A Burst Chasing X-ray Polarimeter

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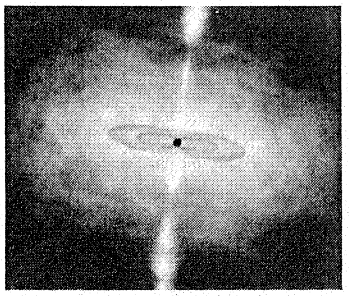
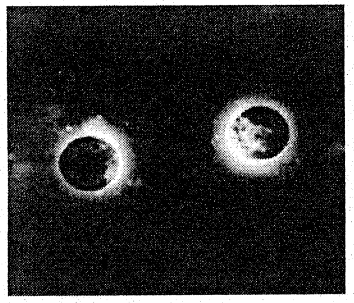
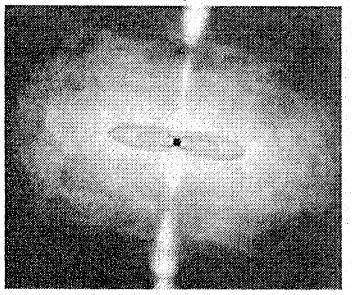


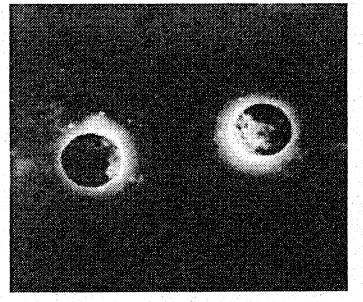
Overview



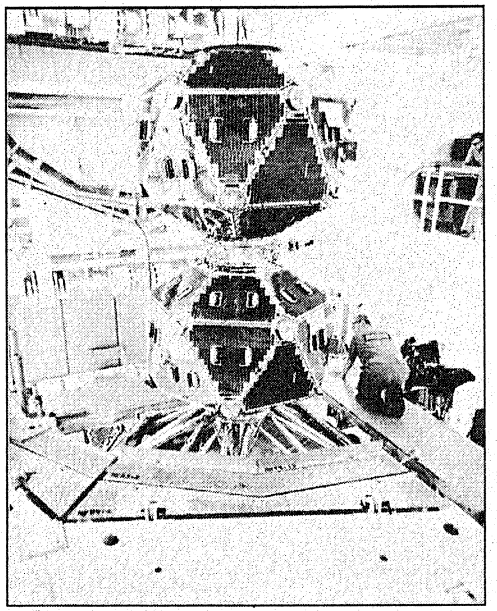
- Gamma-ray Bursts
- Time-Projection Chamber Photoelectric Polarimeter
- MidSTAR-2 Mission
- POET: POlarimeters for Energetic Transients

