center of the galaxy?
- What happens to gas near accreting neutron stars?
- Do magnetars show polarization of the vacuum?





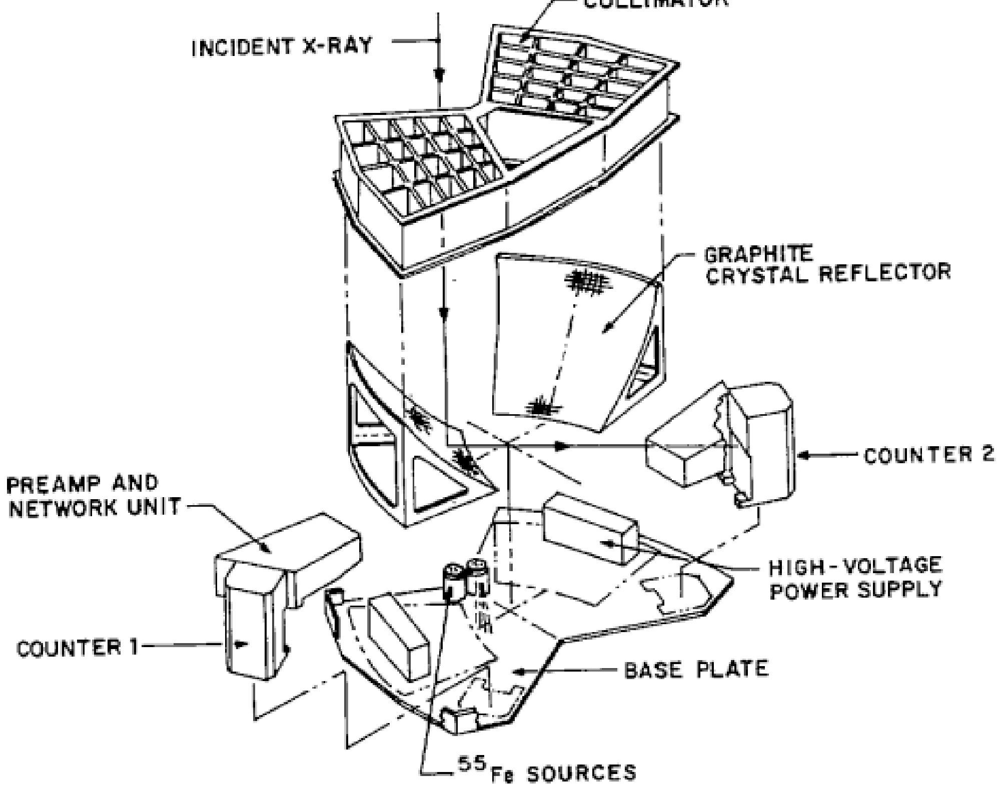
Quest for the holy grail

- X-ray polarimetry will be a valuable diagnostic of high magnetic field geometry and strong gravity…..
- One definitive astrophysical measurement (1978) at two energies:
  - Weisskopf et al.
  - P=19.2% ±1.0%
  - @ 156°

