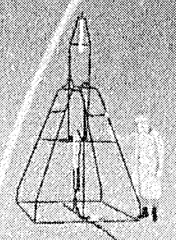


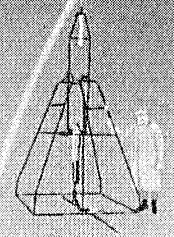
A Burst Chasing X-ray Polarimeter

Joe Hill

Astrophysics Science Division

NASA/Goddard Space Flight Center

Joint Physics/Space Physics Seminar
University of Iowa: 6th March 2007



Overview

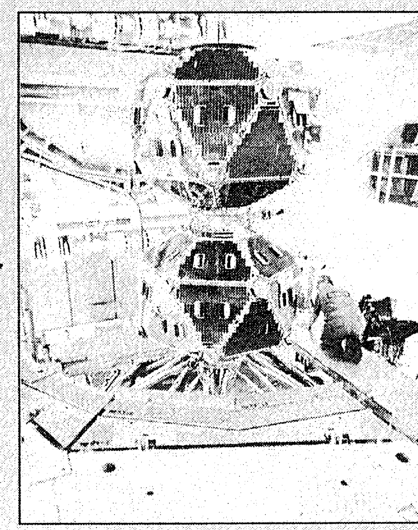
- Science Drivers for GRB Polarimetry
- Small pixel CCD Polarimeters
- Micropattern Gas Polarimeters
- Time-Projection Photoelectric Polarimeter
- Prototype Results
- Plans for the Future

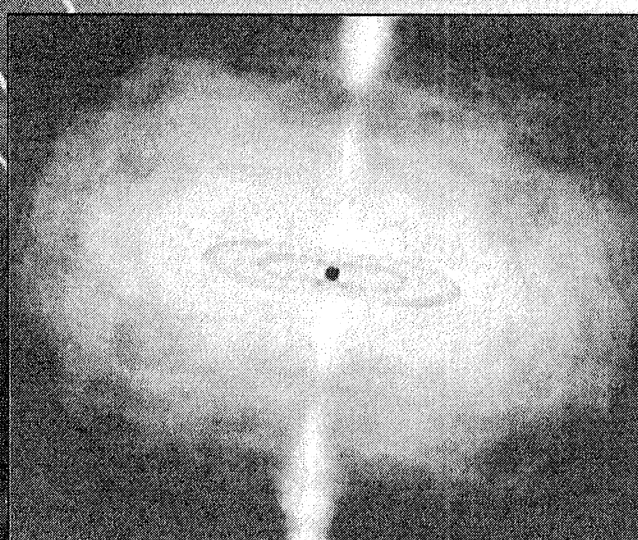
Context

- X-ray polarimetry will be a valuable diagnostic of high magnetic field geometry and strong gravity
- Only one definitive astrophysical measurement (1978)

What are GRBs?

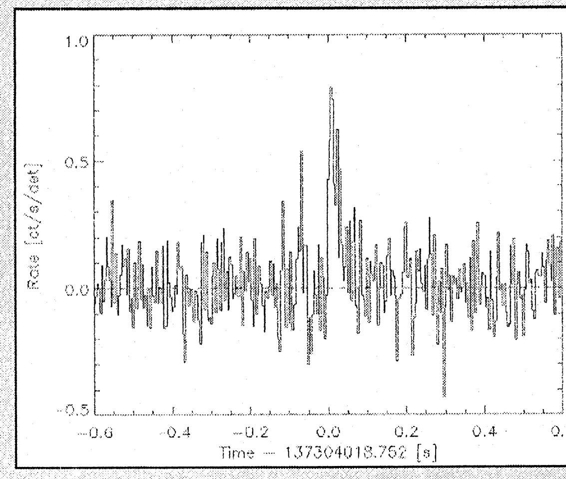
- Discovered in 1967 by the Vela Satellites
  - Data classified until 1973
- Gravitational collapse of a massive star to form a Black-hole- Long bursts
- Merger of two compact objects (BH-NS or NS-NS) - Short bursts

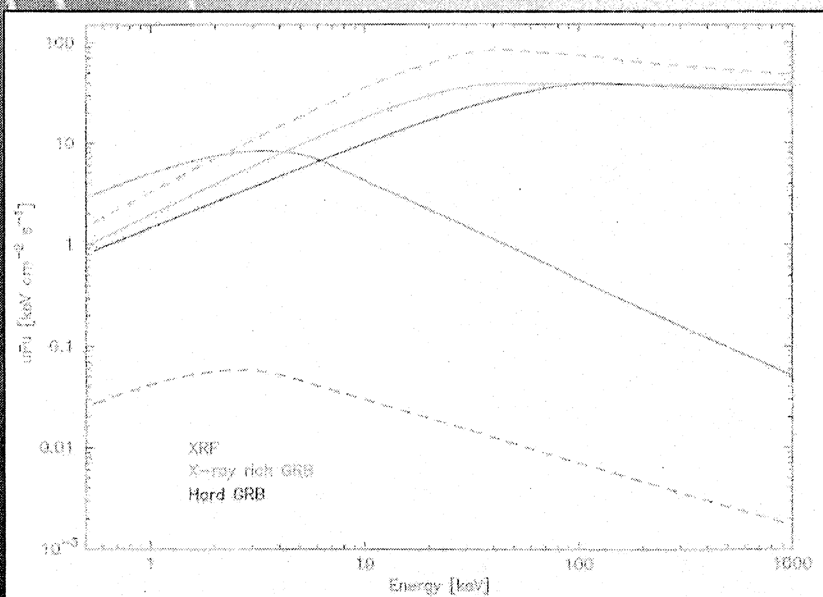


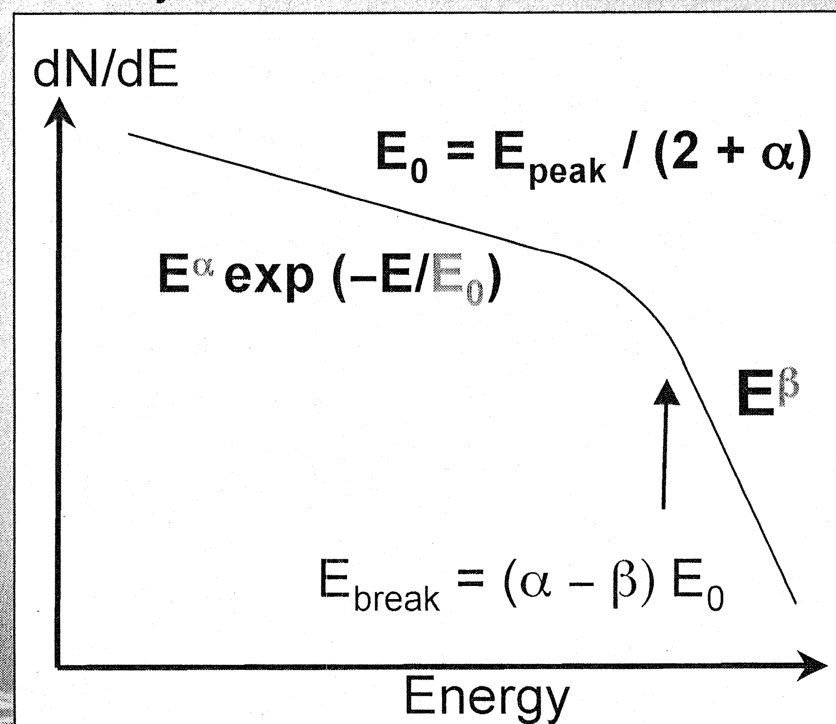


Observed Prompt Properties

- High variability: ~ms
- Prompt Spectrum:
  - Band Function $\alpha \approx -1 \pm 1 \quad \beta \approx 2^{+1}_{-2}$
- Huge release of energy: 10^{51} erg
- Relativistic process to avoid pair-production opacity paradigm
- Achromatic steepening implies GRB jet

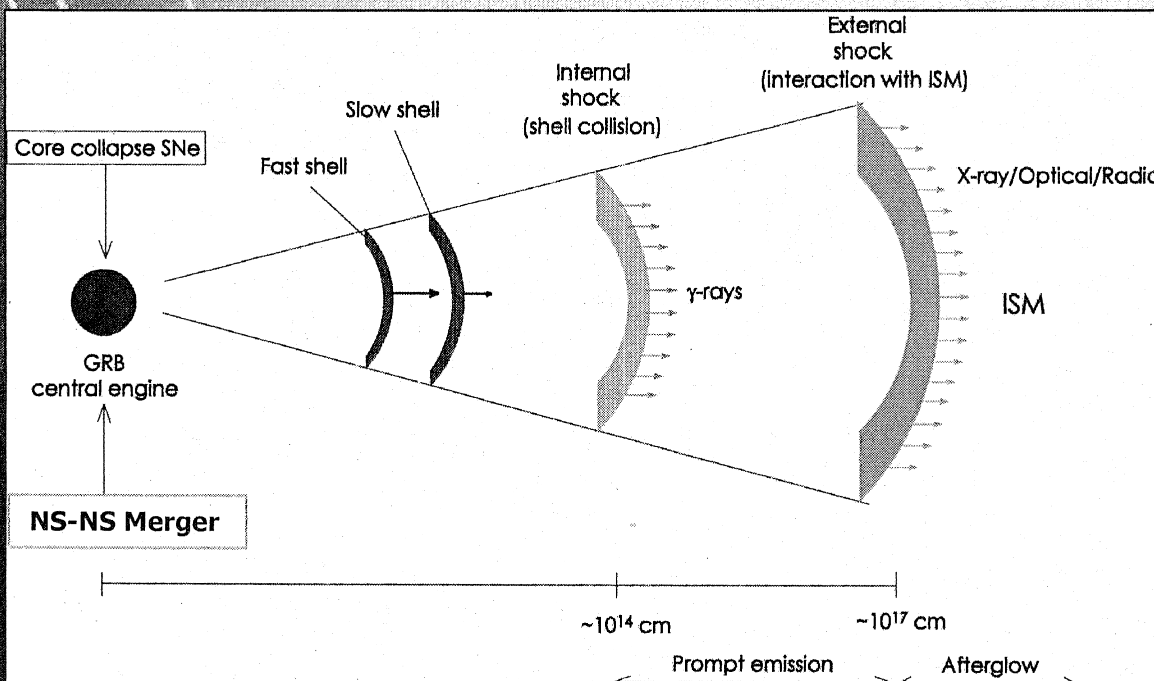


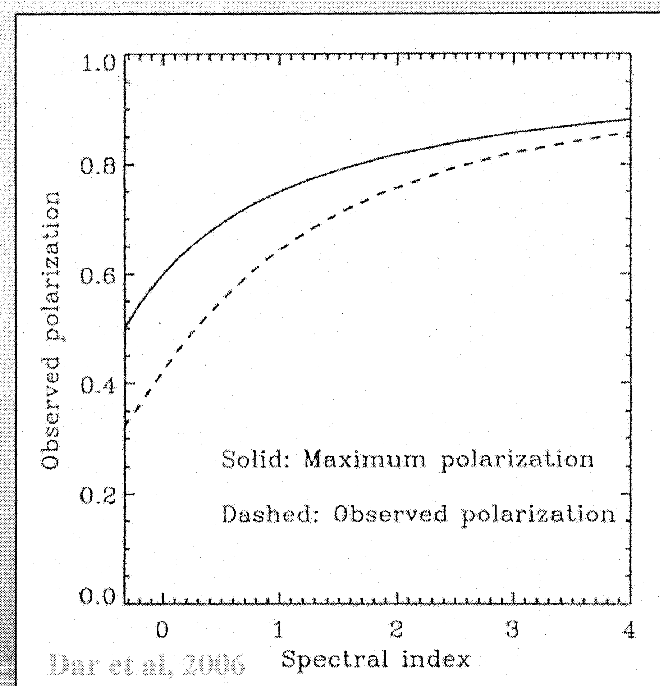




Standard Fireball Model

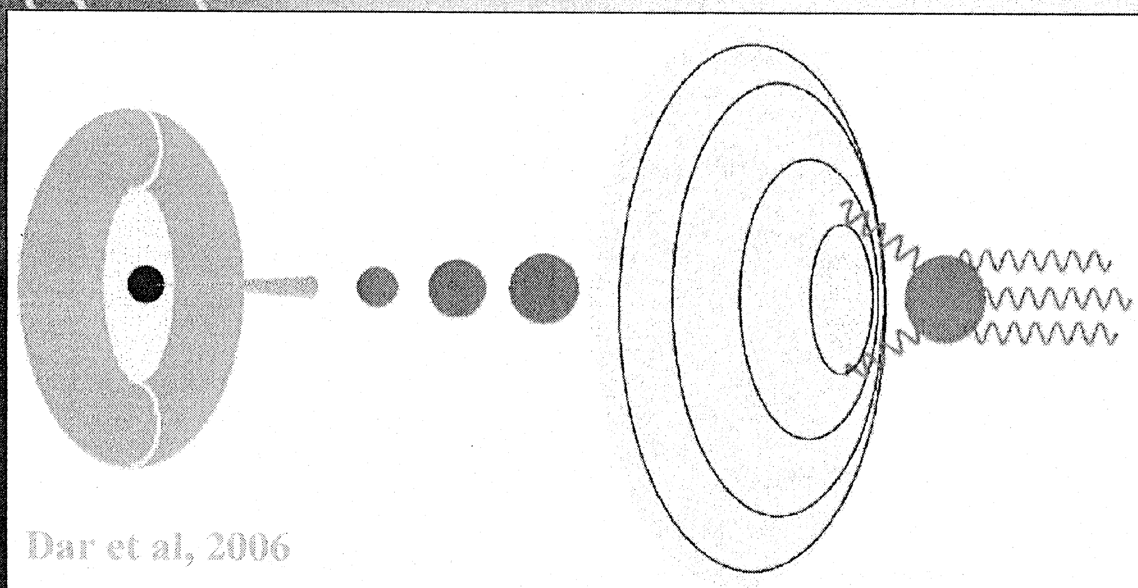
- Explains the afterglow observations well
- Debates for prompt emission on-going
  - Internal shock model solves the rapid variability problem
  - Energy has to be extracted from KE of shells
    - Low efficiency
    - Requires additional mechanisms