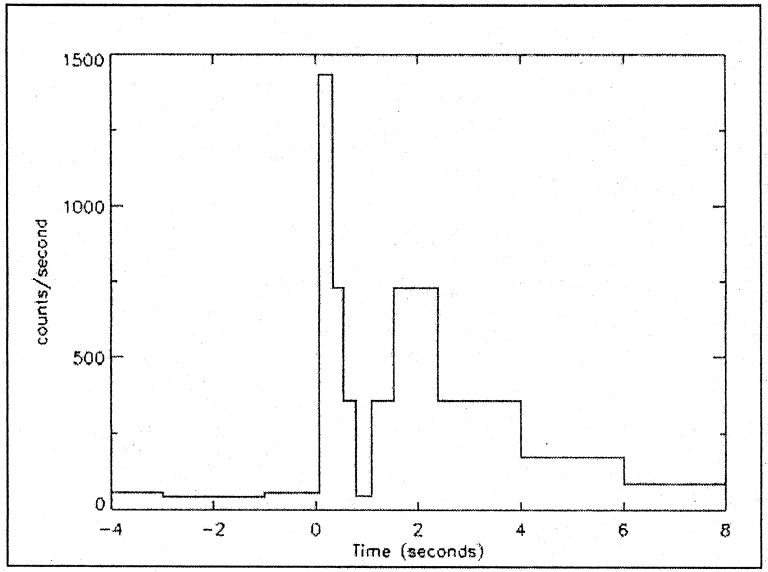


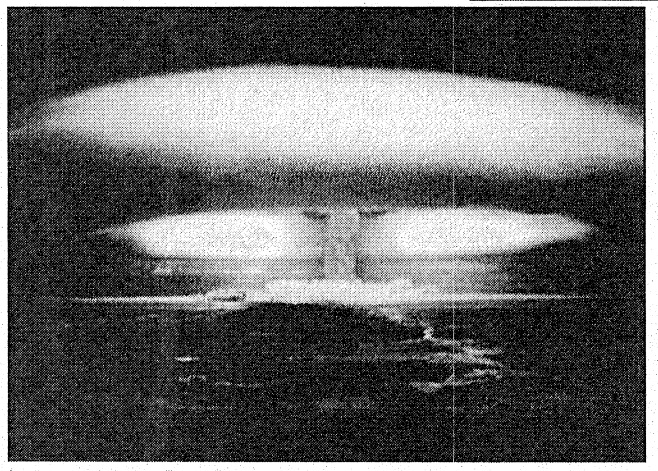
Gamma-ray Bursts

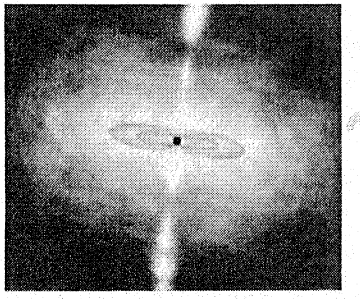


- Vela Satellites launched in mid-1960s to monitor the Atmospheric Test Ban Treaty
- Strange pulses discovered in 1969 by Ray Klebesadel of LANL
  - Data classified until 1973