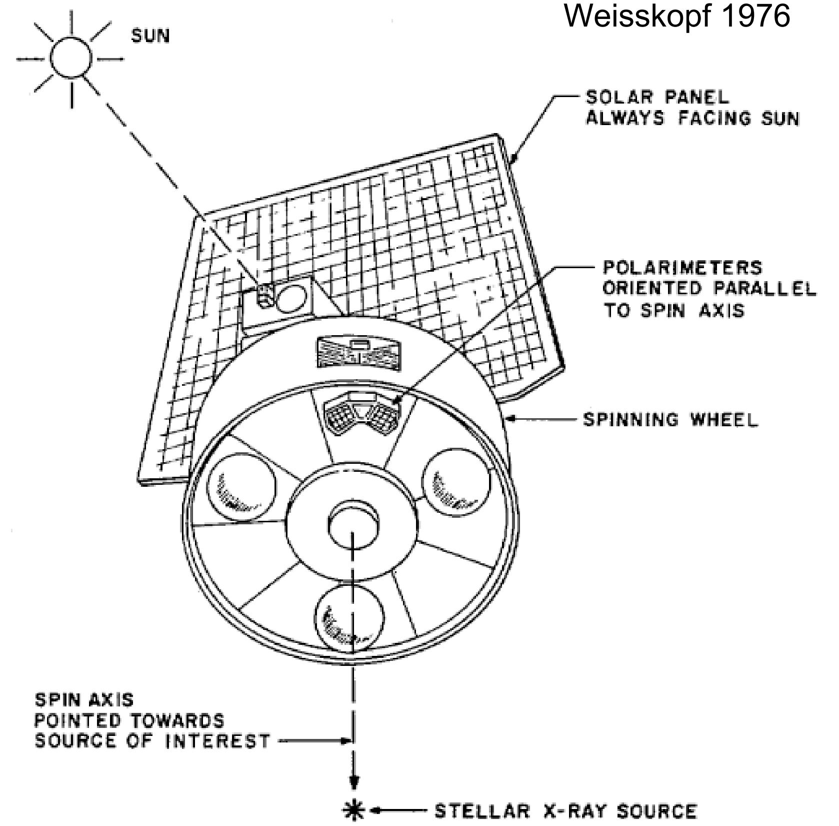


OSO-8 Polarimeter Assemblies

Weisskopf et al, 1976

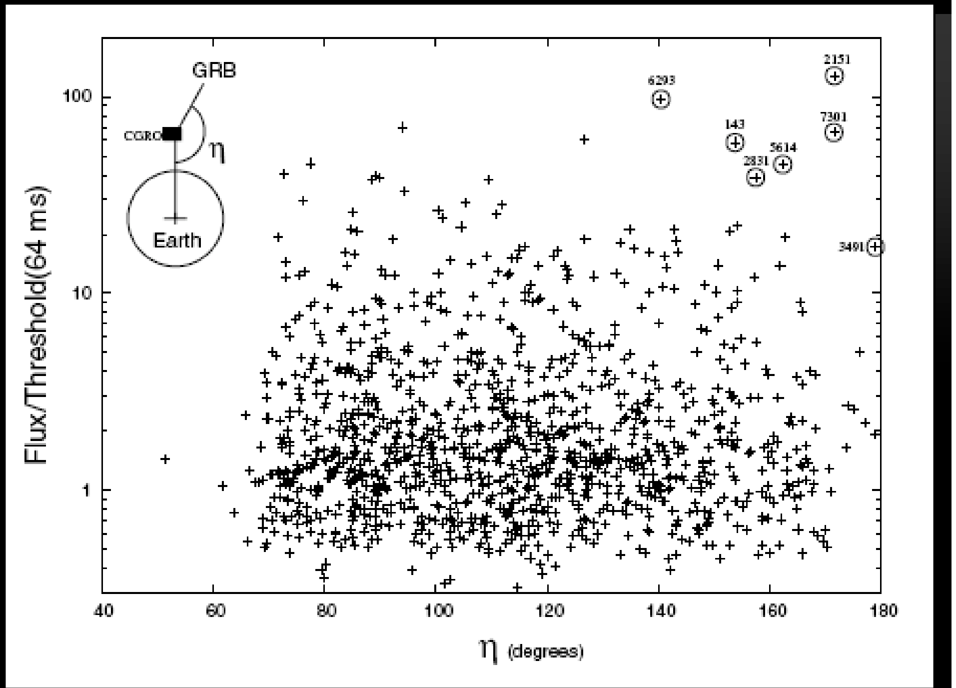


Weisskopf 1976

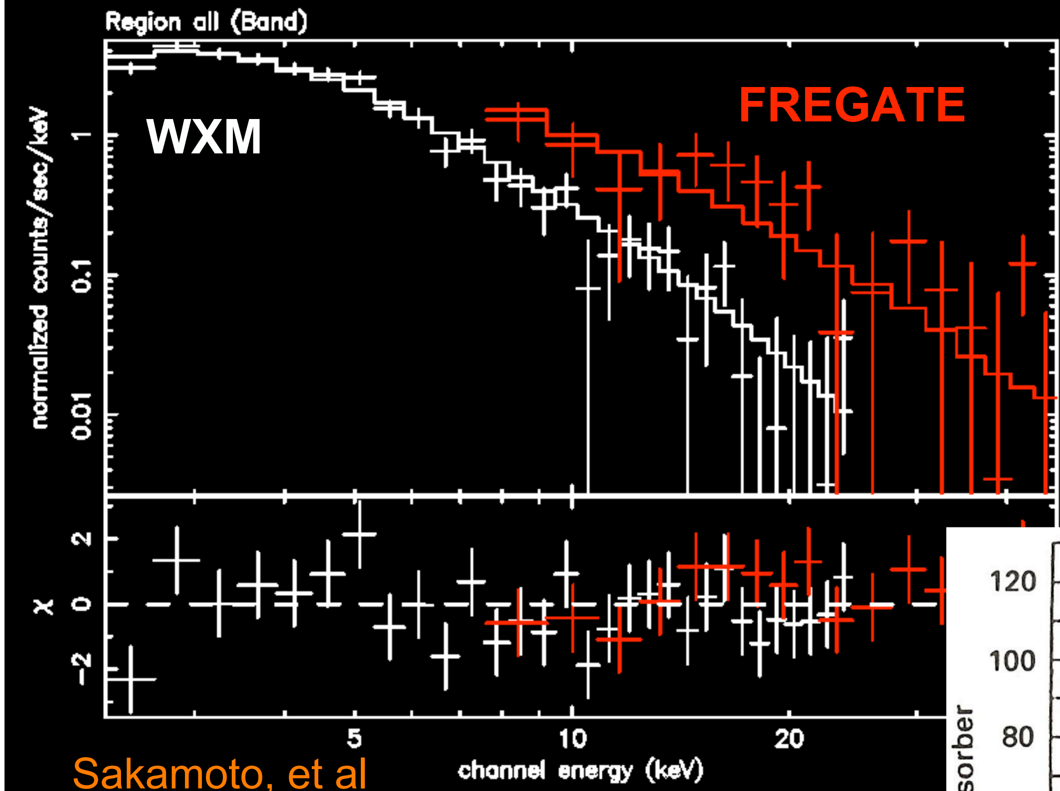


Other Measurements

- Intercosmos (Tindo)
  - Solar Flares
- Rhessi (Coburn & Boggs)
  - GRB 021206
- BATSE Albedo Polarimetry System (Willis)
  - GRB 930131 P>35%
  - GRB 960924 P>50%
- INTEGRAL (2 groups)
  - 2σ result
  - 98±33%

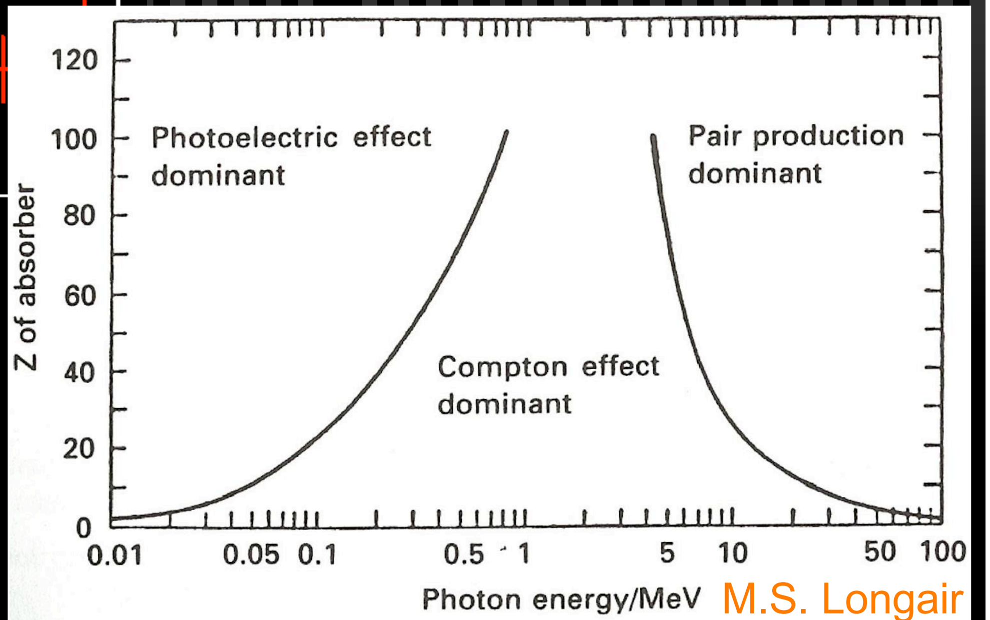


Typical Source emission



Sakamoto, et al

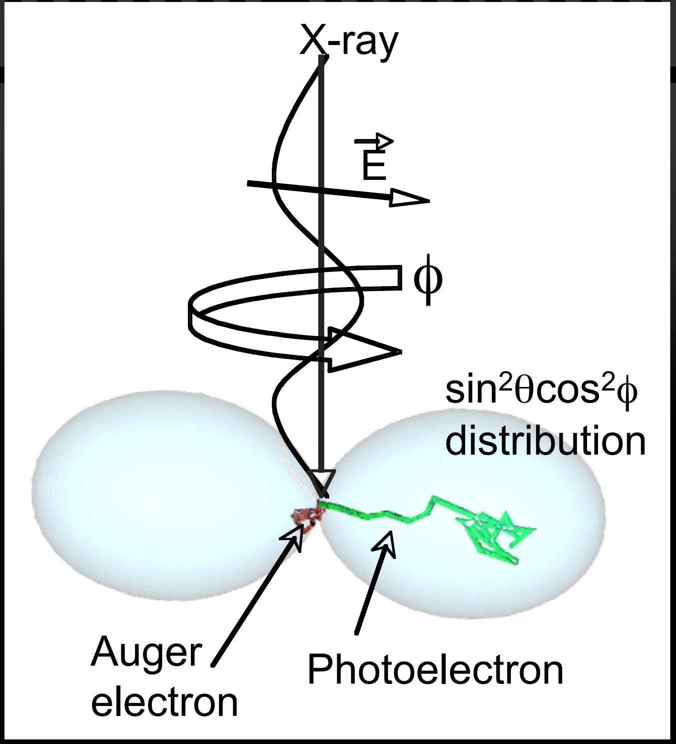
- X-ray is where the photons are
- Photoelectric effect is dominant process

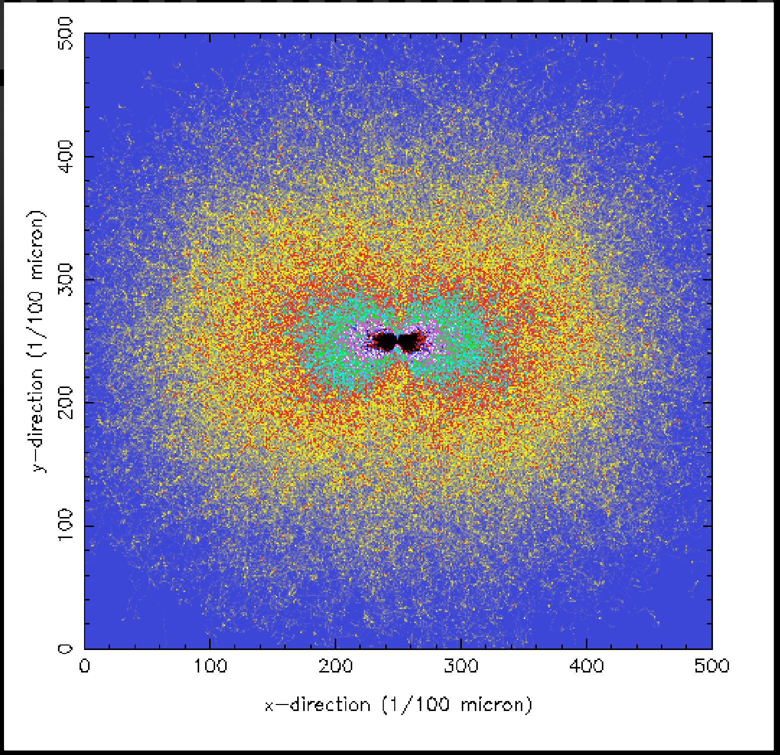


M.S. Longair

The Photoelectric Effect

- The photoelectron is ejected with a $\sin^2\theta\cos^2\phi$ distribution aligned with the E-field of the incident X-ray
- The photoelectron looses its energy with elastic and inelastic collisions creating small charge clouds





Polarimeter Figure of Merit

- Polarimeter Minimum Detectable Polarization
  (apparent polarization arising from statistical fluctuations in unpolarized data):

$$MDP = \frac{1}{\mu\varepsilon}\frac{n_\sigma}{S}\left(\frac{2(\varepsilon S + B)}{t}\right)^{1/2}$$