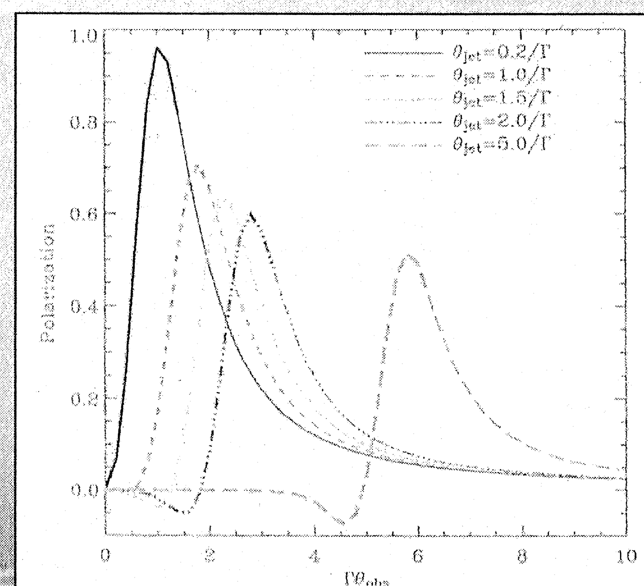




Cannon-ball model

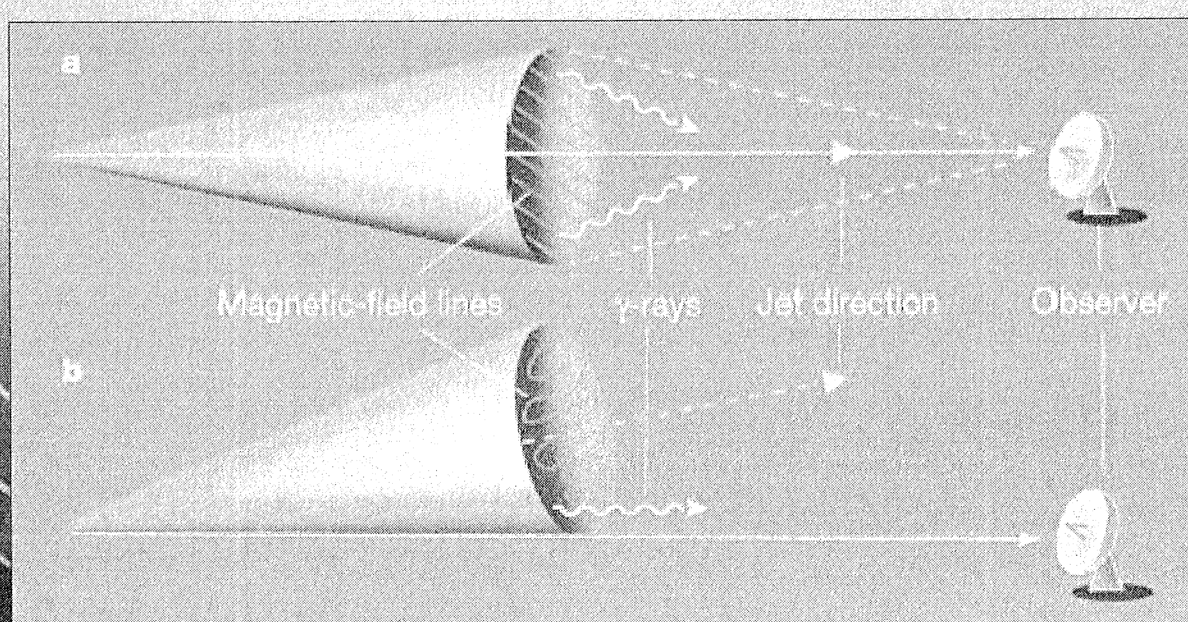
- Cannon balls ejected from central engine
- Inverse Compton scattering of ambient light
- Unclear how the cannon balls would survive acc^n over large dynamic range and Lorentz factors





Motivation

- Discriminating between emission models
- Discriminating between central engine models
- Proof of Jet structure
- Proof of technology concept for larger missions



Waxman, Nature, 2003

Gamma-ray Burst Polarization

- The theories on the GRB production mechanism can be constrained by different degrees of linear polarization (P):
  - P>80% IC with optimum view
  - P~80% shock accelerated synchrotron emission or a tuned Compton-drag model
  - 20%<P<60% implies synchrotron emission as the dominant source of radiation or as a result of viewing the burst from just out-side the edge of the jet
  - Low degrees of polarization can be expected flux with a high degree of polarization experiencing partial depolarization, e.g. electrons in a randomly orientated magnetic field

How do we measure it....?

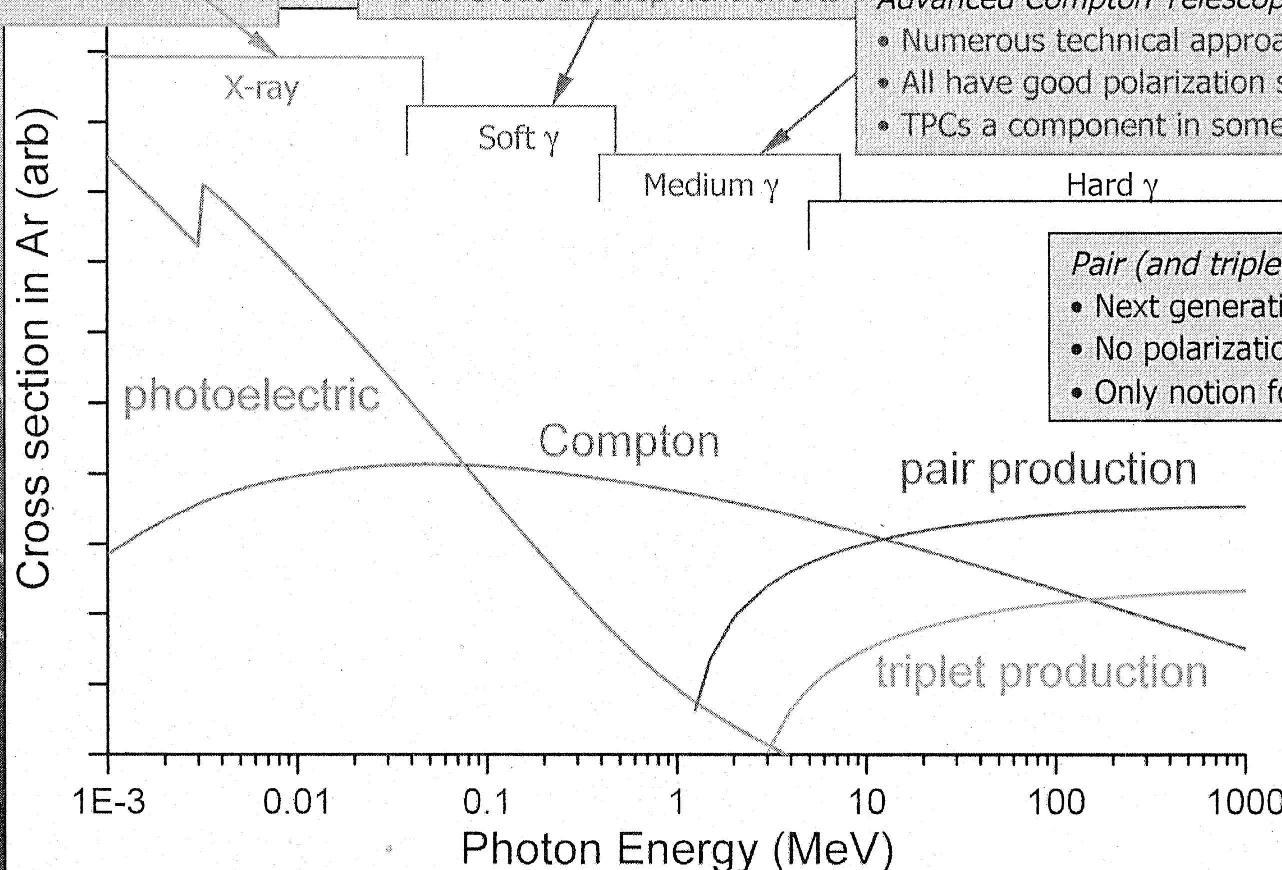
The Experimental Landscape

An Overview of Development Efforts

Dedicated Polarimeters:
- Thompson Scattering
- Bragg Scattering (SXRP)
- Small Pixel CCDs
- Gas Pixel Detectors
- Dichroic Materials
- TPCs

Dedicated Polarimeters:
- Low-Z converter, High-Z absorber (lower E)
- High-Z converter, absorber (higher E)
- Numerous development efforts

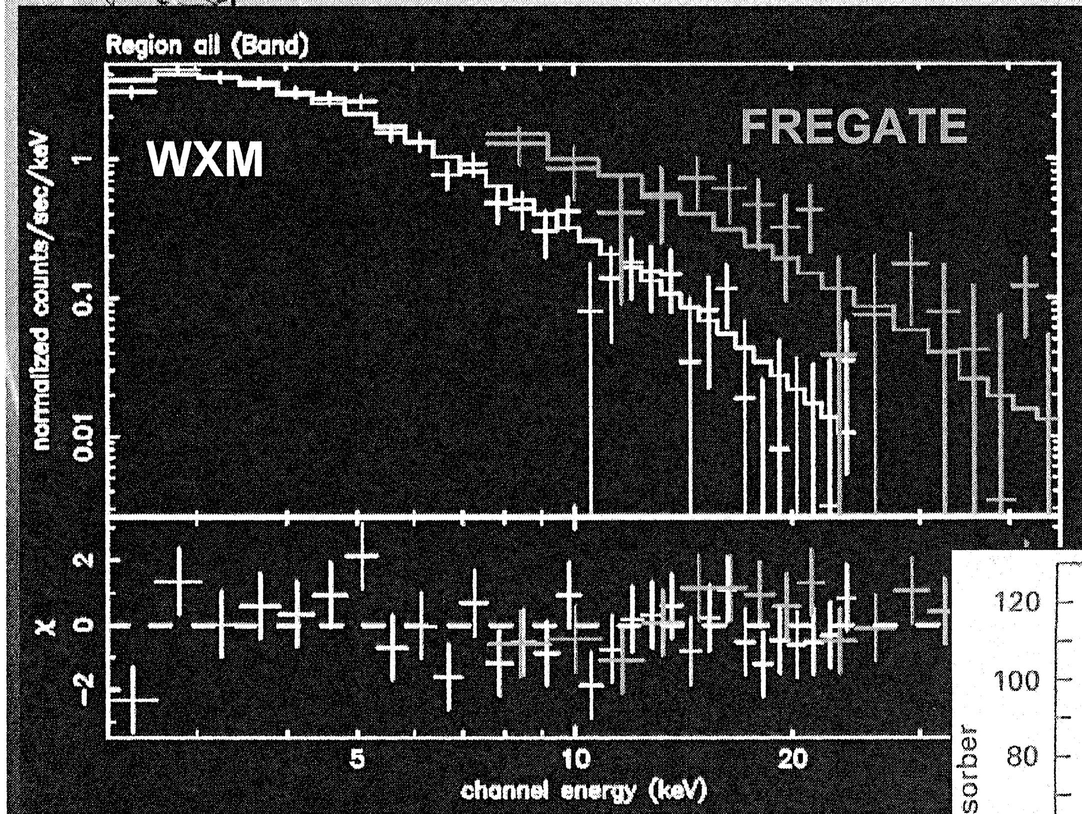
Advanced Compton Telescopes:
- Numerous technical approaches
- All have good polarization sensitivity
- TPCs a component in some



Pair (and triplet) Telescopes:
- Next generation soon to launch
- No polarization sensitivity
- Only notion for polarimetry w/TPCs

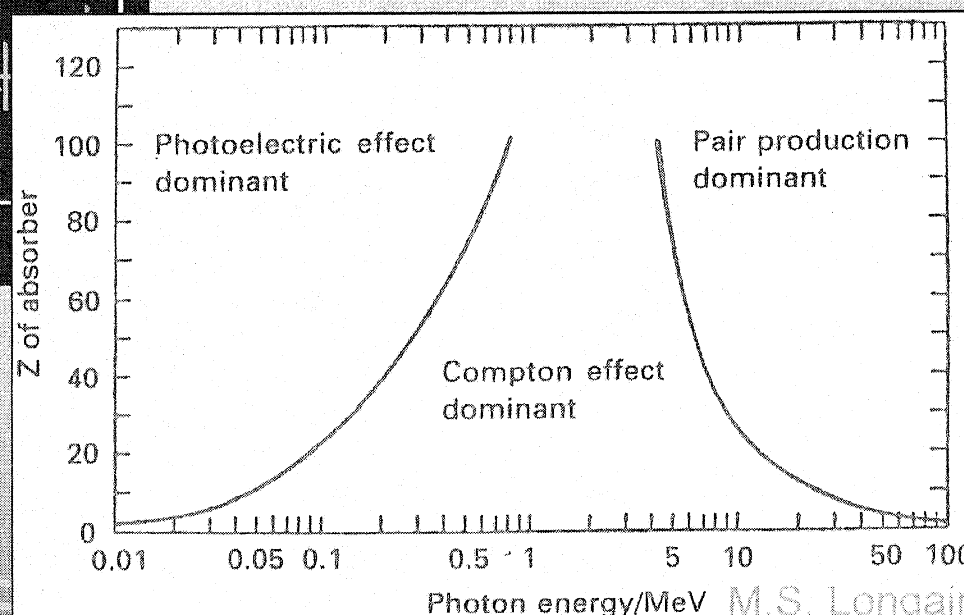
J.K. Black, Journal of Physics: Conference series, to be published

GRB X-ray emission



Sakamoto, et al

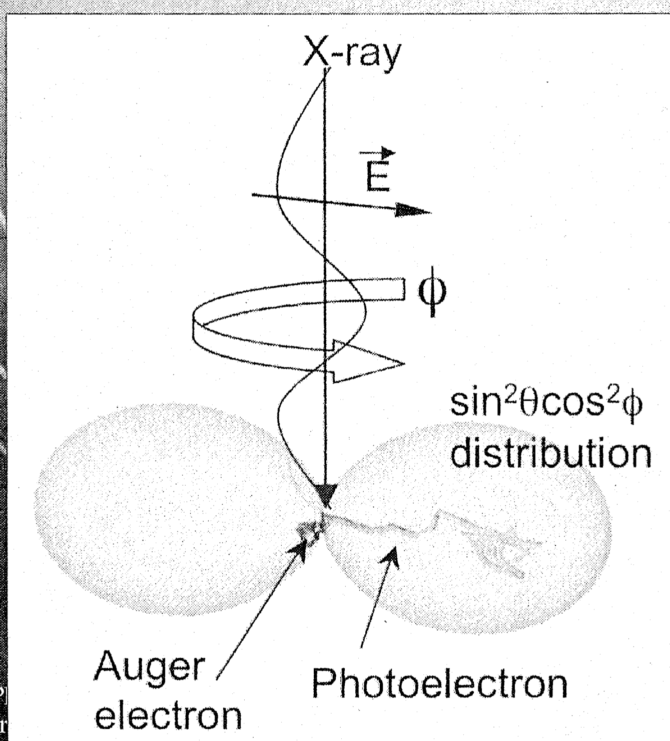
- X-ray is where the photons are
- Photoelectric effect is dominant process