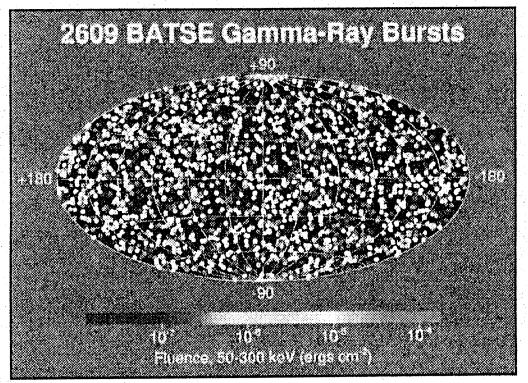


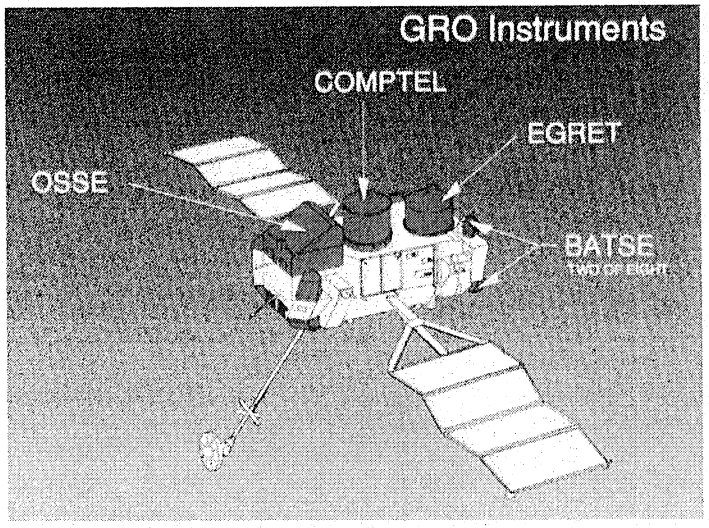




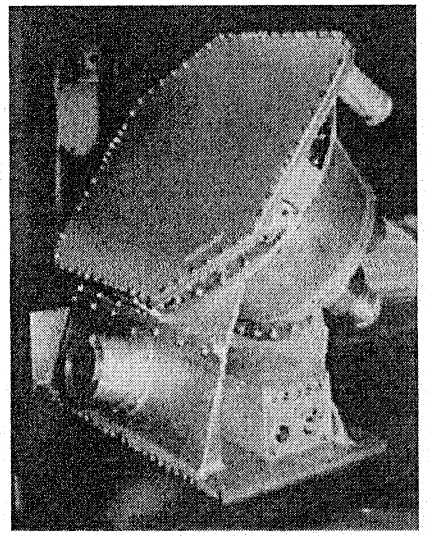


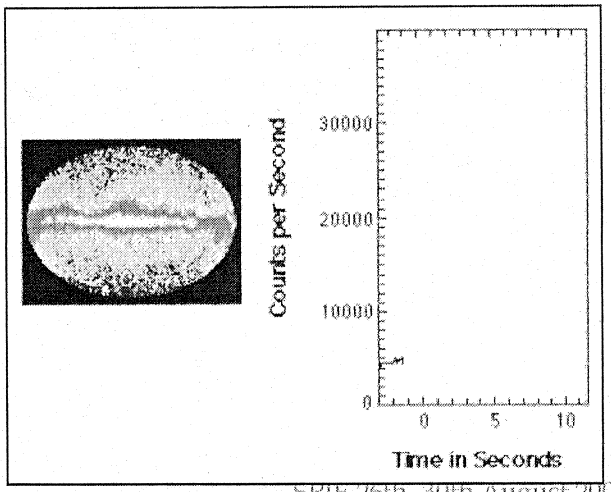
~30 Years after discovery

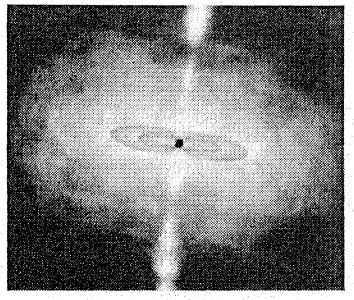




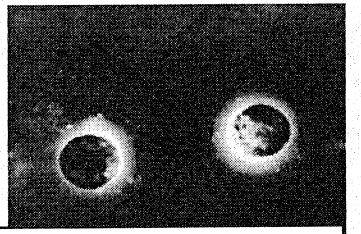
- Compton Gamma-Ray Observatory launched in April 1991
- BATSE: 2609 bursts in 8.5 years
  - Bursts are isotropic
  - Frequency ~ 1 burst per day
  - Not clear whether they are nearby or distant