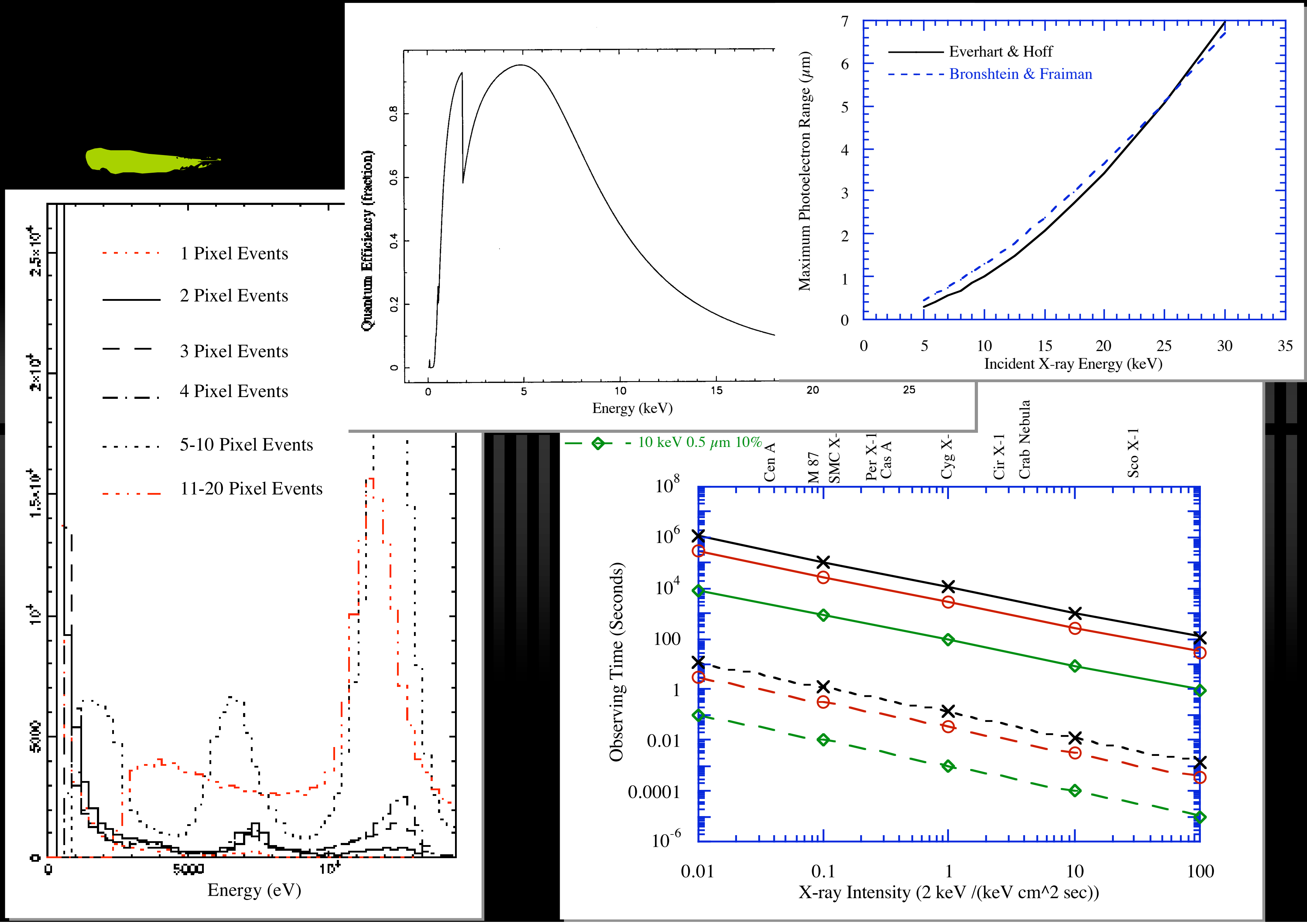
- Polarimeter Figure of Merit (in the signal dominated case):

$$FoM = \mu\sqrt{\varepsilon}$$

but, systematics are important!

Challenge: High modulation AND high QE

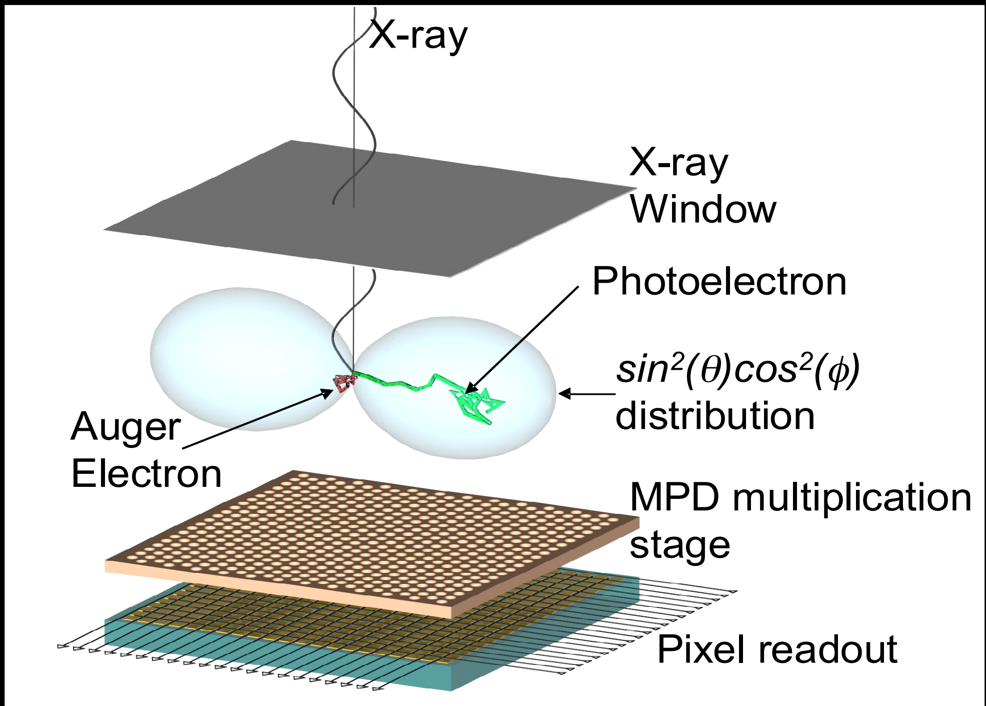
Small Pixel CCD Polarimeters



Polarimeter Requirements

- Challenge: both good modulation and high QE
- Ideal polarimeter is an electron track imager:
  - resolution elements < mean free path
    - Can only begin to approach this in a gas detector