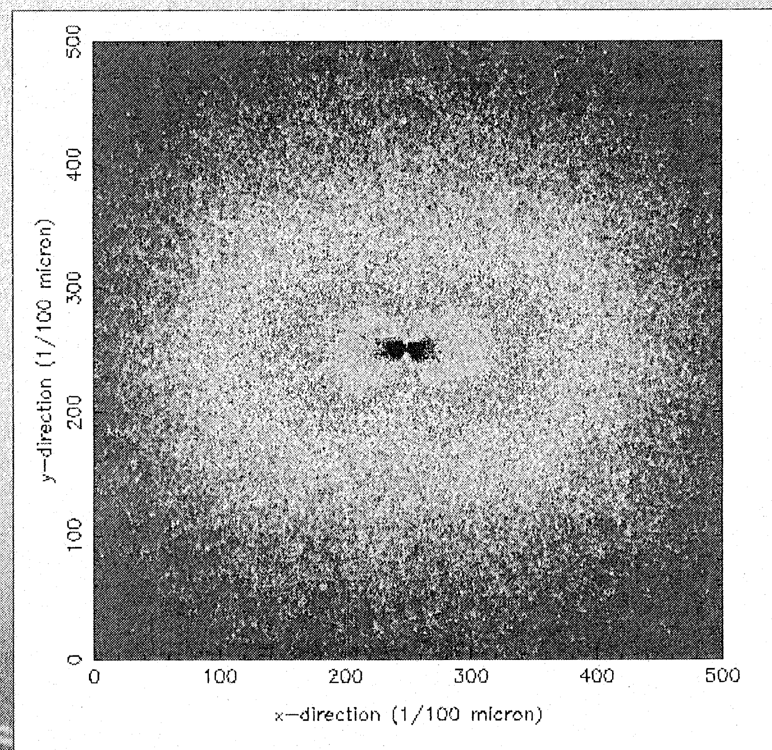


M.S. Longair

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





Photoelectric Polarimetry

- Capitalizes on: correlation between the X-ray electric field vector and the photoelectron emission direction:

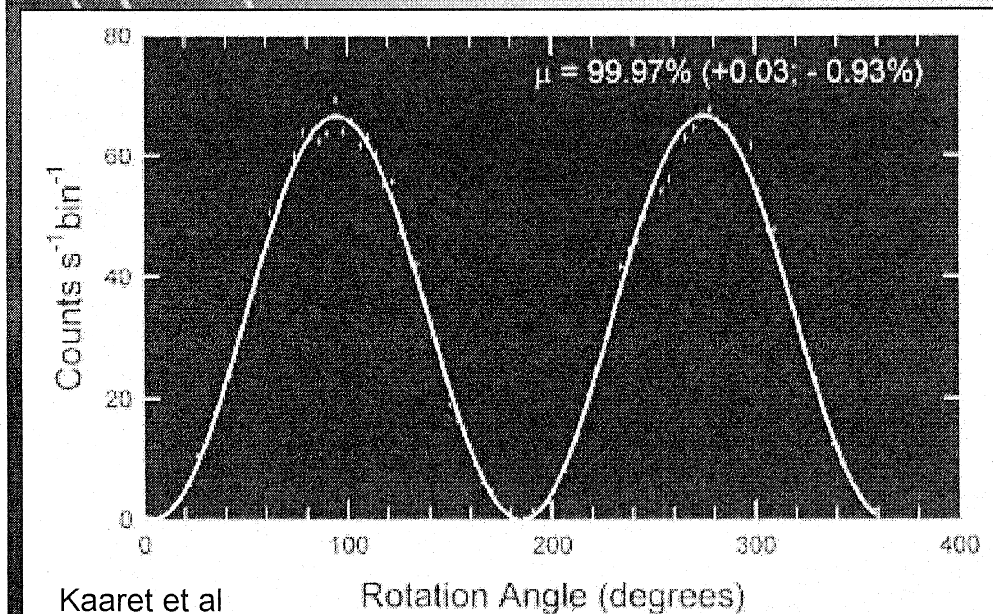
$$\frac{\partial\sigma}{\partial\Omega} = r_0{}^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$

- Fit function to the angular distribution:

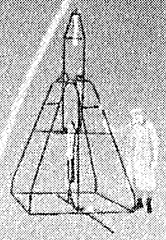
$$N(\phi) = A + B\cos^2(\phi + \phi_{pol})$$

- Modulation Factor, μ:

$$\mu = \frac{N_{\max} - N_{\min}}{N_{\max} + N_{\min}} = \frac{B}{2A+B}$$



Kaaret et al



Polarimeter Figure of Merit

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

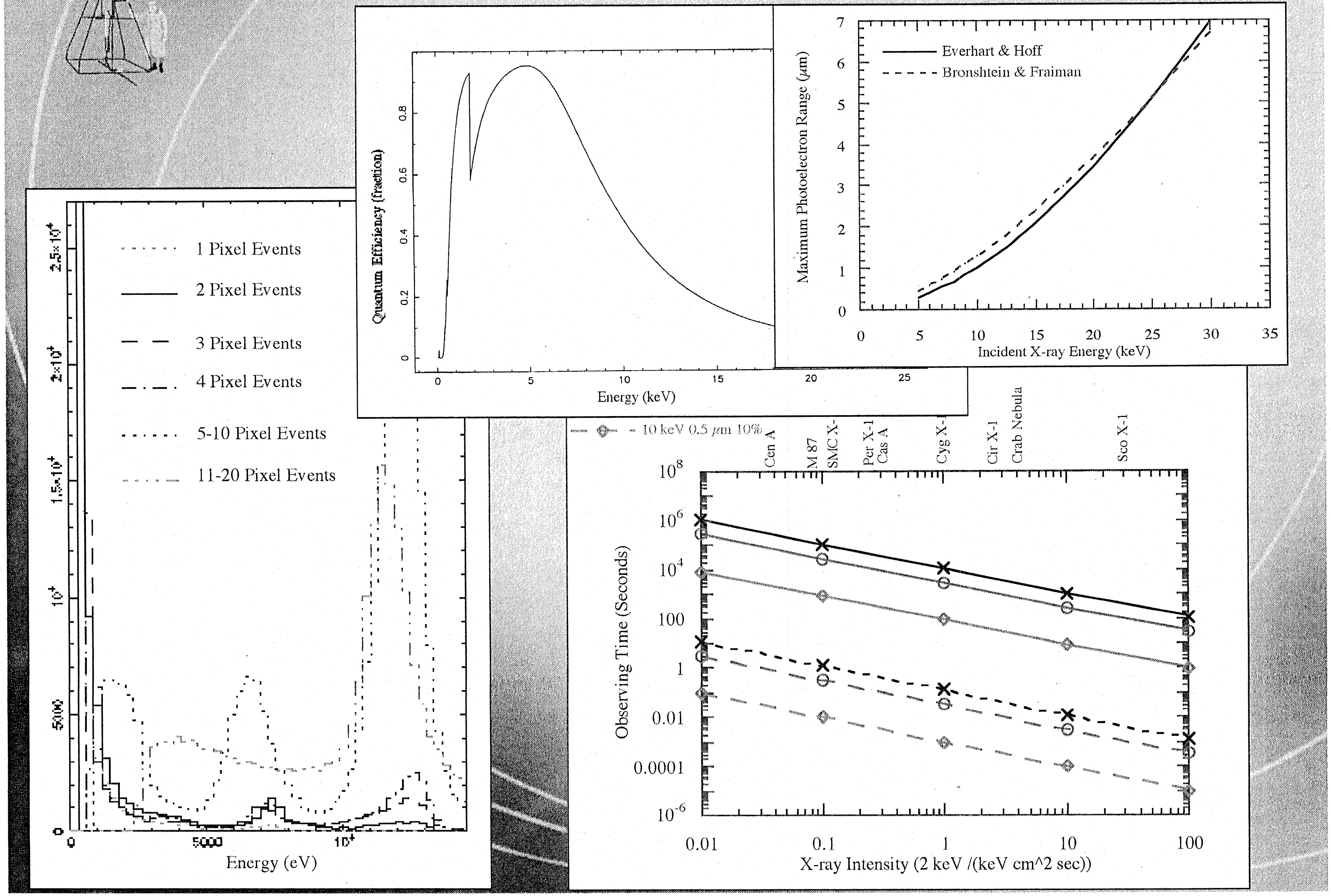
$$MDP = \frac{1}{\mu\varepsilon}\frac{n_\sigma}{S}\left(\frac{2(\varepsilon S + B)}{t}\right)^{1/2}$$

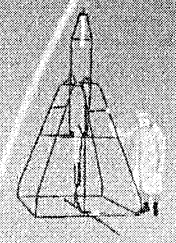
- Polarimeter Figure of Merit (in the signal dominated case):

$$FoM = \mu\sqrt{\varepsilon}$$ but, systematics are important!

Challenge: High modulation AND high QE

Small Pixel CCD Polarimeters



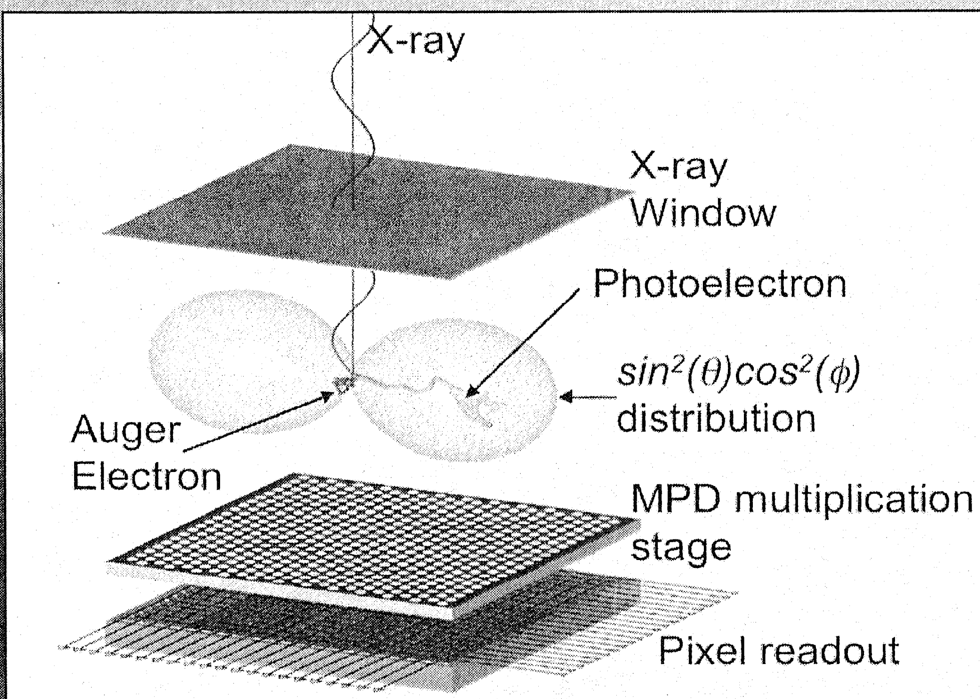


Polarimeter Requirements

- <u>Challenge: both good modulation and high QE</u>

- 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

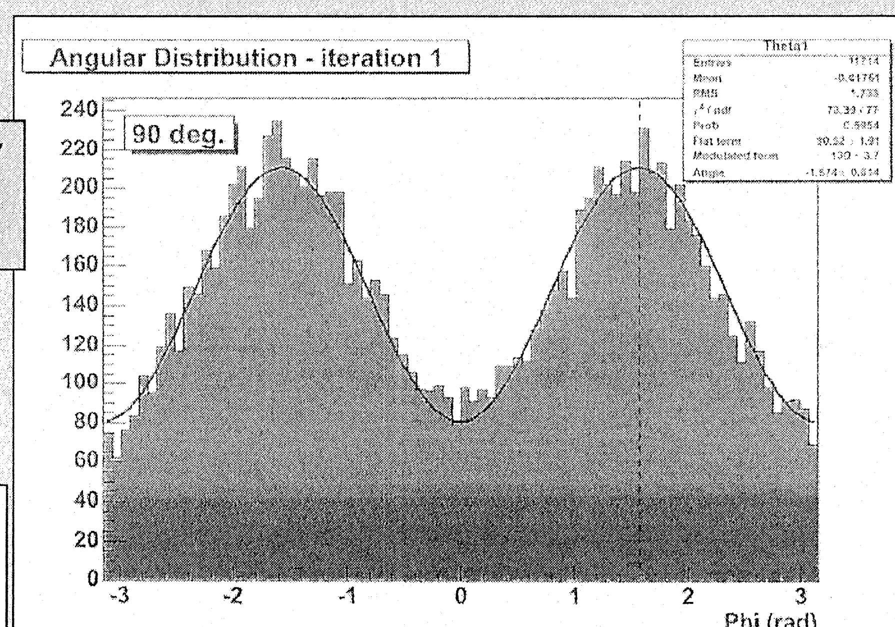


- X-ray interacts in the gas
- K-shell photoelectron ejected
- Photoelectron creates electron cloud
- Electron cloud drifts to cathode
- Electron multiplication occurs between cathode and anode
- Charge collected at the pixel readout