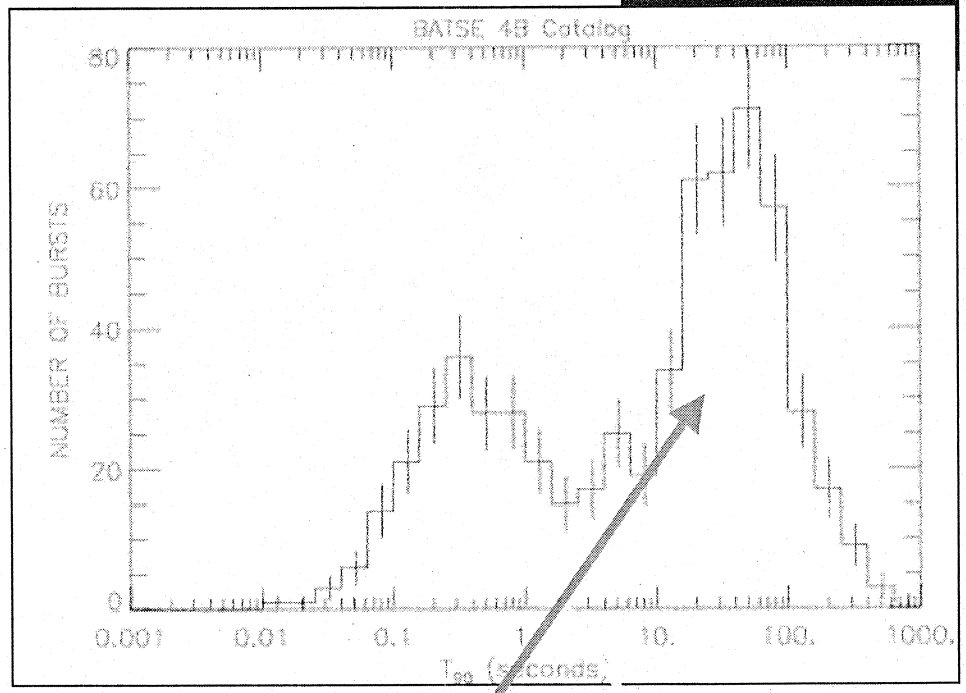


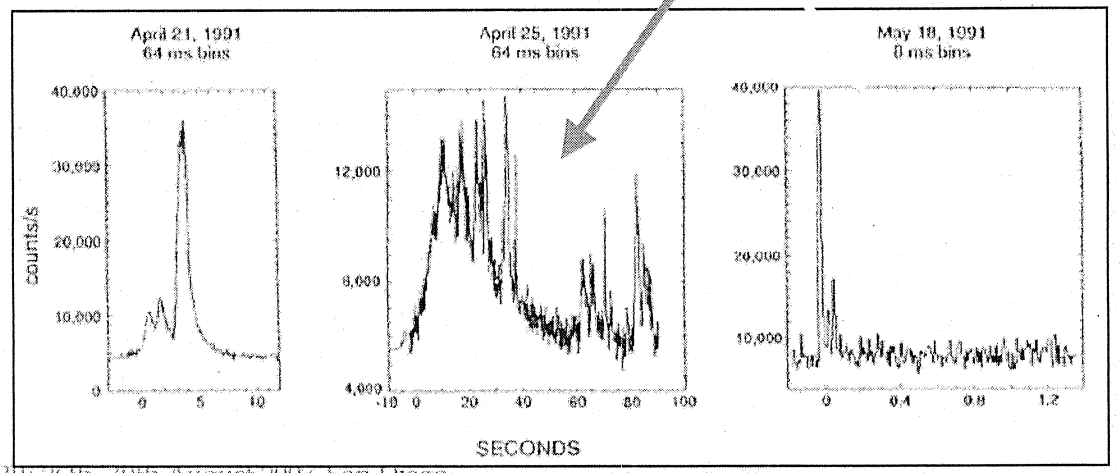


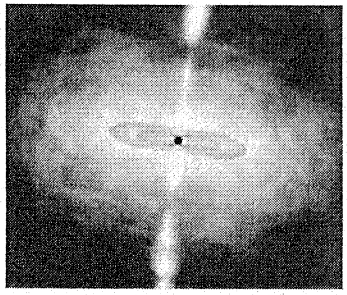
GRB Characteristics (BATSE)



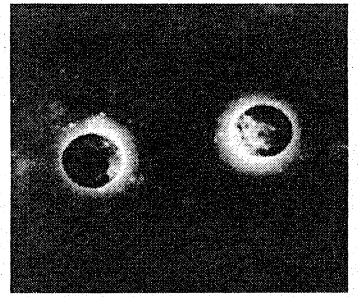
- Characteristics:
  - About 1 per day
  - Powerful
    - brightest γ-ray object in sky
    - Typically 10^{51} ergs
  - Isotropic distribution
  - Bi-model distribution of durations
  - Unique lightcurves
  - Finite extent