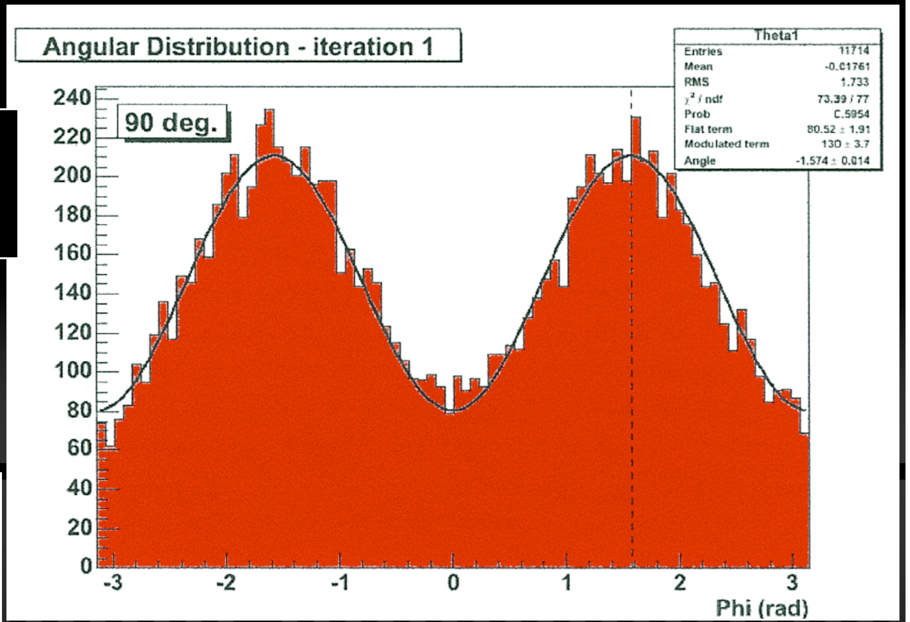
Micropattern Gas Polarimeter



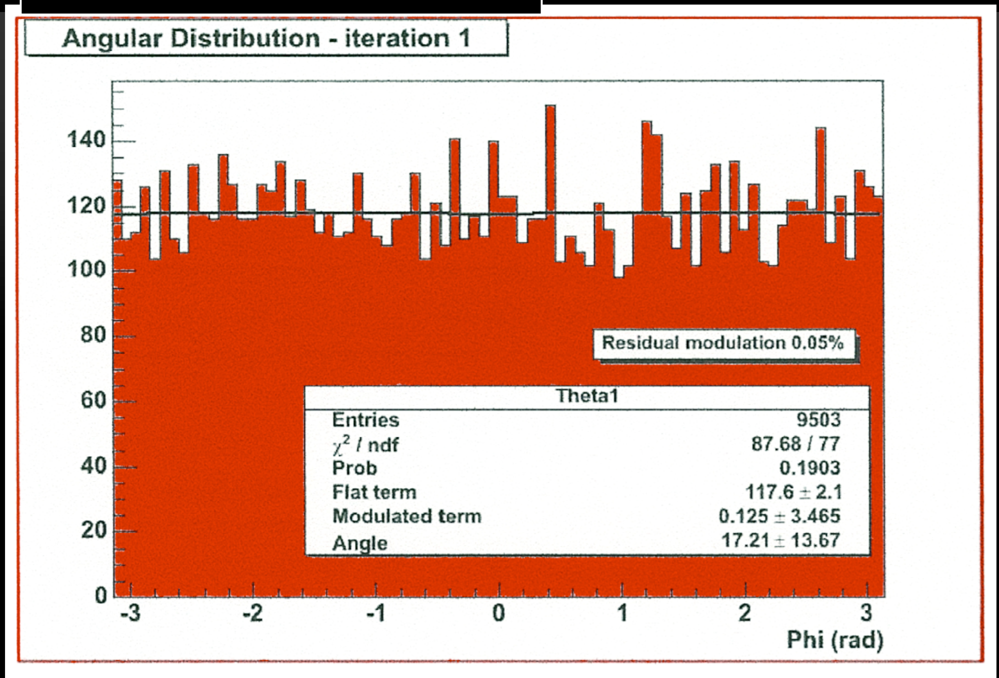
- X-ray interacts in the gas
- K-shell photoelectron ejected
- Photoelectron creates electron cloud
- Electron cloud drifts to cathode
- Electron multiplication occurs between cathode and anode
- Charge collected at the pixel readout