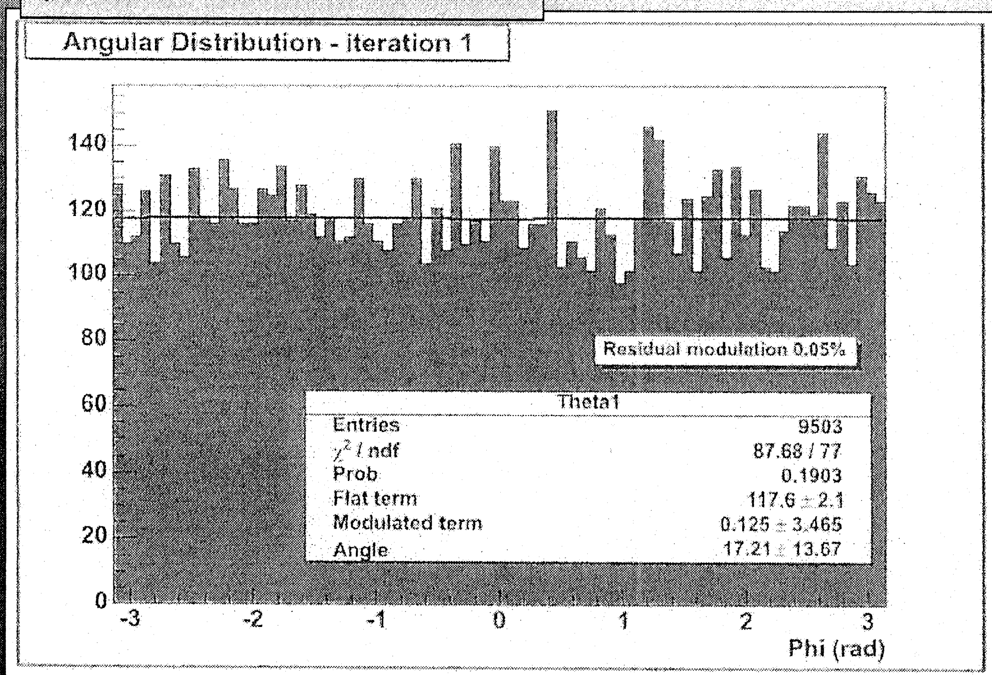
Gas Micropattern Polarimeter Results

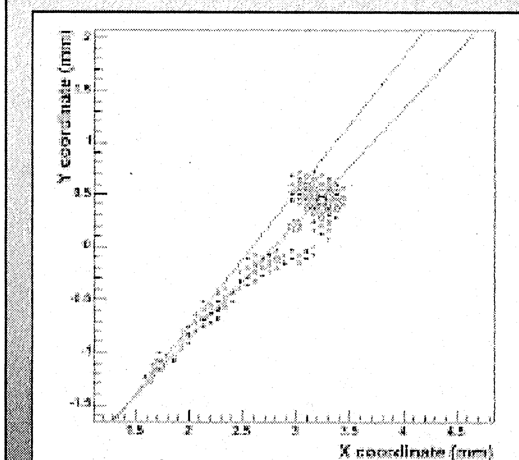
- 1 atm 50:50 Ne:DME

Polarized 5.41 keV
μ=51.1+/-0.9%



Unpolarized 5.9 keV
μ=0.05+/-1.47%

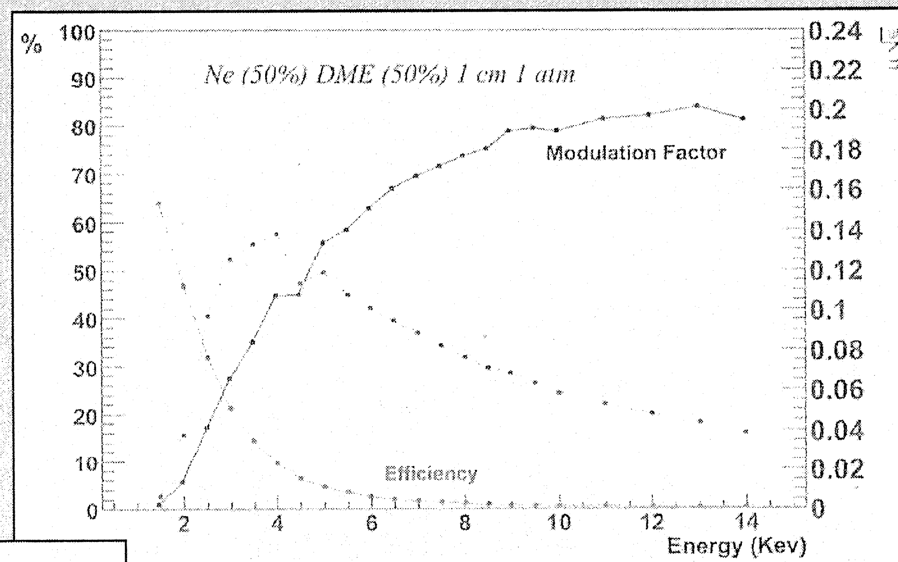


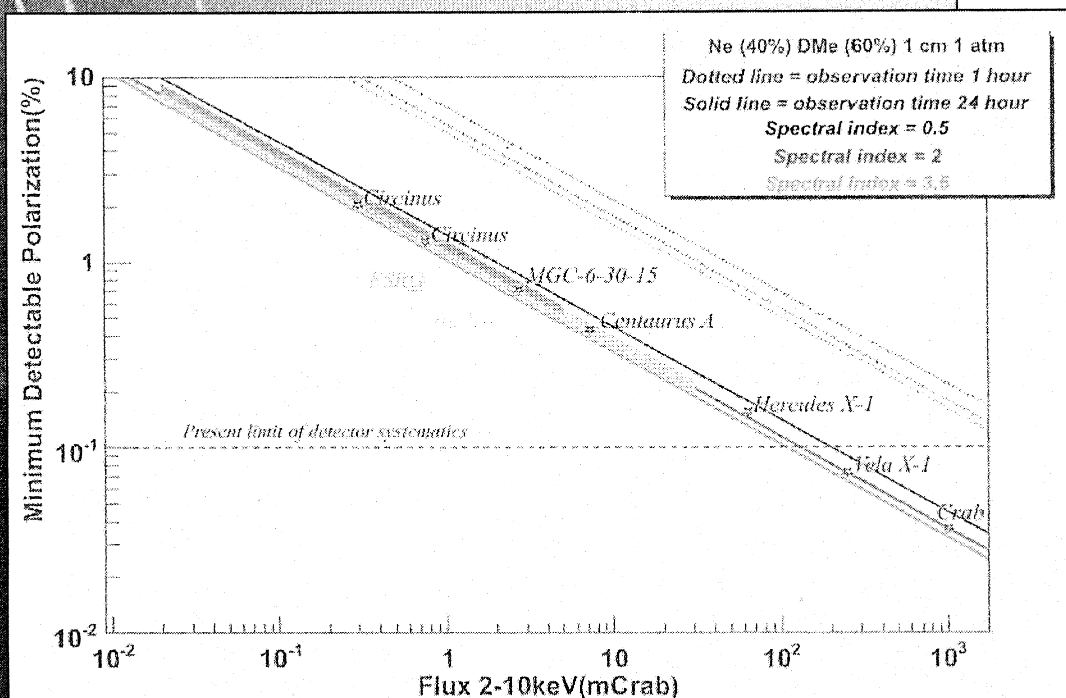


Bellazzini, SPIE, 2006

Gas Micropattern Polarimeter Results

- High Modulation
- Limited QE:
  - requires XEUS Optics





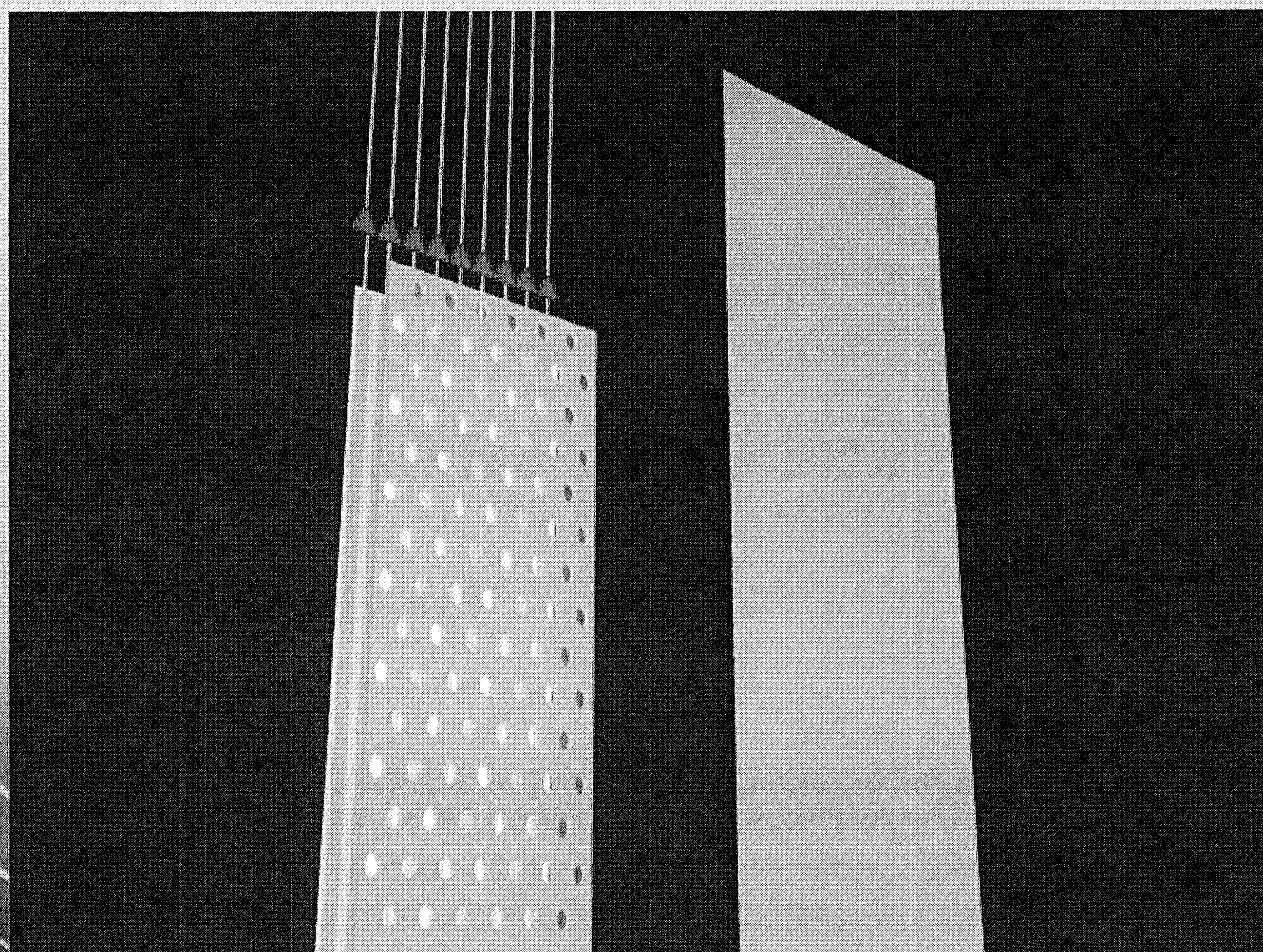
Bellazzini, SPIE, 2006

Polarimeter Requirements

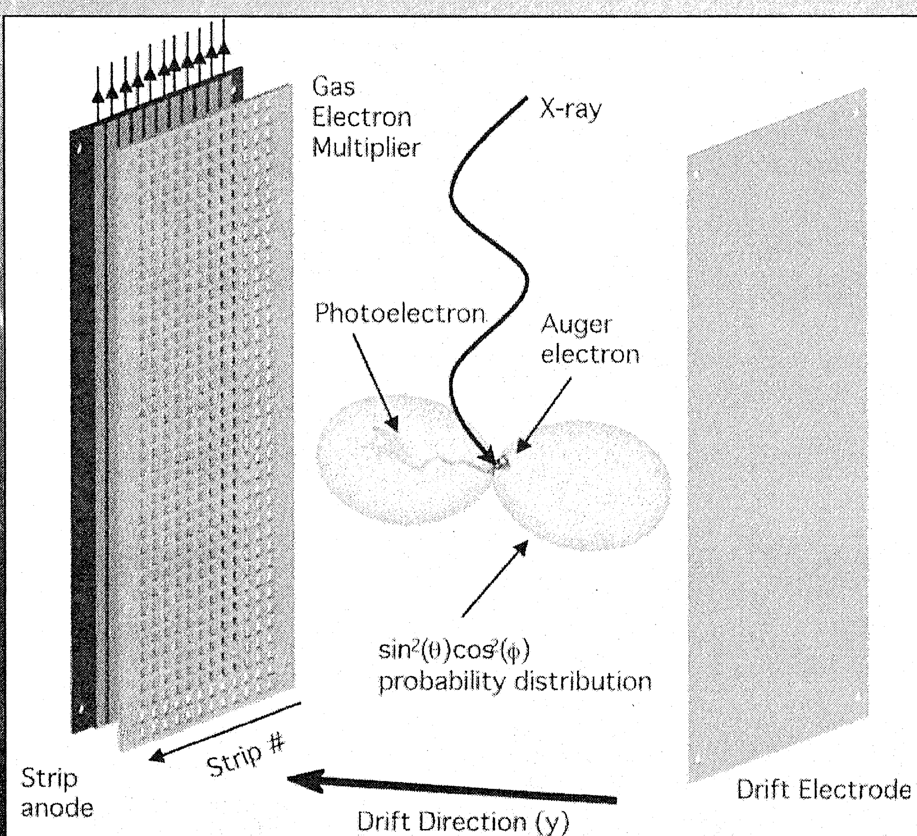
- Challenge: both good modulation and high QE
  - Scattering mean free path ~ 0.1% X-ray absorption depth
  - Electron diffusion in the drift region creates a tradeoff between quantum efficiency, modulation
- Ideal polarimeter is an electron track imager with:
  - resolution elements < mean free path
    - Gas Detector
  - active depth >= absorption depth
    - **=> resolution elements < depth/10^3**