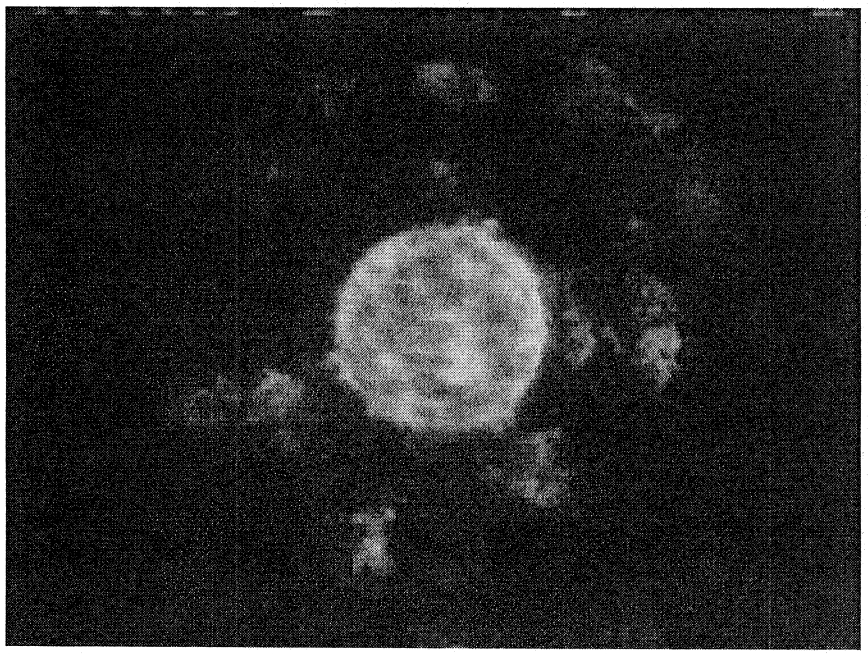


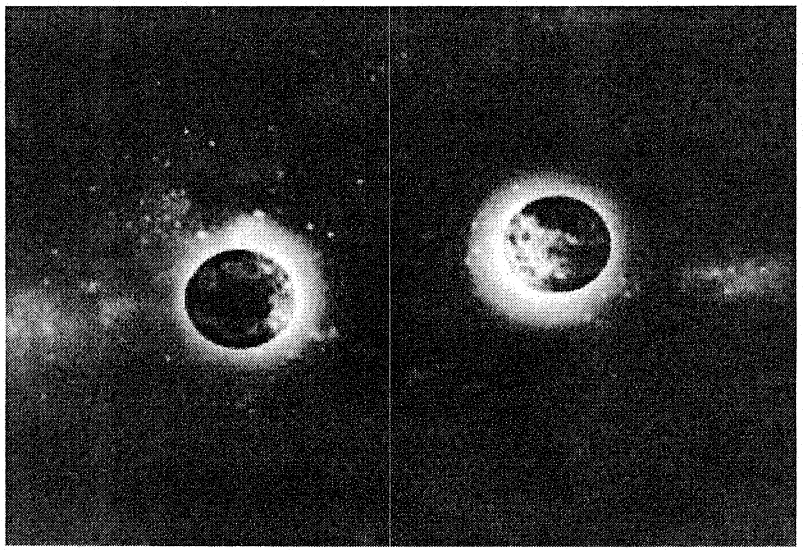


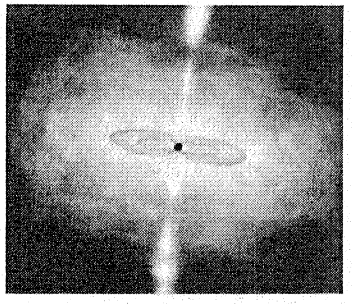
Gamma-ray Bursts



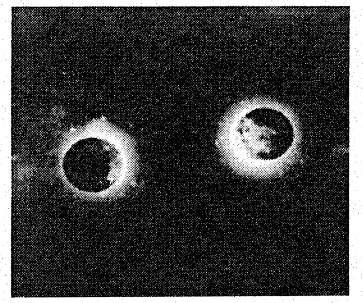
- Gravitational collapse of a massive star to form a Black-hole- Long bursts
- Merger of two compact objects (BH-NS or NS-NS) - Short bursts