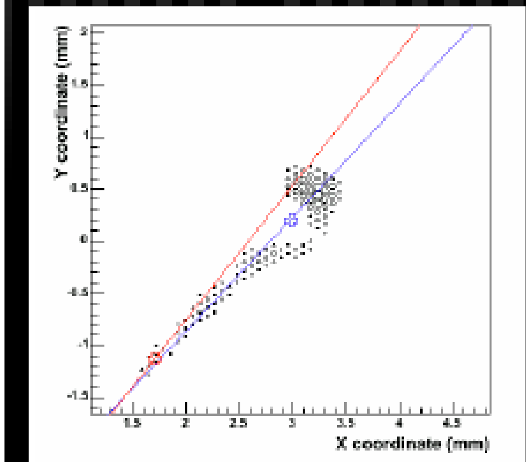
Gas Micropattern Polarimeter

Polarized 5.41 keV
μ=51.1+/-0.9%



Unpolarized 5.9 keV
μ=0.05+/-1.47%

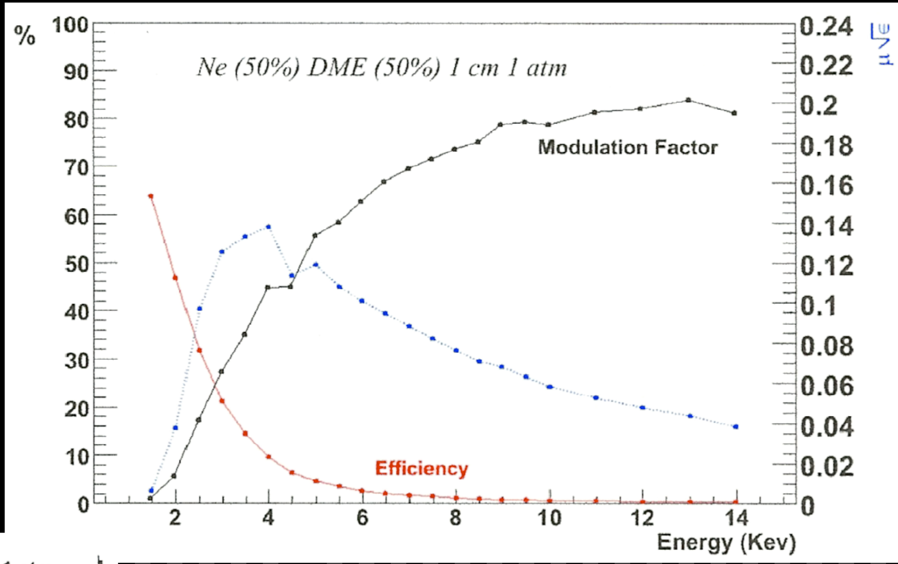


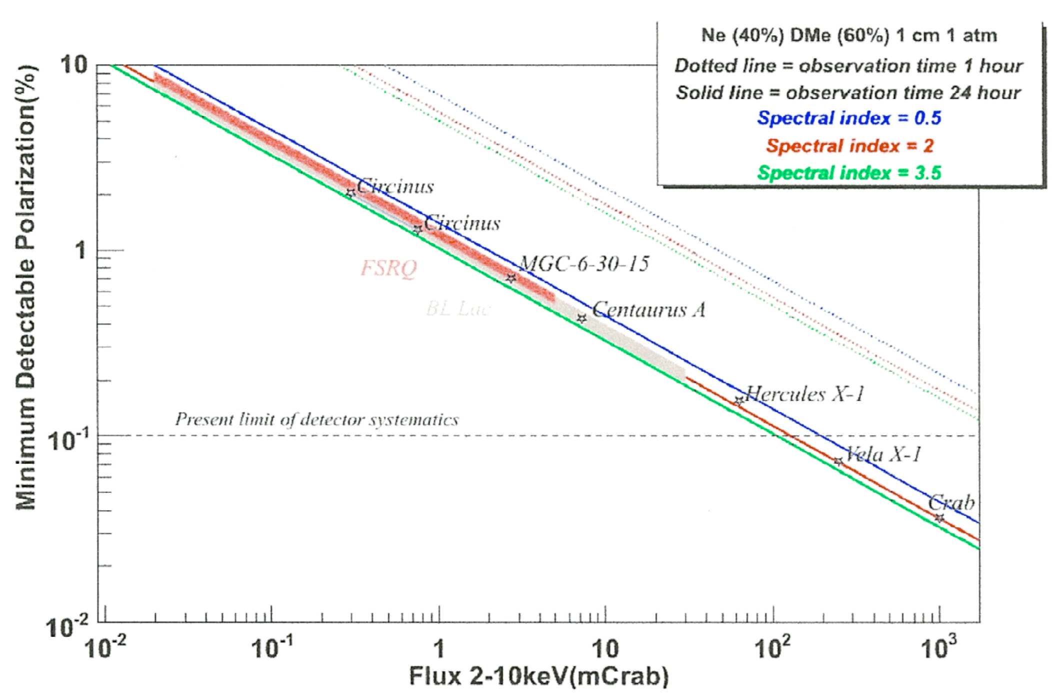


Bellazzini,SPIE, 2006

Gas Micropattern Polarimeter

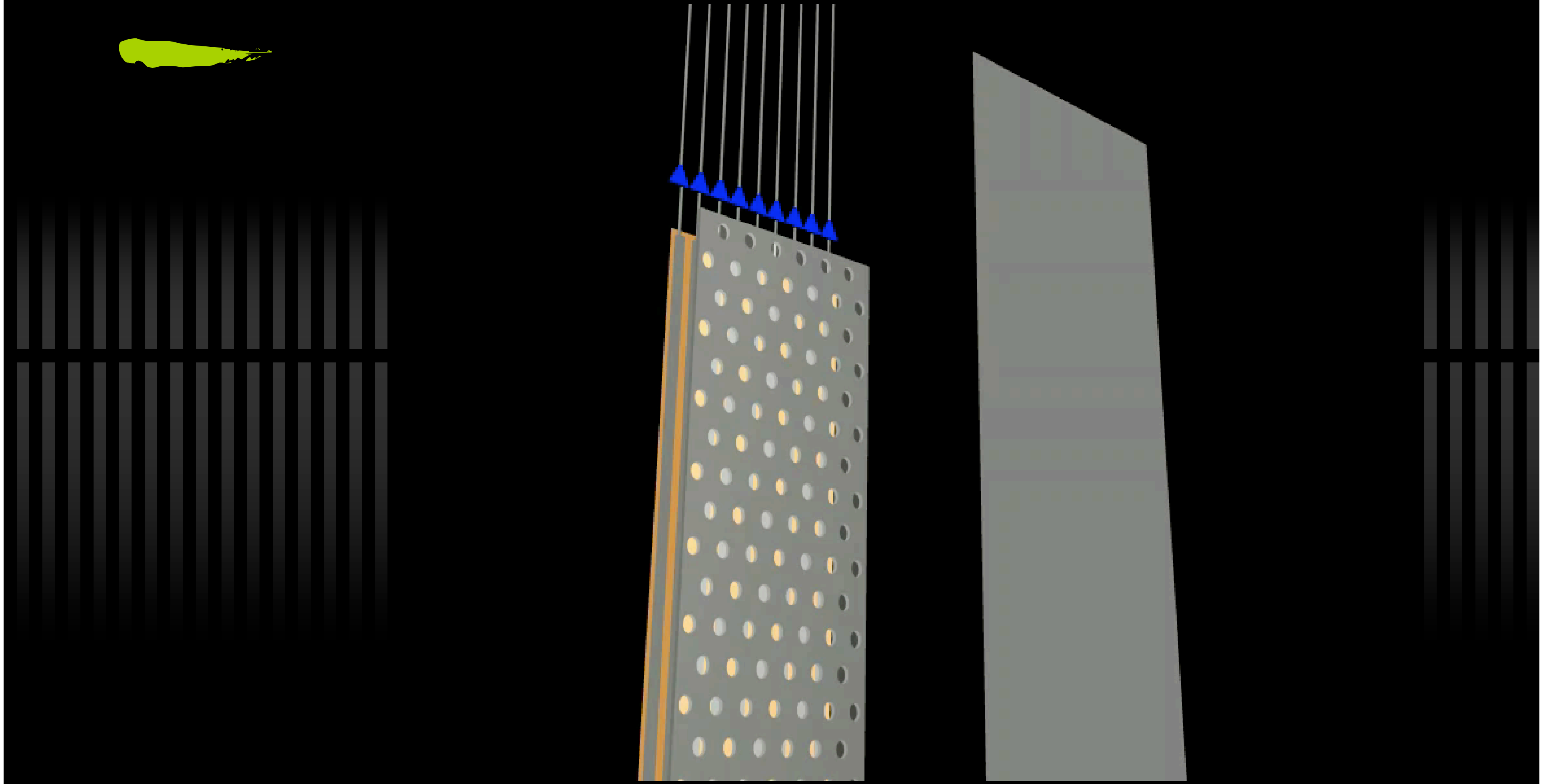
- High Modulation
- Imaging
- Limited QE: Requires Large Optics



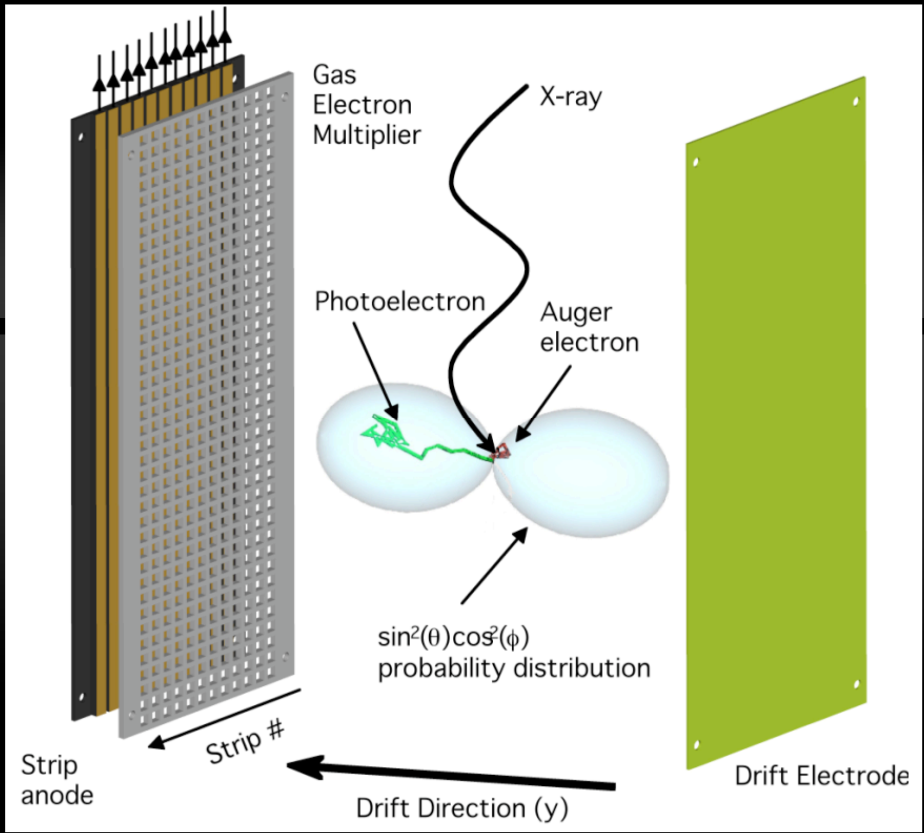


Bellazzini,SPIE, 2006

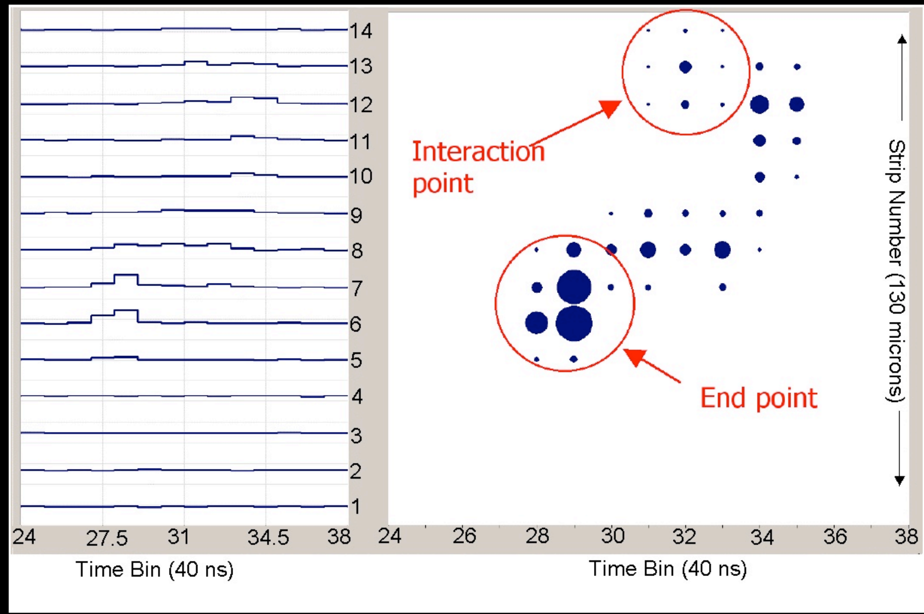
A Time-Projection Chamber (TPC) X-ray polarimeter