One Solution is TPC Polarimeter

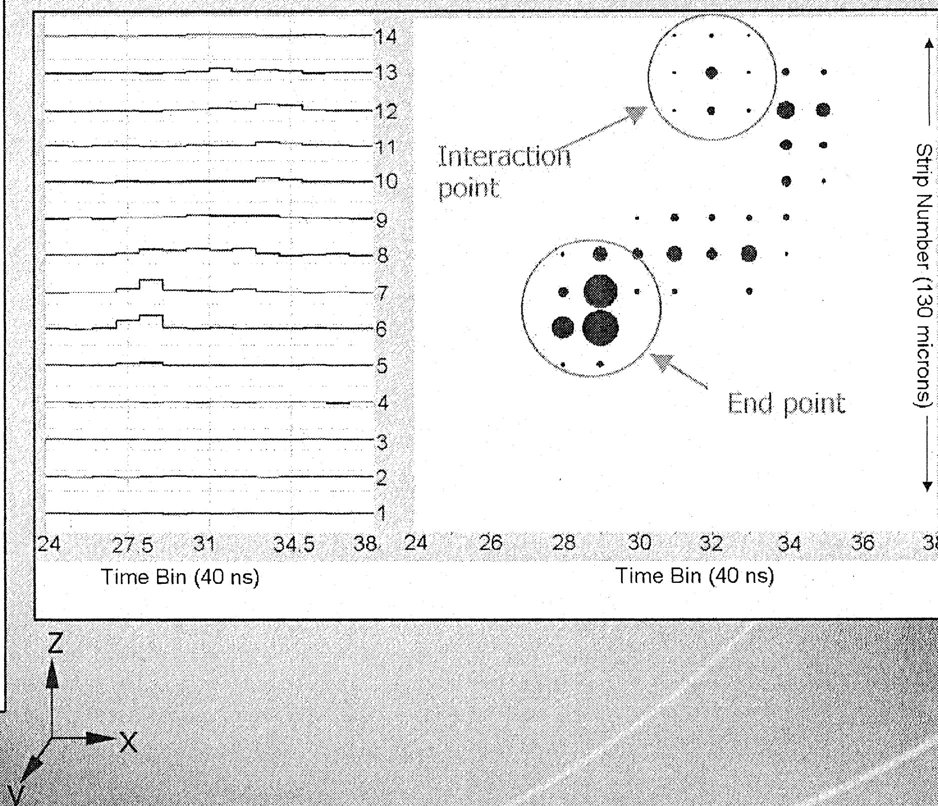
A Time-Projection Chamber (TPC) X-ray polarimeter



Time-Projection Chamber Polarimeter

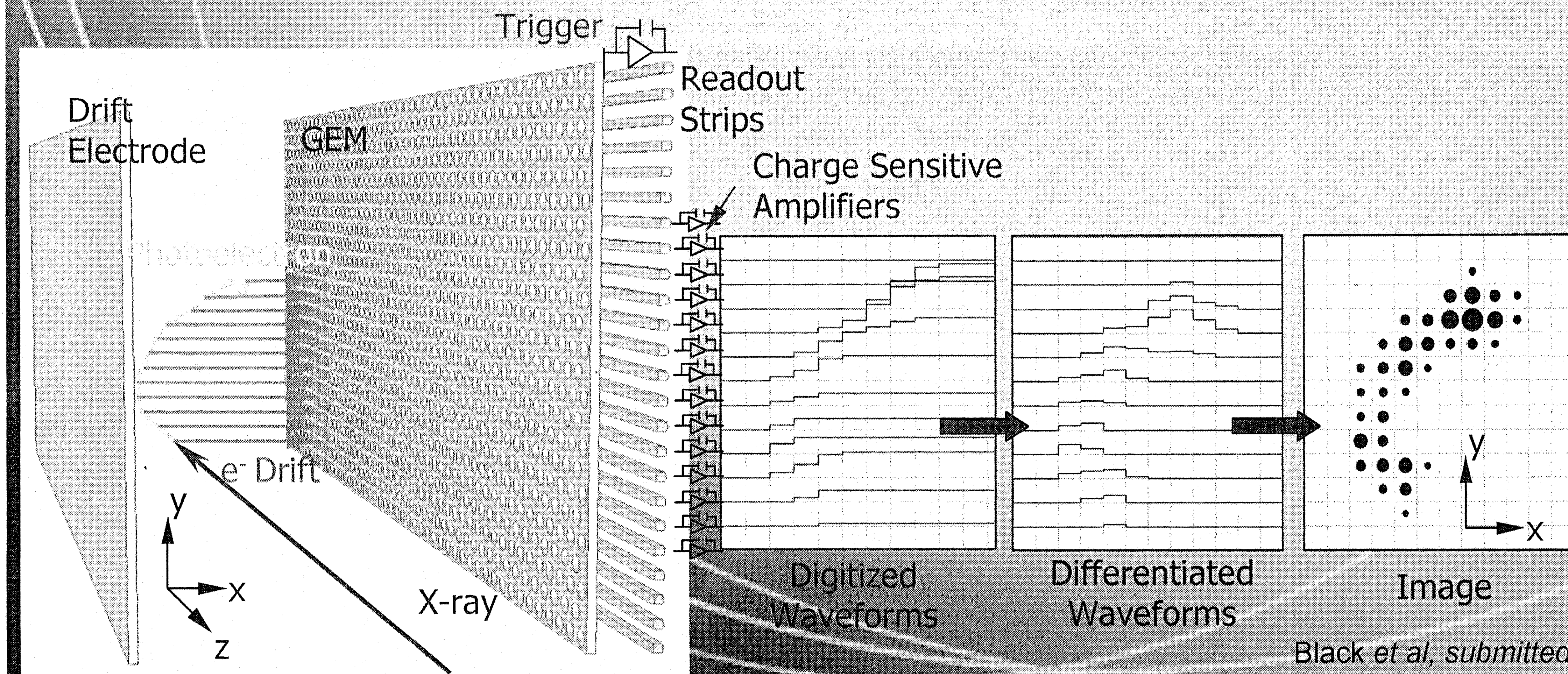


Charge pulses
arriving at the strips



The TPC Polarimeter

- GEM with strip readout
  - Track images formed by time-projection by binning arrival times
- Resolution is (largely) independent of the active depth
  - Max depth determined only by degree of X-ray beam collimation



Black *et al*, *submitted to NIM A*

Trade-offs in a TPC polarimeter

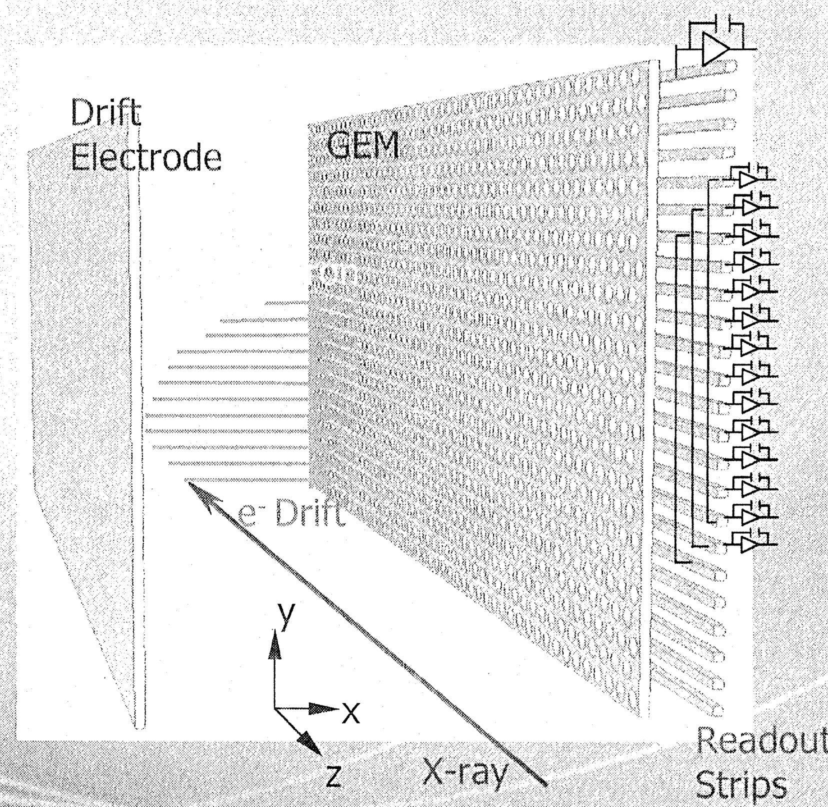
Pros

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

Cons

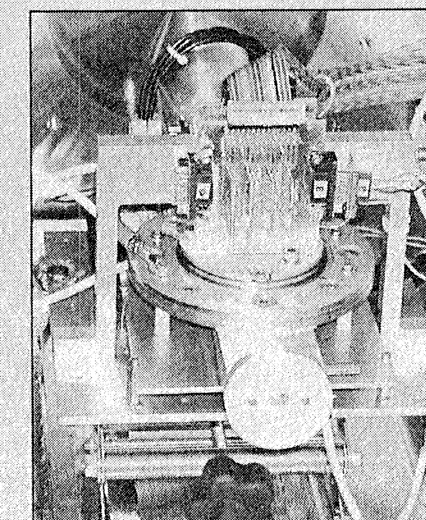
1. Rotationally asymmetric: requires careful control of systematic errors
2. Not focal plane imaging

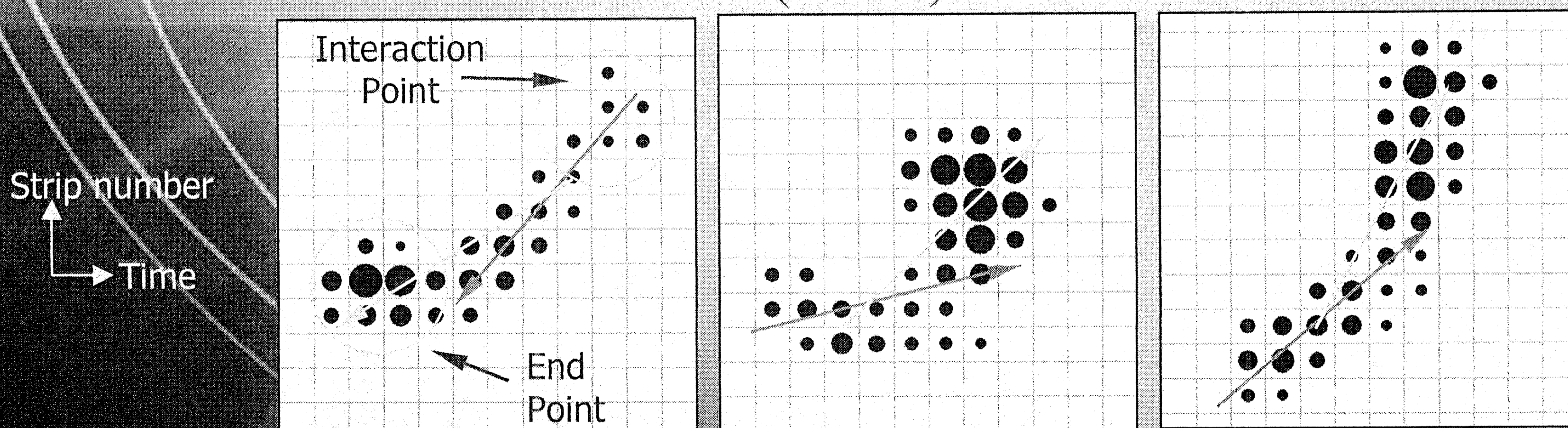
The TPC polarimeter measures the orthogonal coordinates in fundamentally different ways, making it rotationally asymmetric. Care is required to prevent the high statistical sensitivity from being lost to systematic errors.



Prototype TPC polarimeter

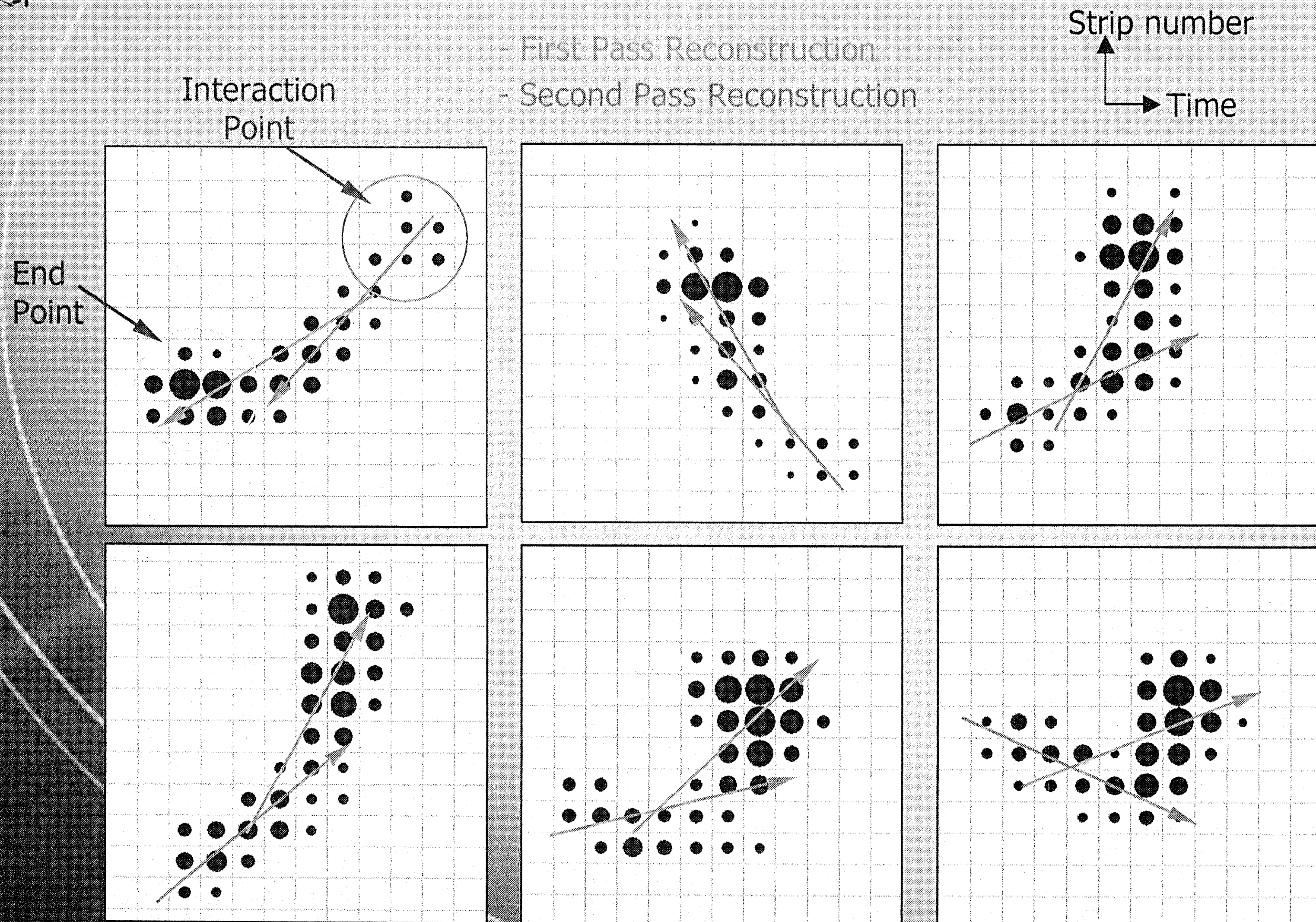
- Made from off-the-shelf components:
  - 130 micron pitch
  - 13mm(w) x 30mm(d) active area
  - 24-channel ADC
  - drift velocity: 40 nsec bin = 130 microns
  - 460 Torr Ne:DME (50:50)