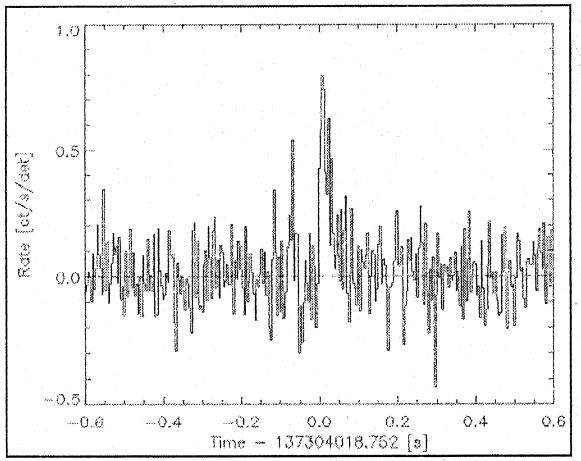


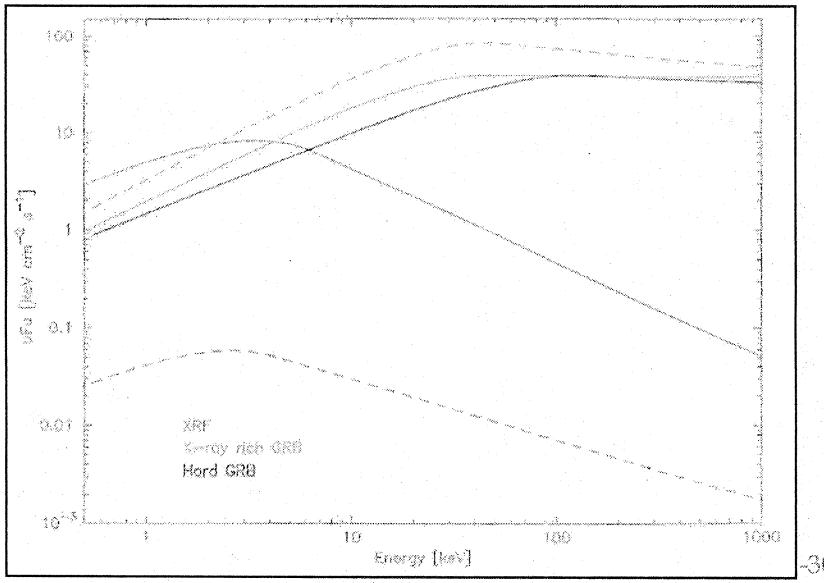


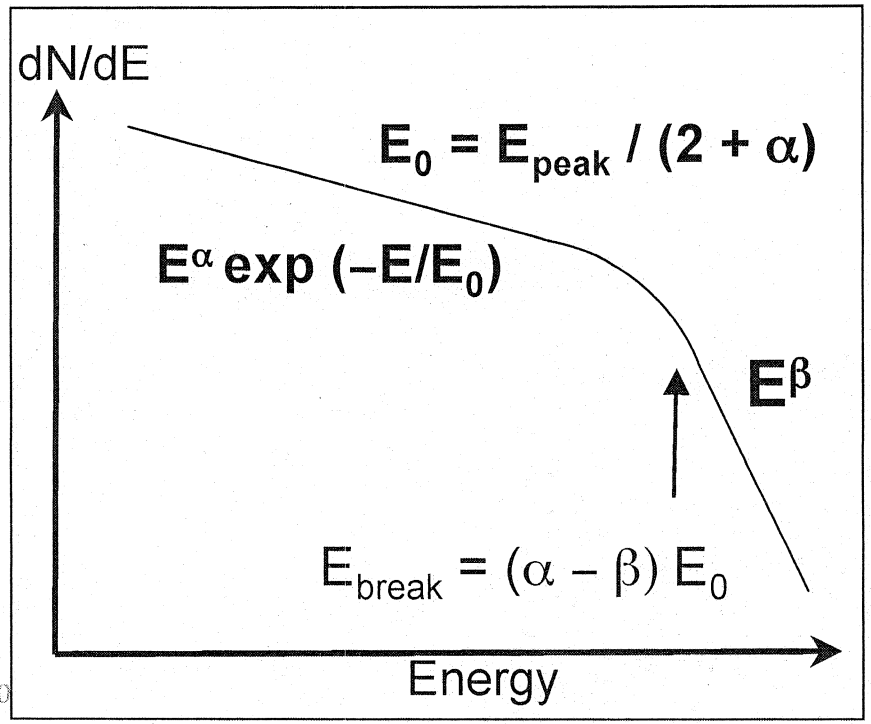
Observed Prompt Properties

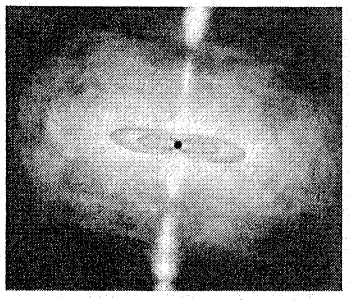


- High variability: ~ms
- Prompt Spectrum:
  - Band Function
- Huge release of energy: 10^{51} erg
- Relativistic process to avoid pair-production opacity paradigm
- Achromatic steepening implies GRB jet