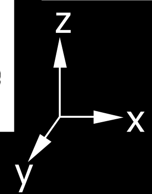


Time-Projection Chamber Polarimeter



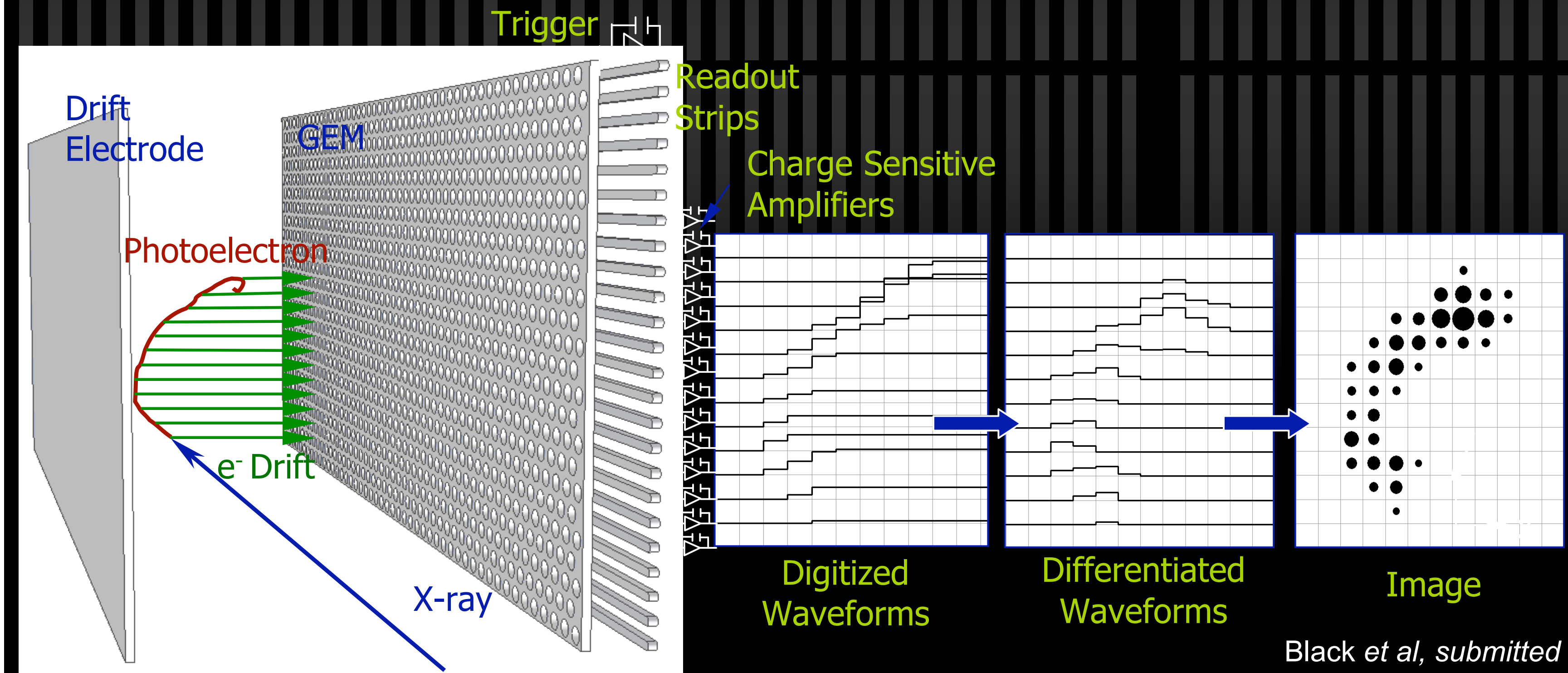
Charge pulses
arriving at the strips





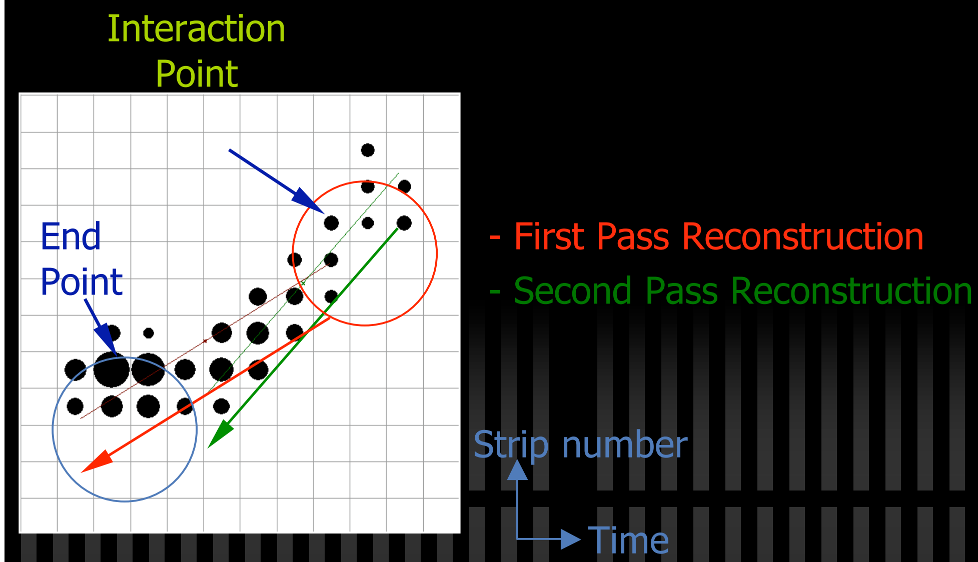
The TPC Polarimeter

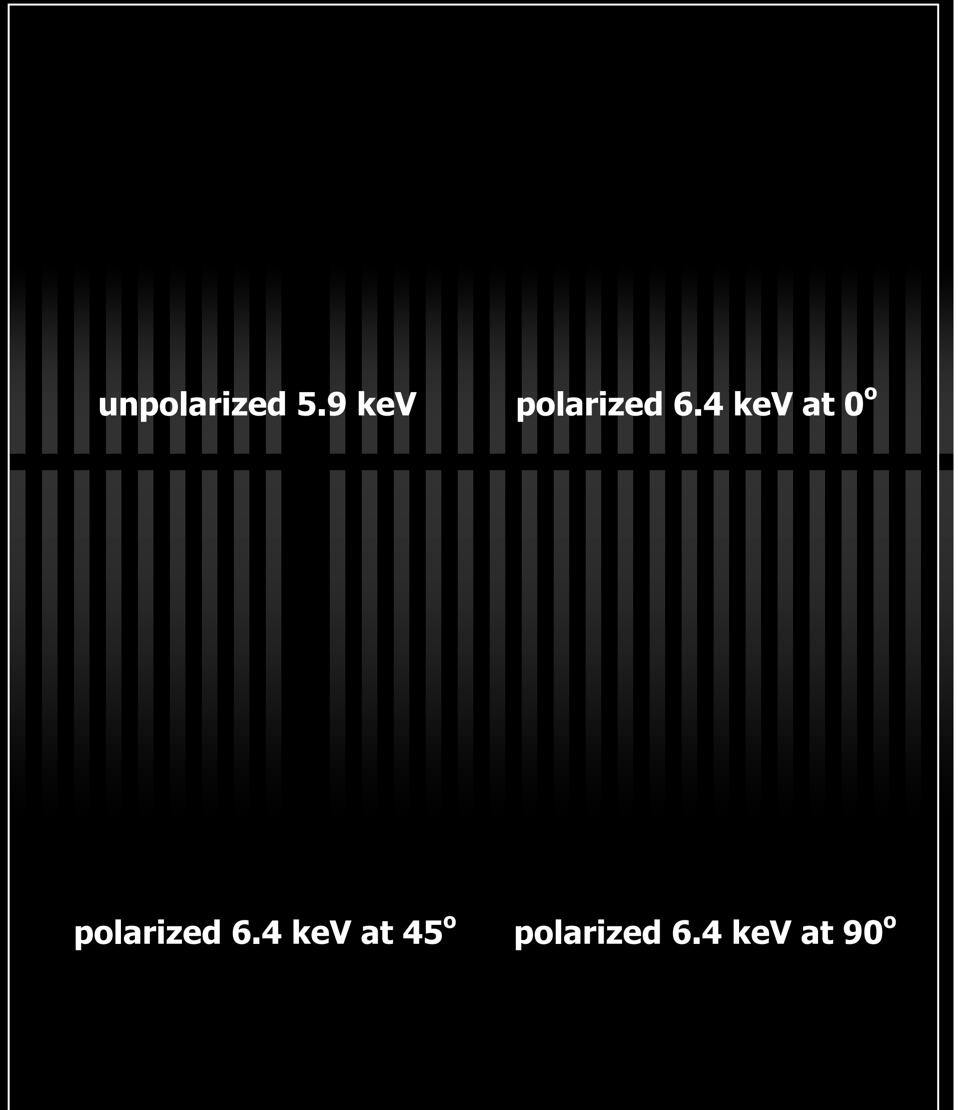
- GEM with strip readout
  - Track images formed by time-projection by binning arrival time of charge
- Resolution is (largely) independent of the active depth



Black *et al, submitted to NIM A*

TPC Polarimeter





Polarization Phase	Measured Parameters		
	Modulation (%)	Phase (degrees)	χ_ν^2
unpolarized	0.49 ± 0.54	44.6 ± 28.7	1.2
0°	45.0 ± 1.1	0.3 ± 0.6	1.1
45°	45.3 ± 1.1	45.2 ± 0.6	1.0
90°	44.7 ± 1.1	-89.9 ± 0.6	1.4