Reconstructed 6.4 keV track images

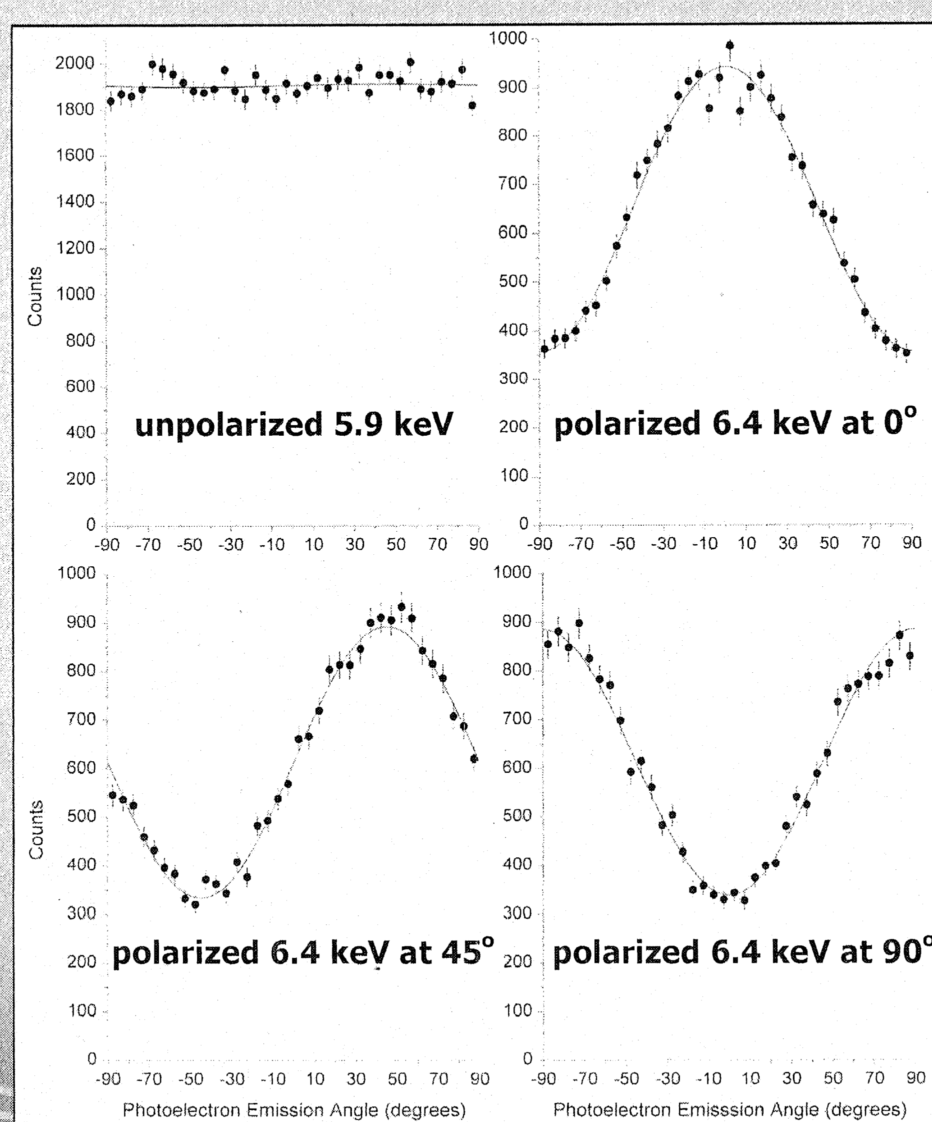
Typical 6.4 keV Tracks



Prototype TPC Polarimeter Results

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

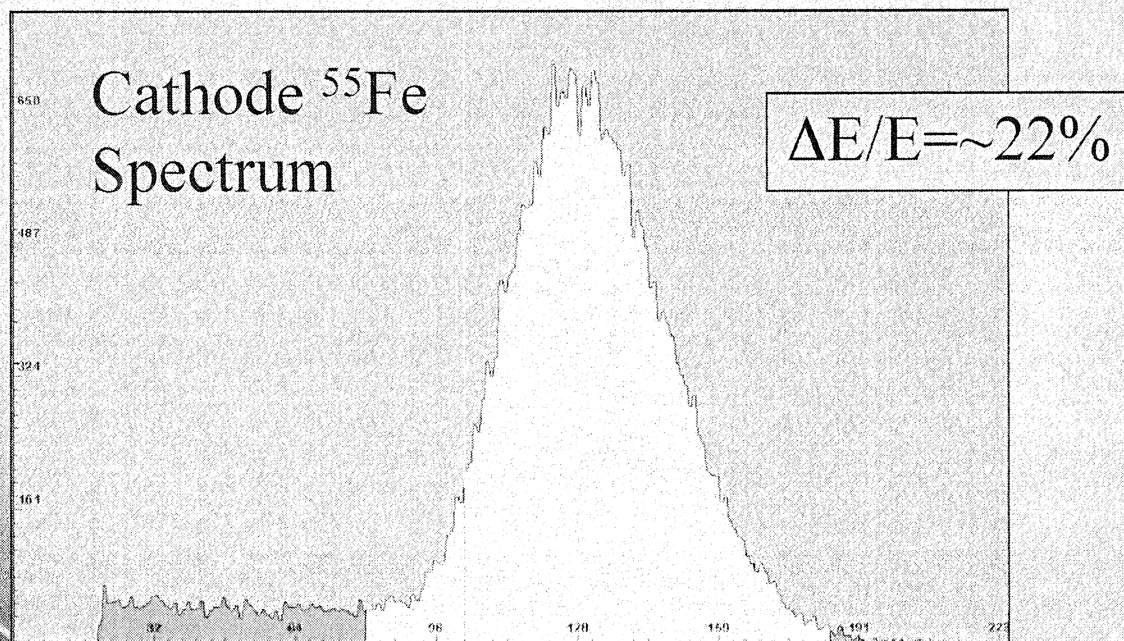
- Uniform response
- No false modulation
- Modulation consistent with gas pixel detectors
- Unit QE possible



Black *et al, submitted to NIM A*

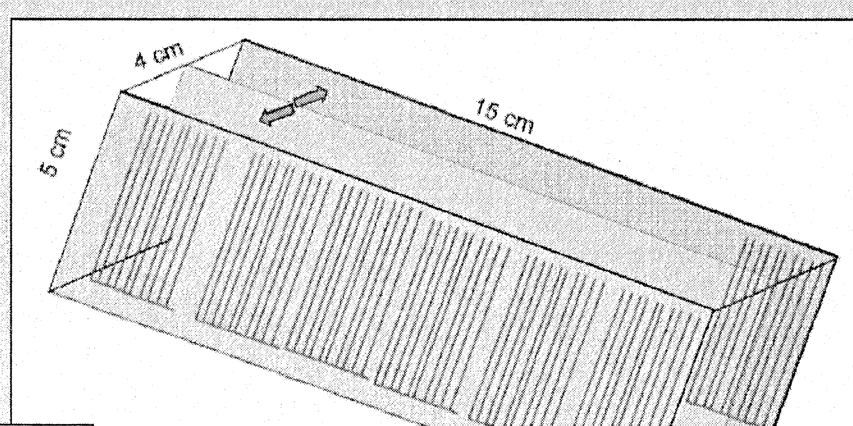
TPC Spectral Response

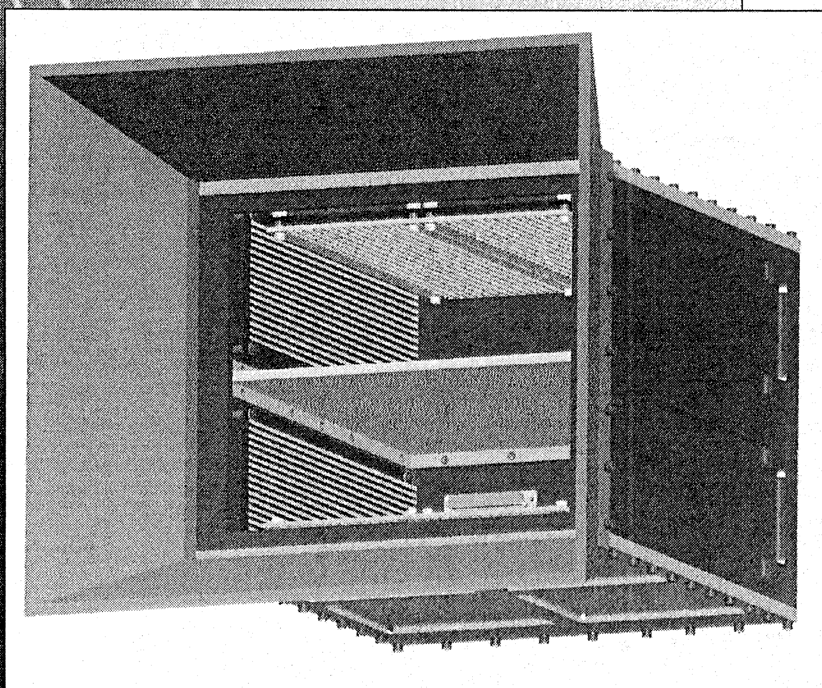
- Spectral response from the cathode (or strip electrode)
  - Typical proportional counter resolution

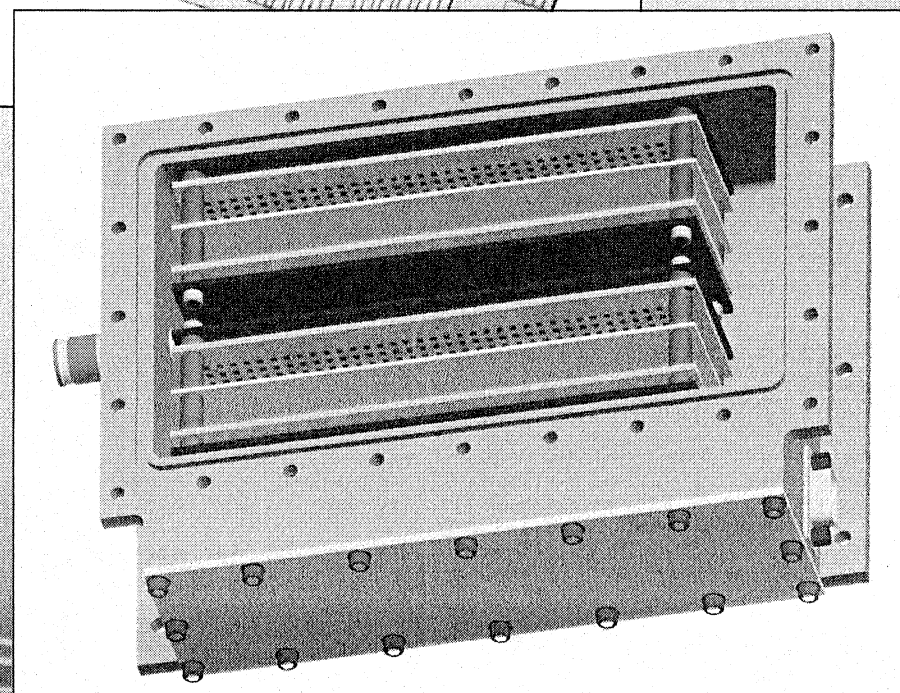


Wide field-of-view GRB polarimeter

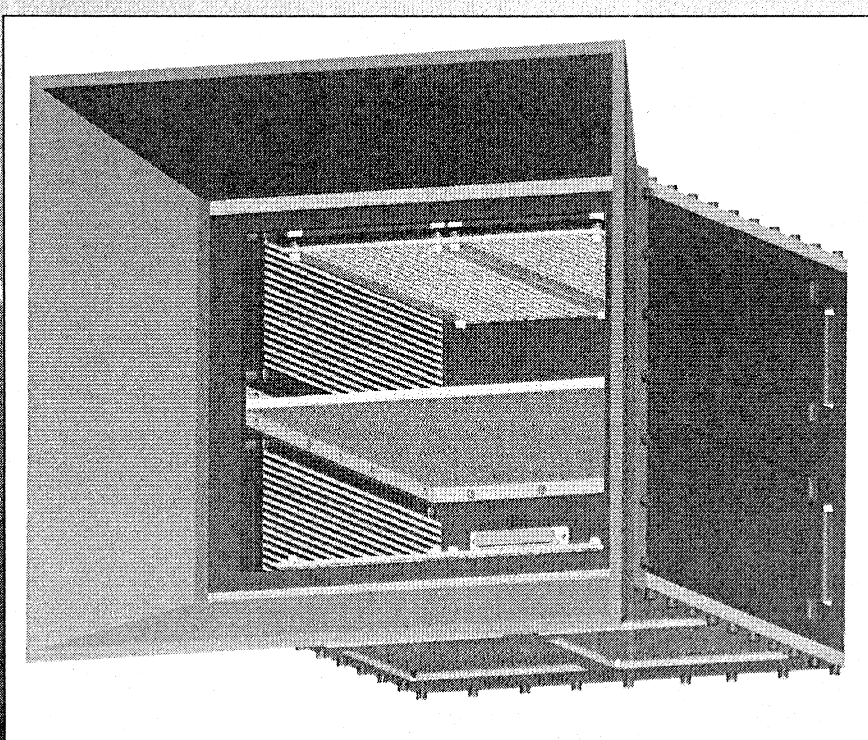
Enables large volume detectors with wide of view





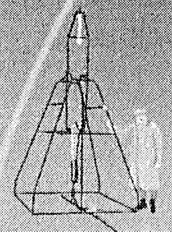


GRB X-ray Polarimeter



- Make a scientific measurement
- Multiple band pass possible
- Low cost proof-of-concept:
  - Measure the expected high levels (10-80%) of polarization of very bright GRBs