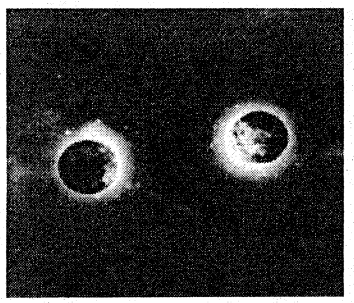




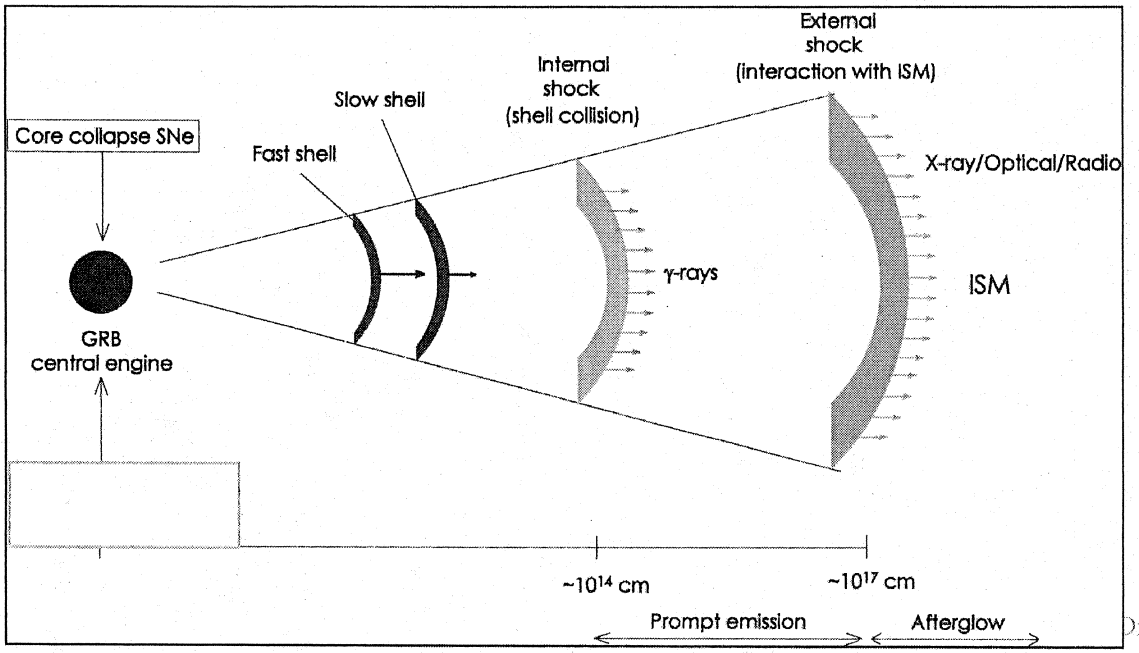


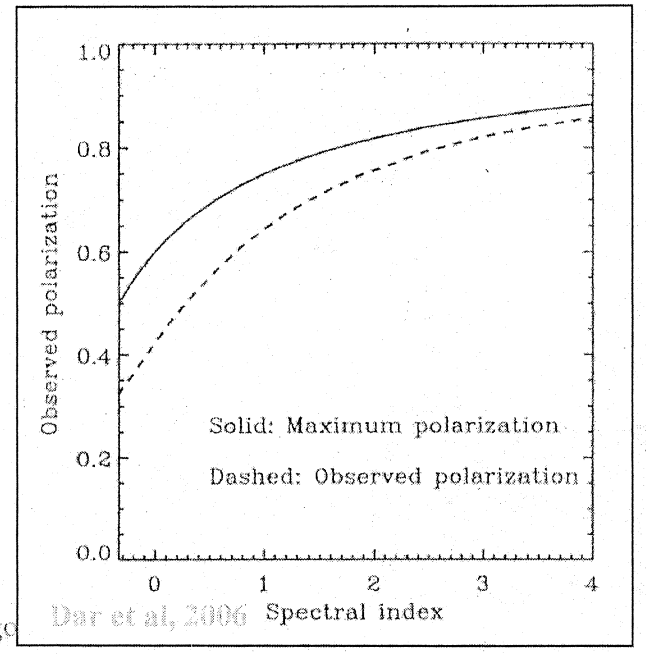


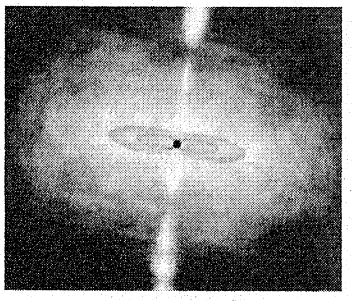
Standard Fireball Model



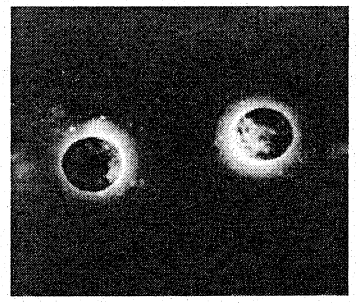
- Explains the afterglow observations well
- Debates for prompt emission on-going
  - Internal shock model solves the rapid variability problem
  - Energy has to be extracted from KE of shells
    - Low efficiency
    - Requires additional mechanisms