- Uniform response
- Modulation 45%
- Unit QE possible

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TPC Polarimeter Features

Pros

1. Potential for 100% quantum efficiency
2. Simplicity of construction
3. Geometry enables multiple instrument concepts

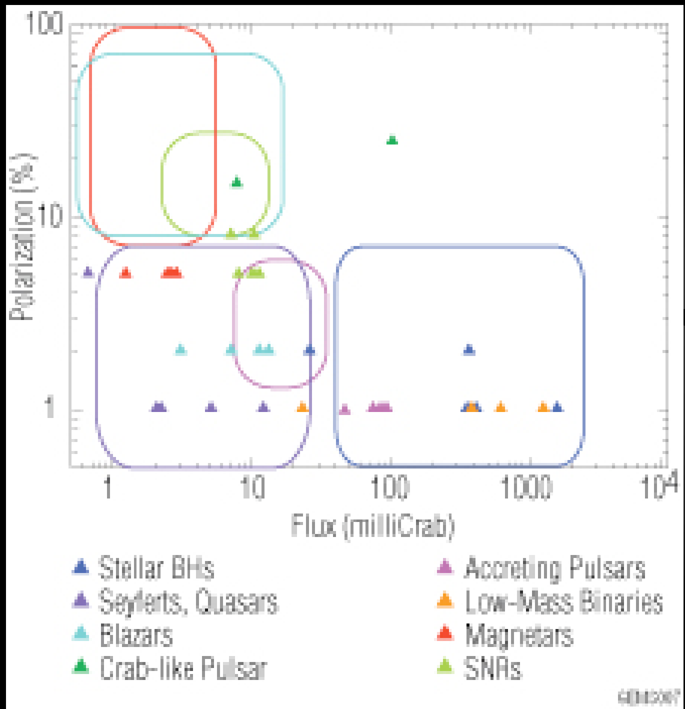
Cons

1. Rotationally asymmetric: requires careful control of systematic errors
2. Not focal plane imaging

Gravity and Extreme Magnetism SMEX

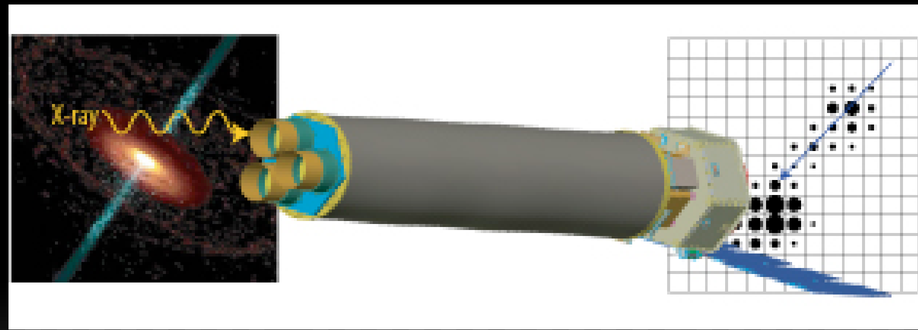
- an X-ray Polarization mission

Currently in Phase A study
Could launch 2012-2014
Huge sensitivity increase



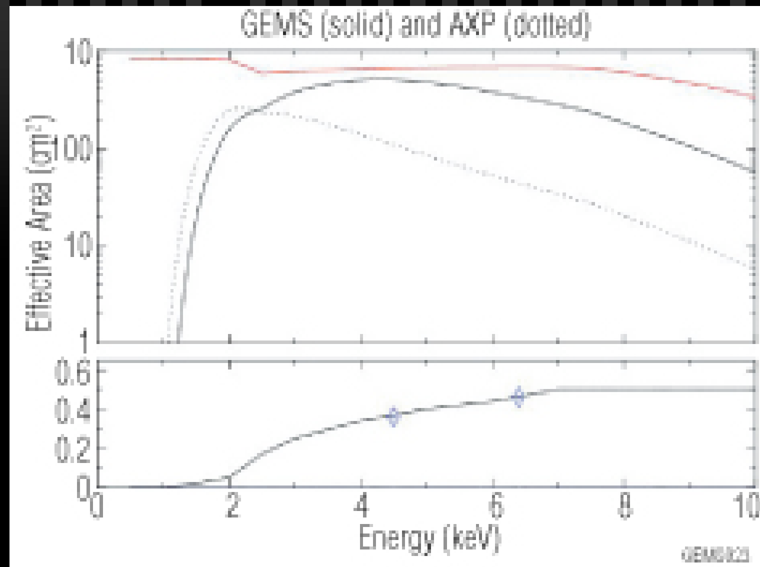
Minimum Mission

35 targets over 9 months
Sample a wide range of source classes

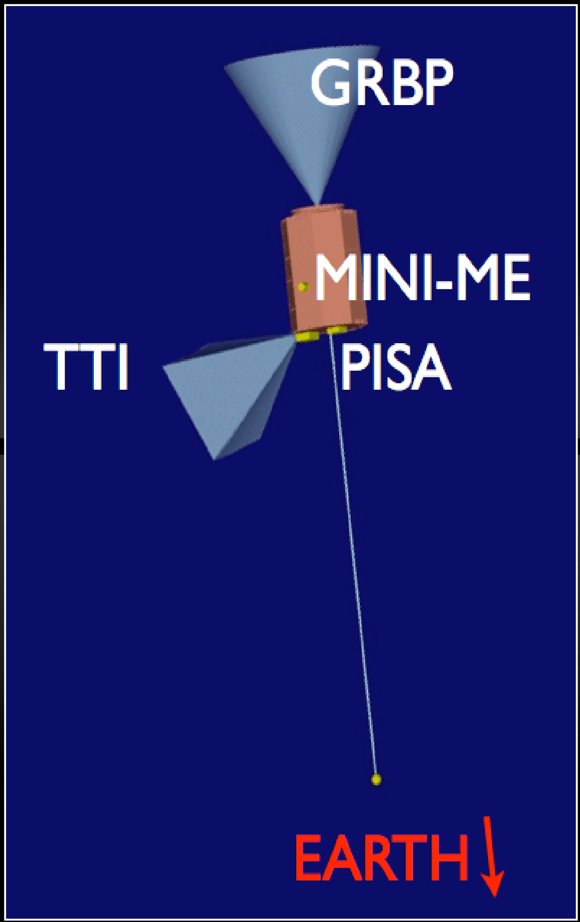


Instrument consists of 3 telescopes

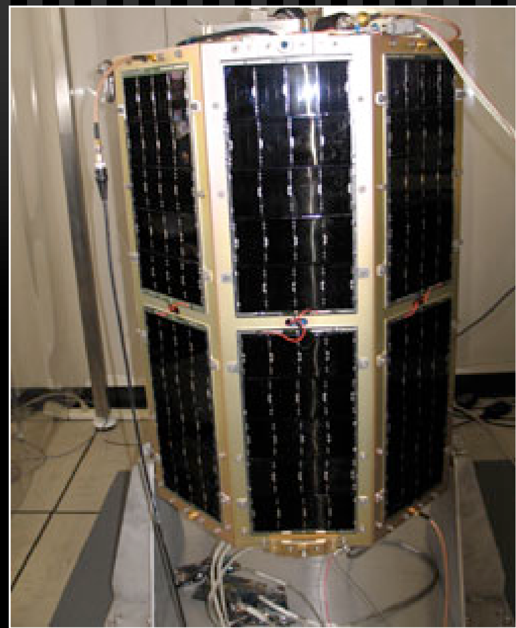
Conical foil mirrors (Suzaku design)
TPC polarimeters



MidSTAR-2

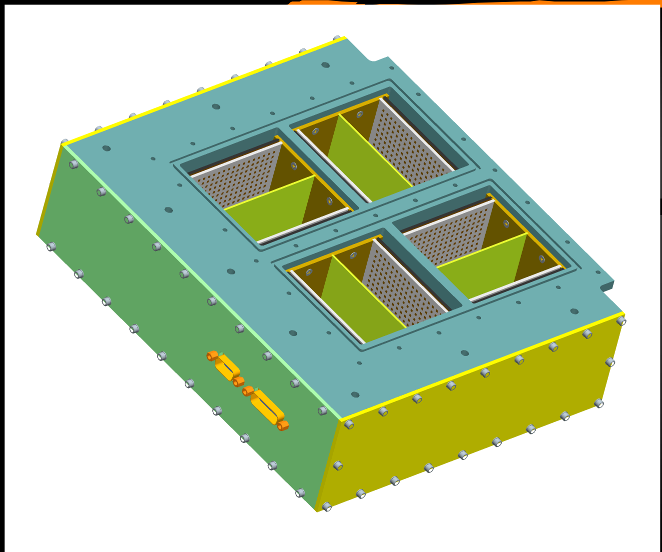


- USNA Project
- High risk Low-cost
- Make a scientific measurement
  - Several GRBs in 2 yr lifetime
- Low cost proof-of-concept
- Launch ~2011