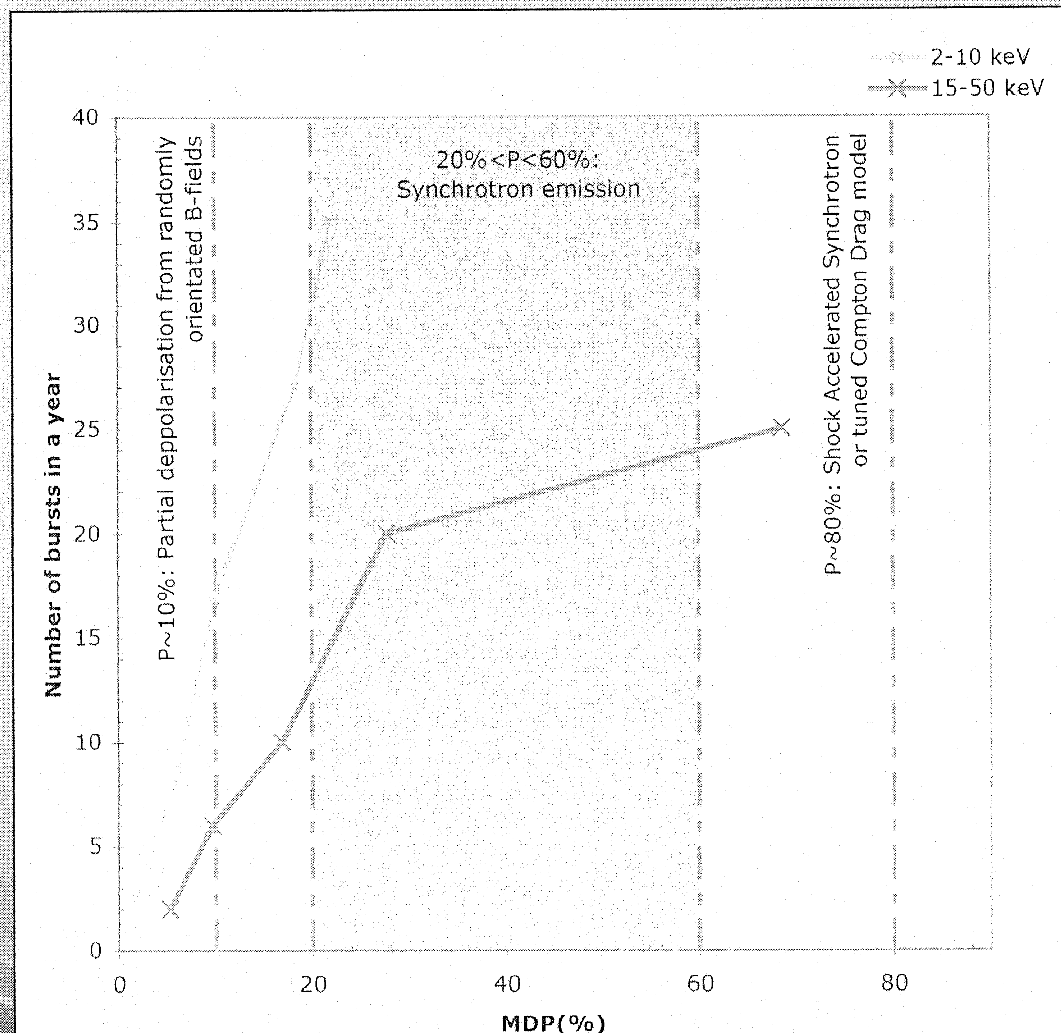
NASA APRA Funded Development



GRB Polarimeter:
MoO
Midex/Smex

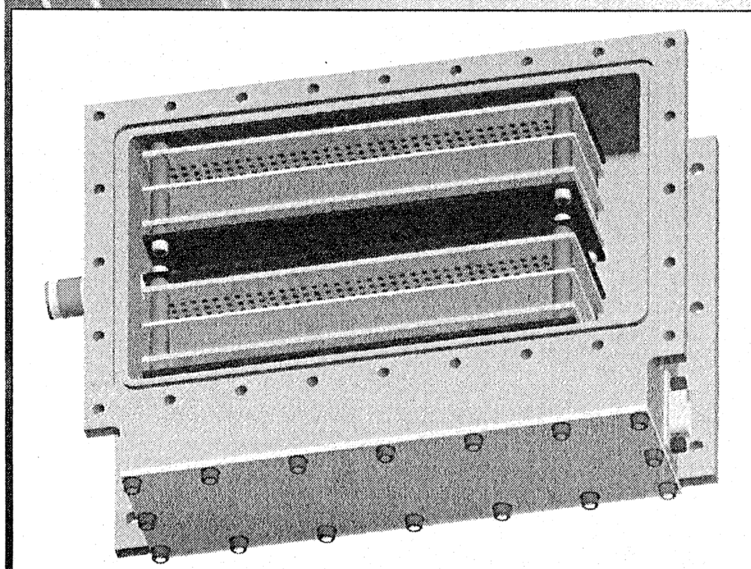
Area: 35 x 35 cm^2
Depth: 30 cm
FoV: 1 steradian
Low E: Ne CS_2
High E: Ar CS_2

Polarization averaged over energy band

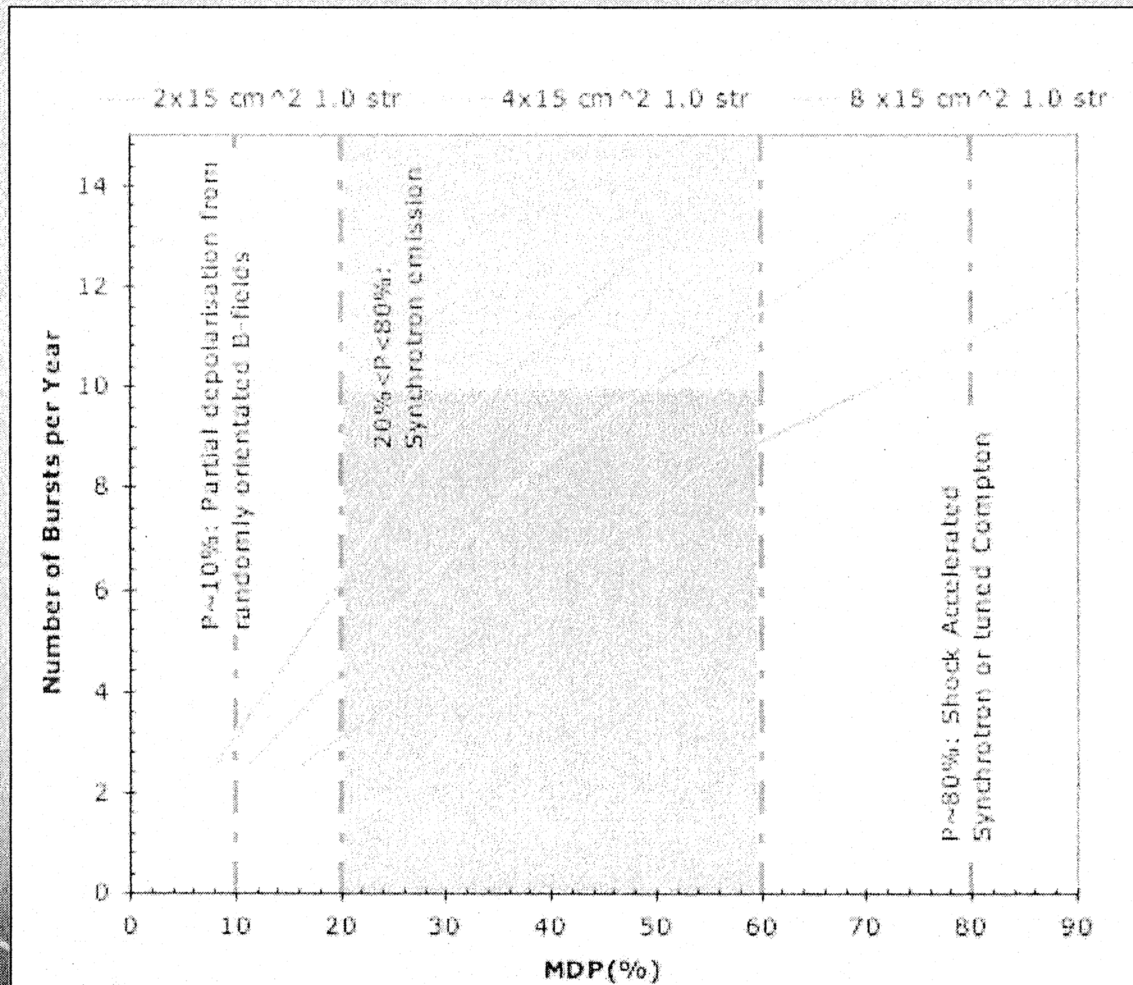


The GRBP: A payload for MidStar 2

Area: See plot
Depth: 5 cm
FoV: 1 steradian
Gas 50:50 Ne:DME
Pressure: 1 atm



Polarization averaged from 2 - 10 keV



The GRBP: A payload for MidStar 2

- MidStar offers dual opportunities:
  - Space qualify an exciting technology
  - Measure the polarization of several Gamma-Ray bursts
- Proposed experiment is sized:
  - To provide an excellent chance of qualifying technology
  - To provide reasonable chance of exciting scientific result

Further Work

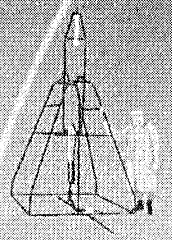
- In-situ drift velocity calibration and monitoring
  - In the lab (rapid turn-a-round)
  - On-orbit
- GEM configuration
  - Alignment
  - Mounting
- Large area GEMs
- Background simulations
  - X-rays
  - Charged-particles

Education & Public Outreach

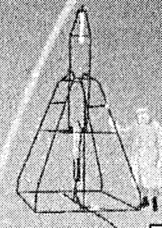
"The Day in the Life of a Scientist":

An interactive experience

- Build a gas chamber based on TPC design
  - 12″x12″x12″ transparent chamber
- Provide hands on experience for visitors
  - Show how tracks differ for Cosmic-rays, Alpha-particles and Beta-particles and X-rays
  - Will show different properties of radiation
  - Demonstrate different stopping materials for the different radiation

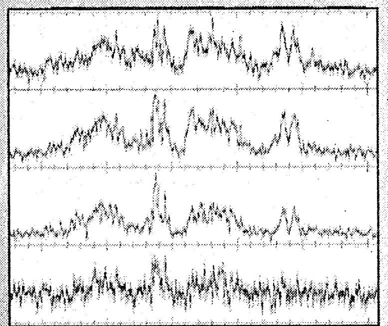


Other Applications……

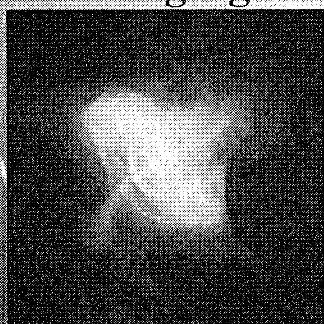


Polarimetry Prospects in X-ray Astronomy (1 keV-100 keV)

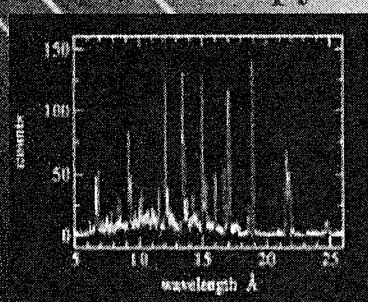
Timing



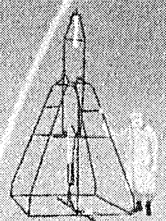
Imaging



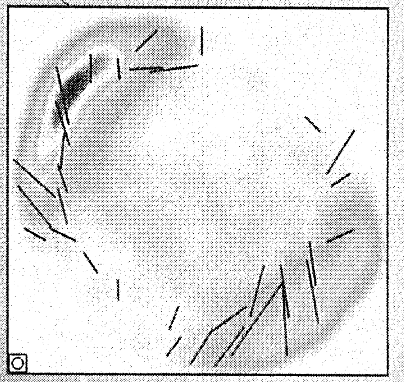
Spectroscopy

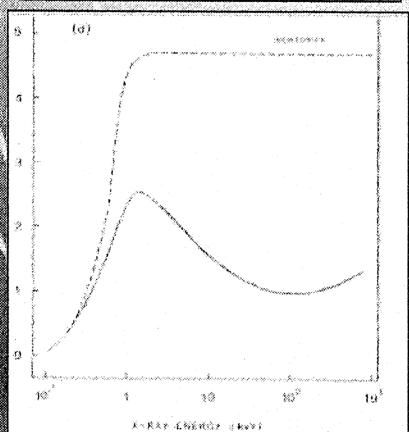


- Remains the only largely unexploited tool
  - Instruments have not been sensitive enough warrant investment
  - Two unambiguous measurements of one source (Crab nebula) at 2.6 and 5.2 keV
  - Best chance for pathfinder (SXRP on Spectrum-X Γ mission ~1993) never flew
- Interest and development efforts 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

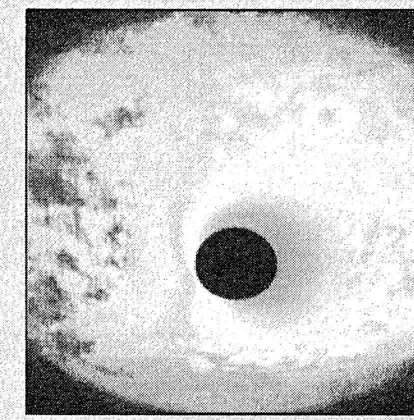


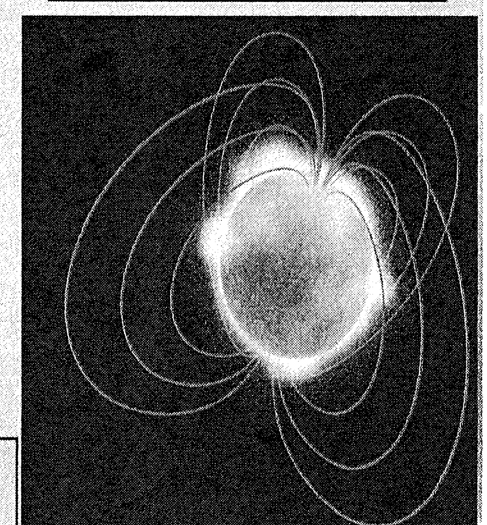
Polarization addresses fundamental physics and astrophysics





- 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 ?



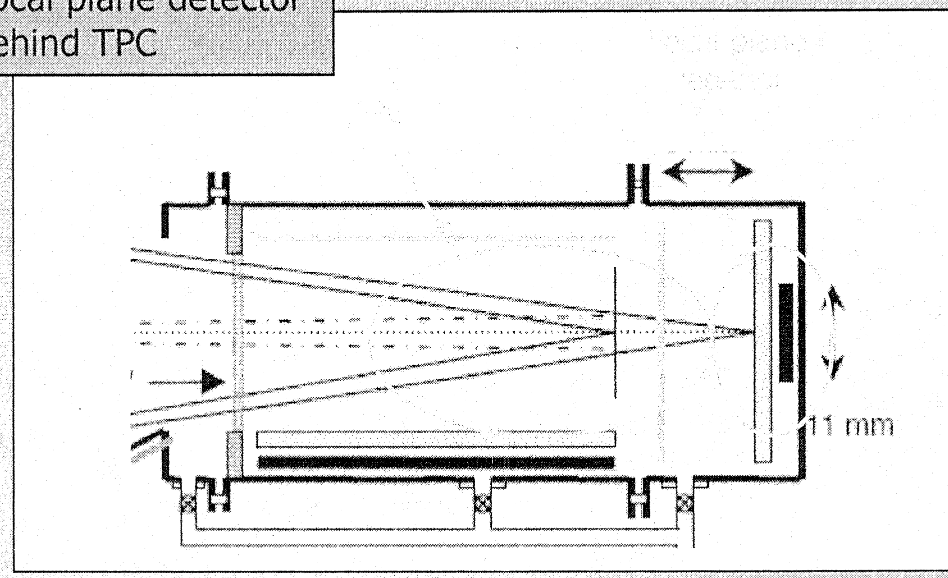


- What is the history of the black hole at the center of the galaxy?
- What happens to gas near accreting neutron stars?
- Do magnetars show polarization of the vacuum?

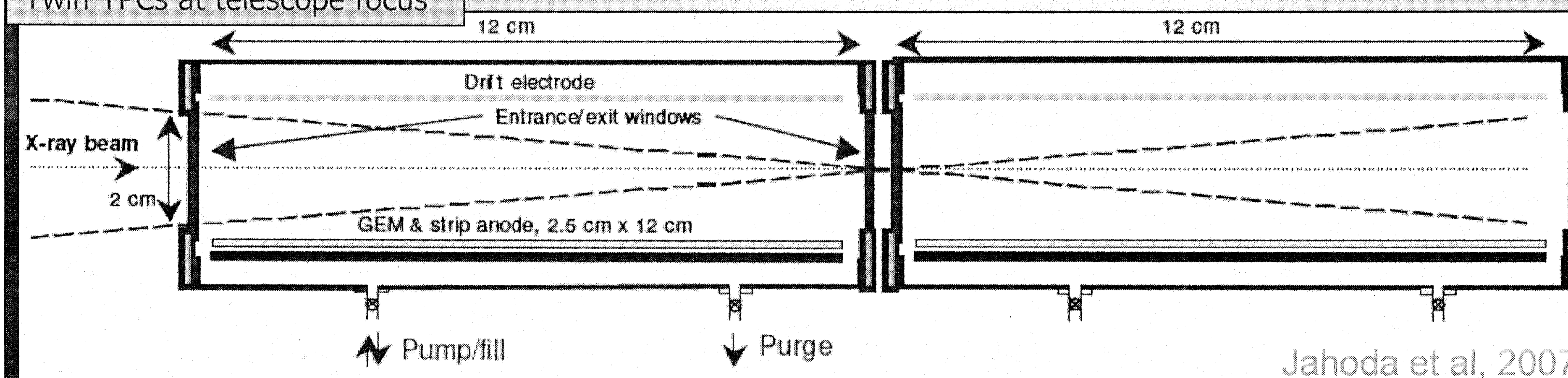
High Efficiency TPC polarimeters for X-ray Telescopes

- **High efficiency enables sensitive observations of extragalactic sources, even in a small mission**
- **Adjustable optical depth allows TPC to be used in conjunction with focal plane instrument in a large multi-purpose mission**

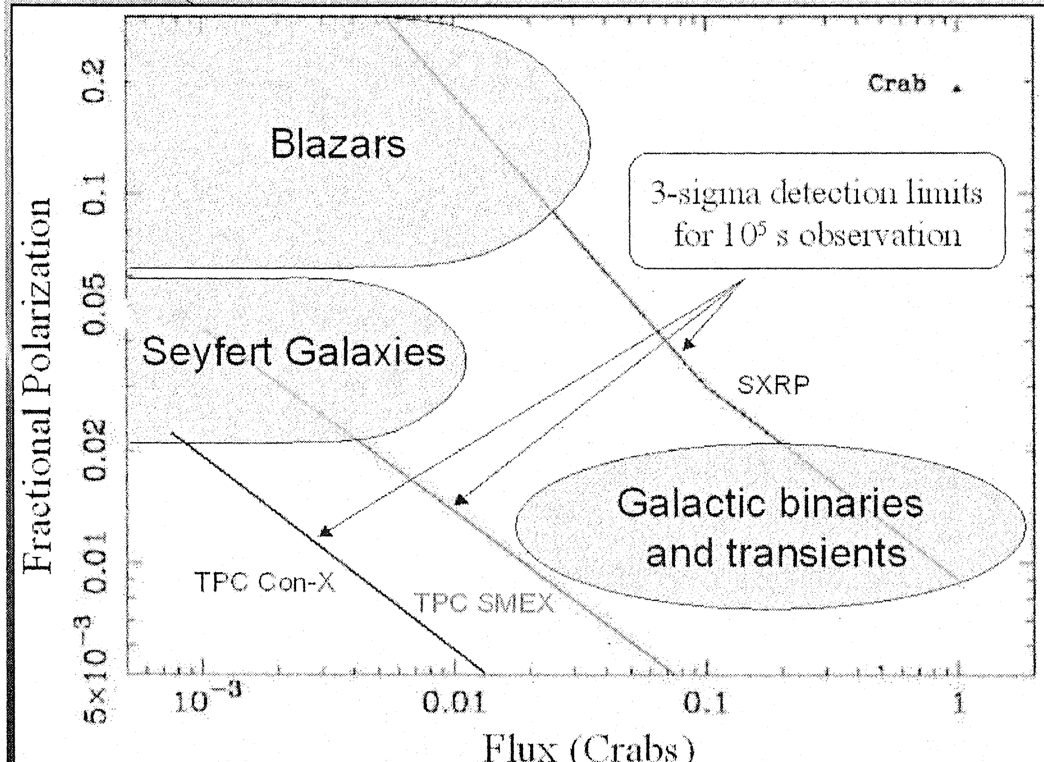
Focal plane detector behind TPC



Twin TPCs at telescope focus

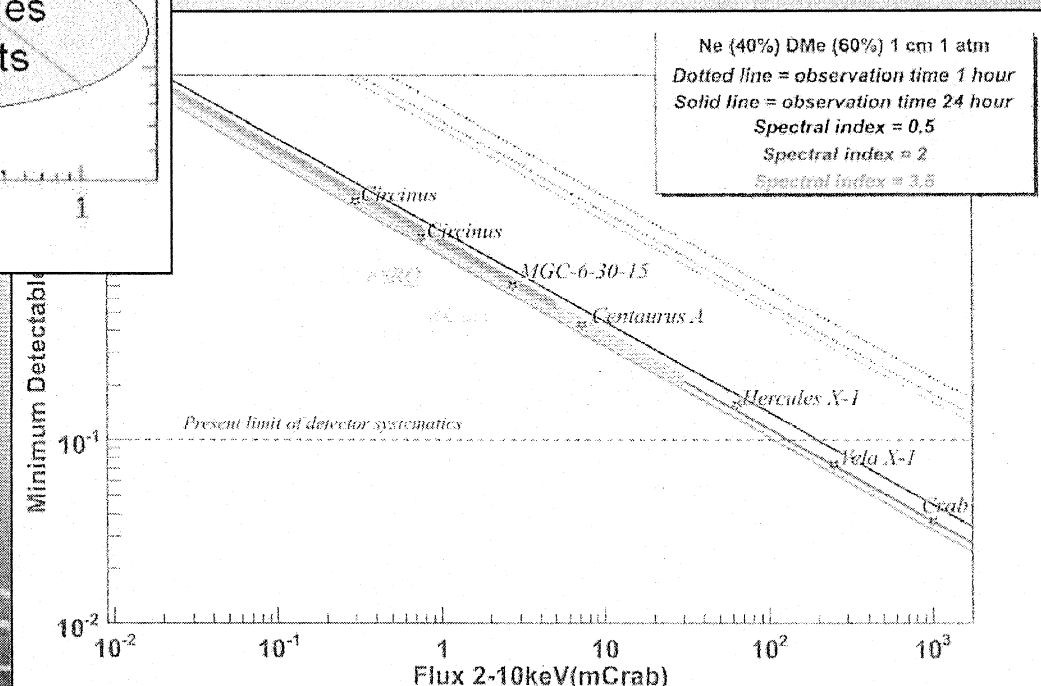


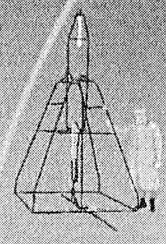
High Efficiency TPC polarimeters for X-ray Telescopes



Jahoda et al, 2007

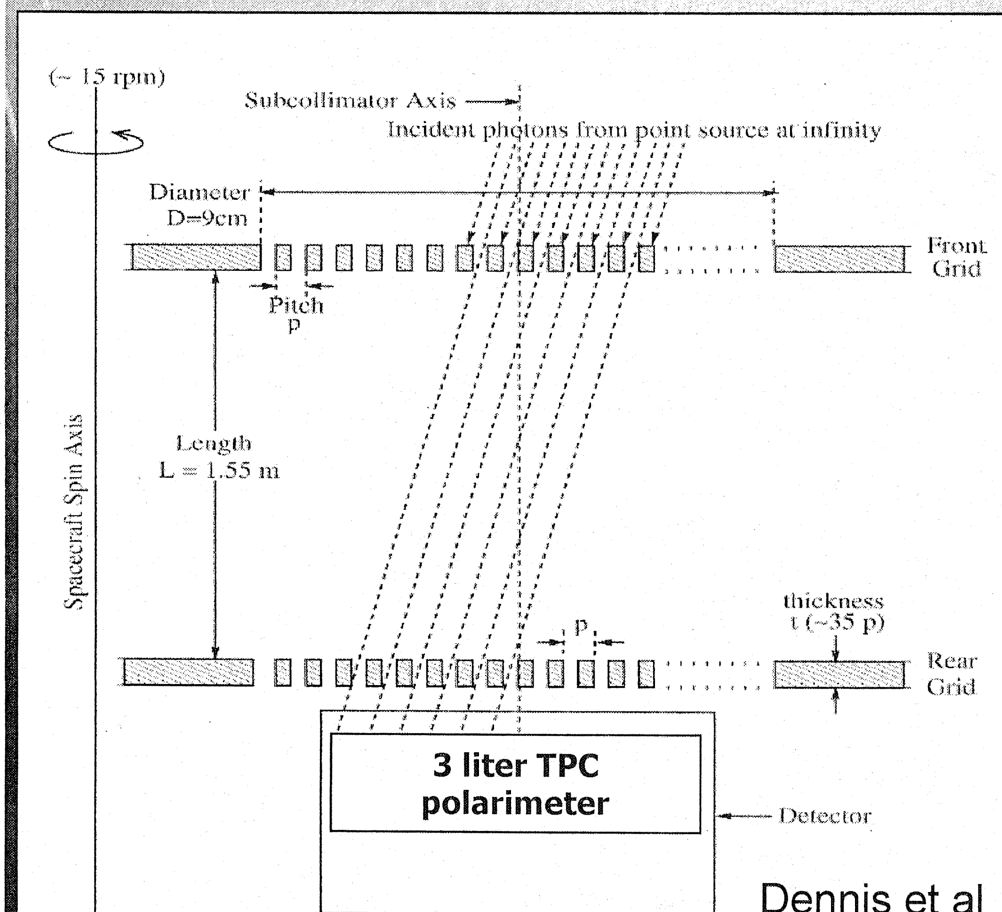
- TPC polarimetry enables measurements of low levels of polarization (<10%) of faint objects, e.g. AGN, with a small mission





Modulation Collimator Imaging Polarimeter for Solar Flares

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



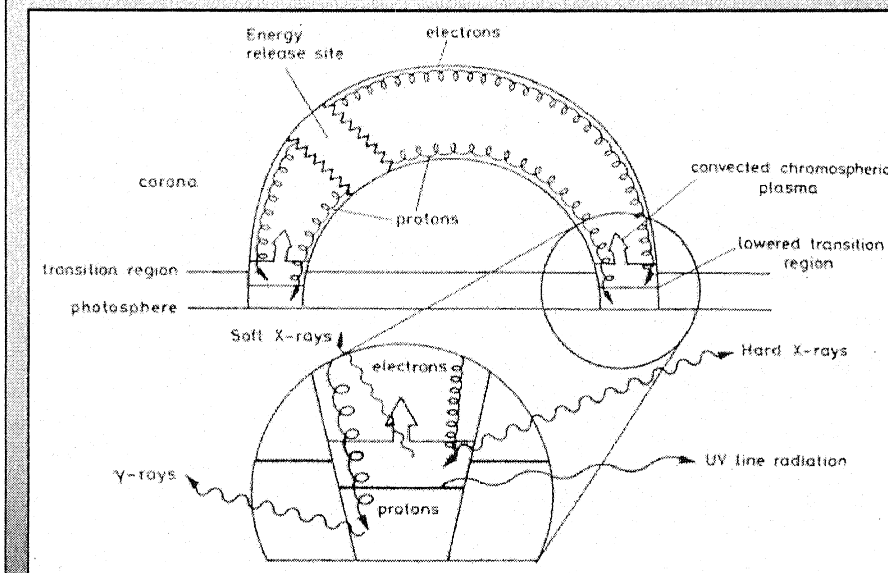


Figure 3.6. A simplified diagram of the magnetic structure and radiation emission sites of a solar flare (Phillips 1992).

Future looks bright for X-ray Polarimetry!!!