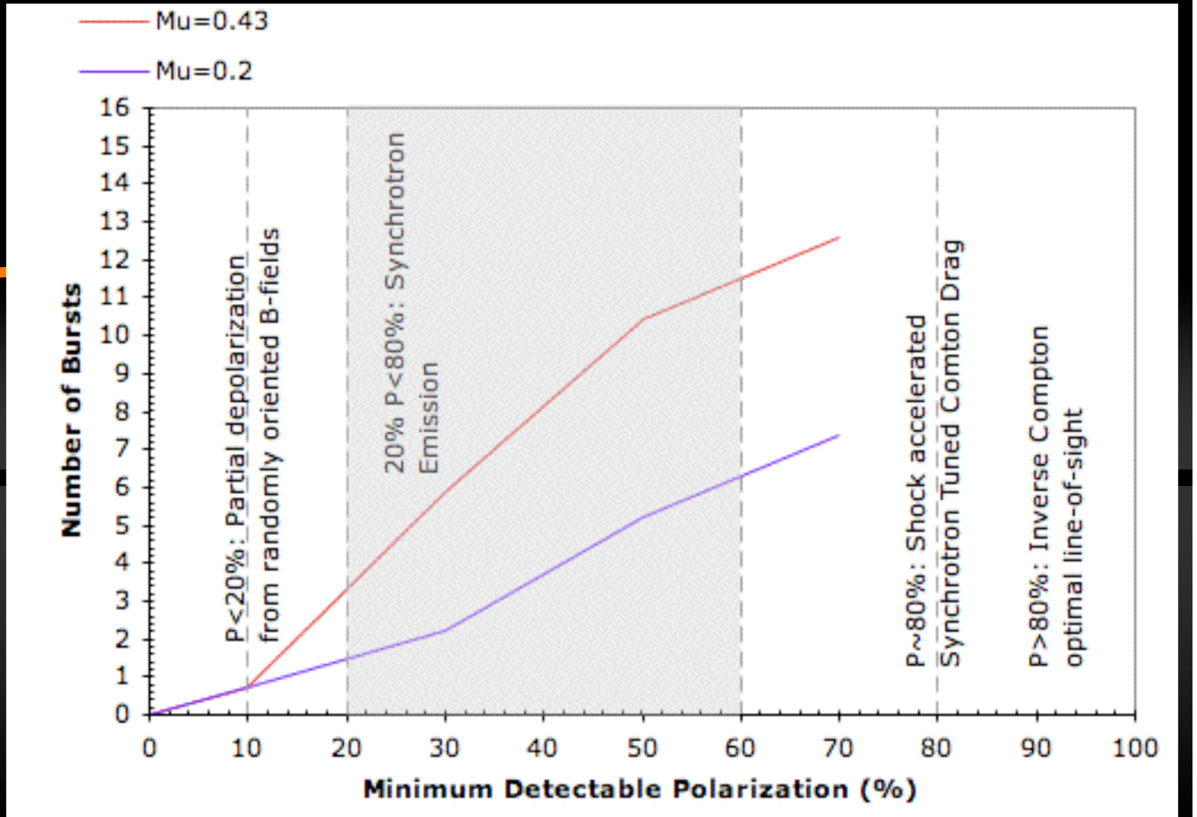


The GRBP: A payload for MidStar 2

Area: 144 cm^2
Depth: 5 cm
FoV: 1 steradian
Gas: $Ne:CO_2:CS_2$
Pressure: 1 atm

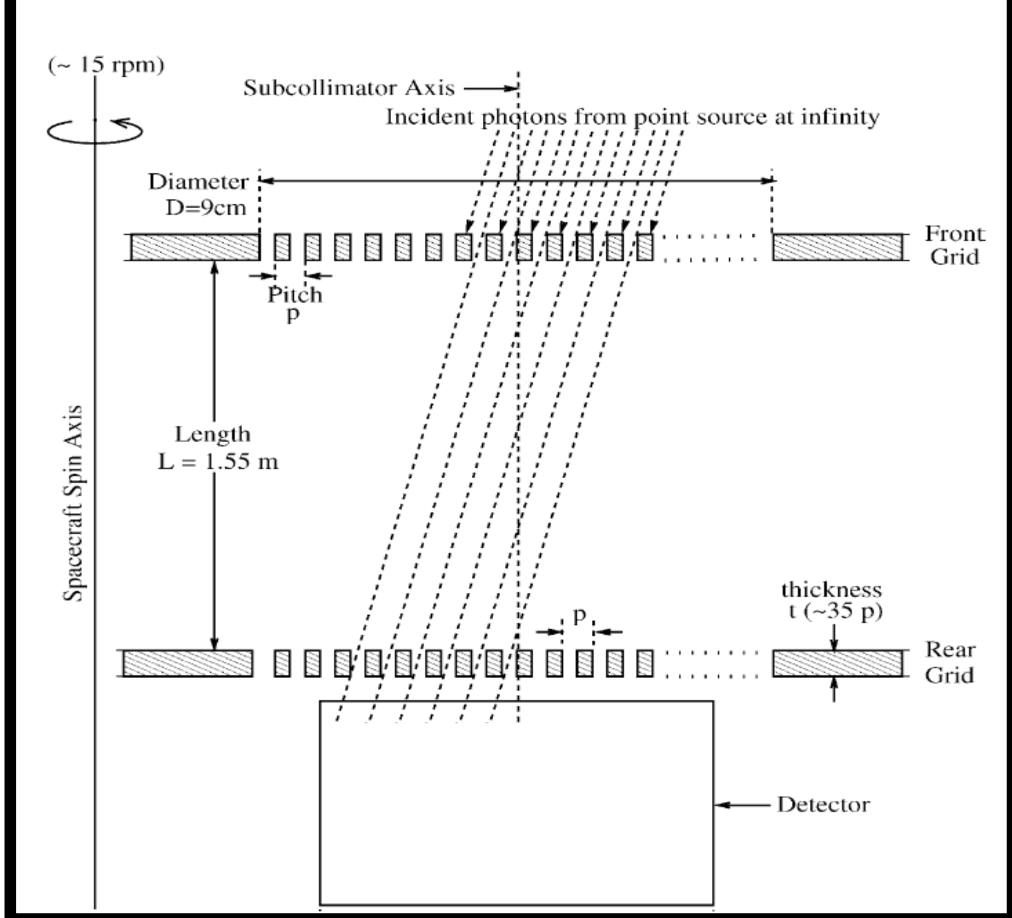


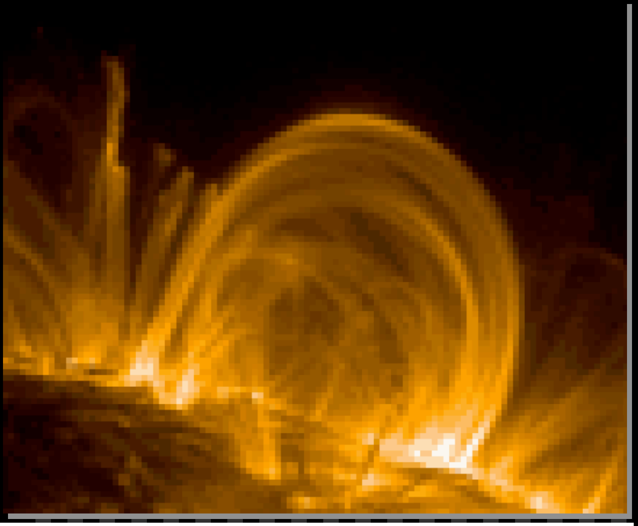
MDP averaged from 2 - 10 keV



Modulation Collimator Imaging Polarimeter for Solar Flares

- Rotation Modulation Collimator provides few arcsecond imaging of extended sources with a non-imaging detector





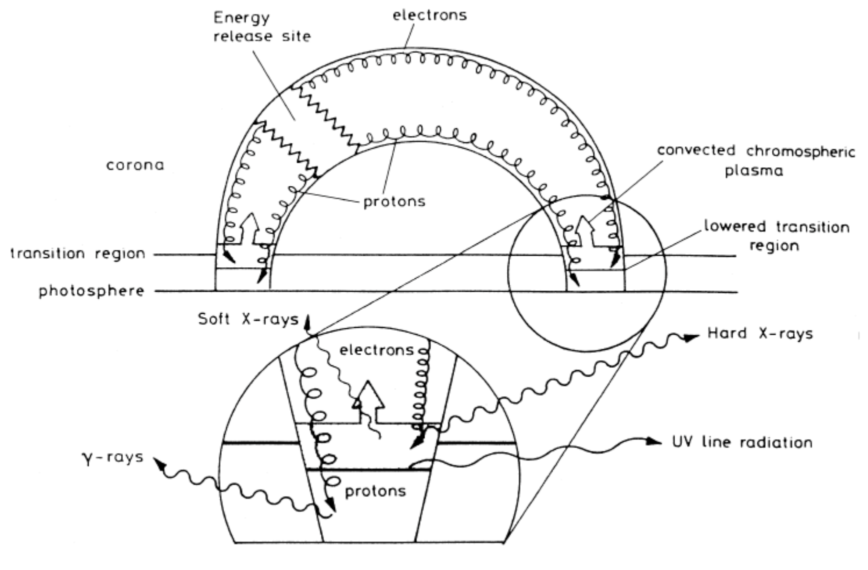


Figure 3.6. A simplified diagram of the magnetic structure and radiation emission sites of a solar flare (Phillips 1992).