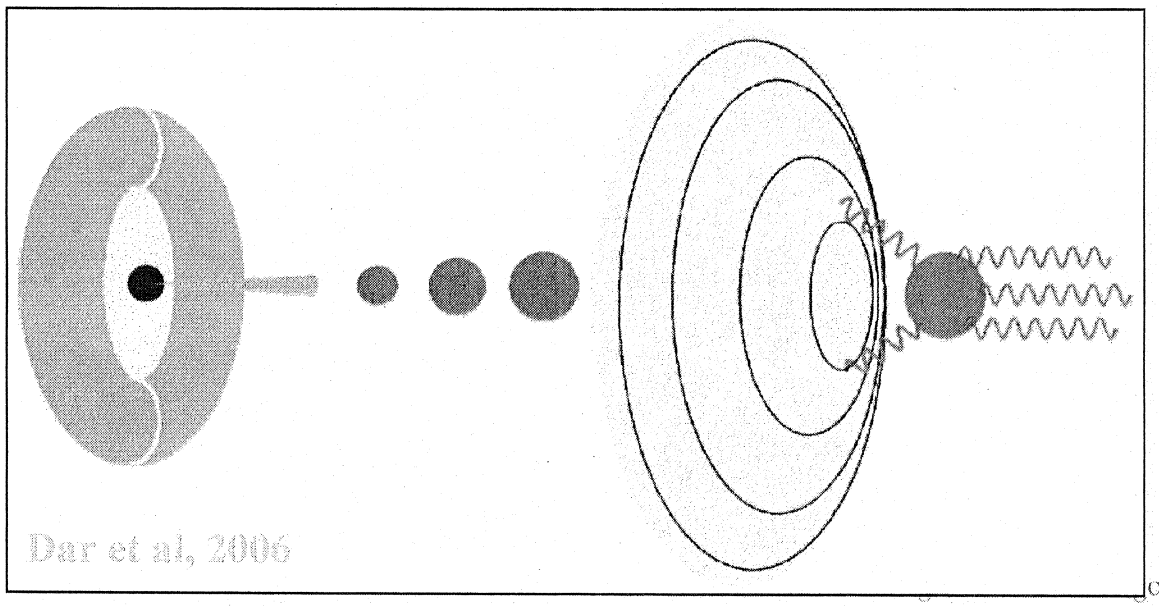


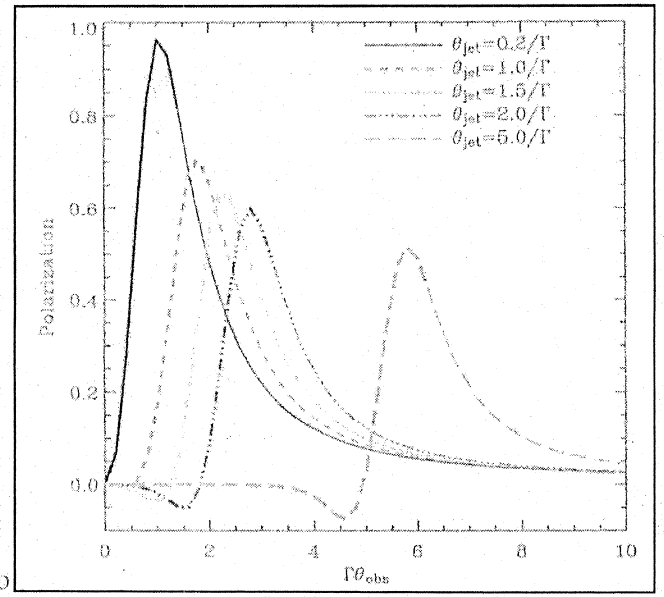


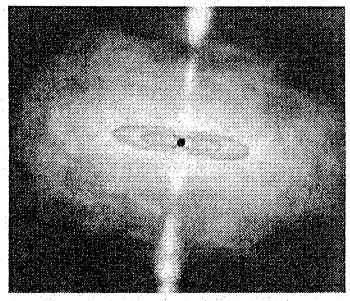
Cannon-ball model



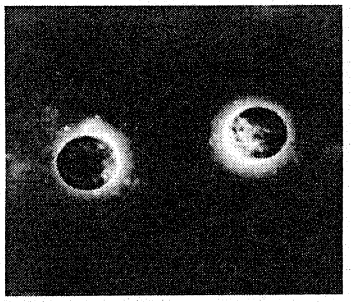
- Cannon balls ejected from central engine
- Inverse Compton scattering of ambient light
- Unclear how the cannon balls would survive acc^{n} over large dynamic range and Lorentz factors



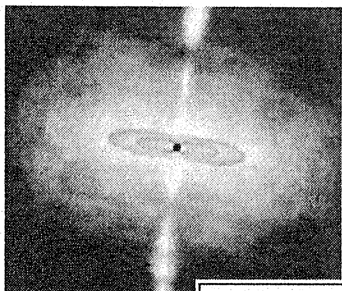




GRB Unknowns

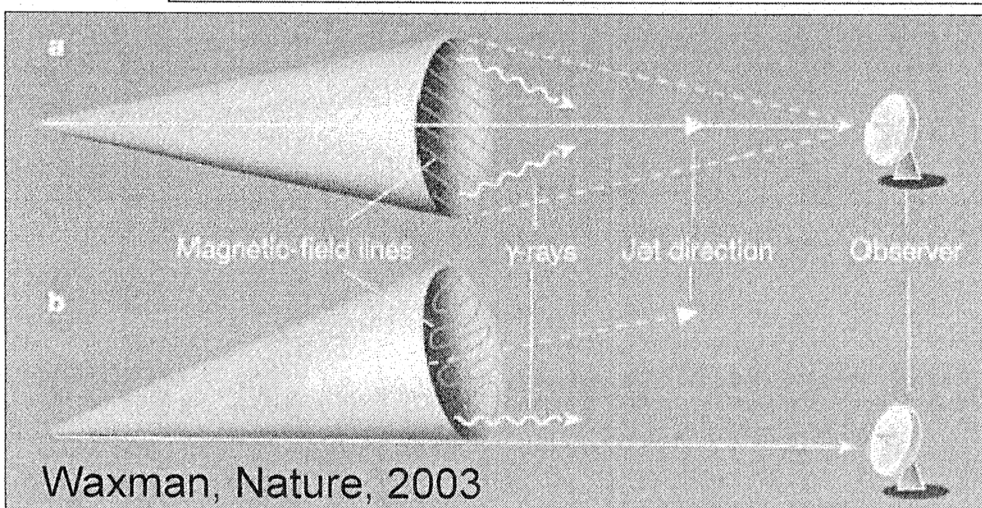


- Unknown Fire Ball content
  - Kinetic Energy or magnetically dominated
- Unknown location of where the prompt emission is produced
  - Internal Shocks - favored
  - External Shocks
- Unknown dissipation mechanism
  - Shocks
  - Magnetic reconnection
- Unknown radiation mechanism
  - Synchrotron
  - Inverse Compton



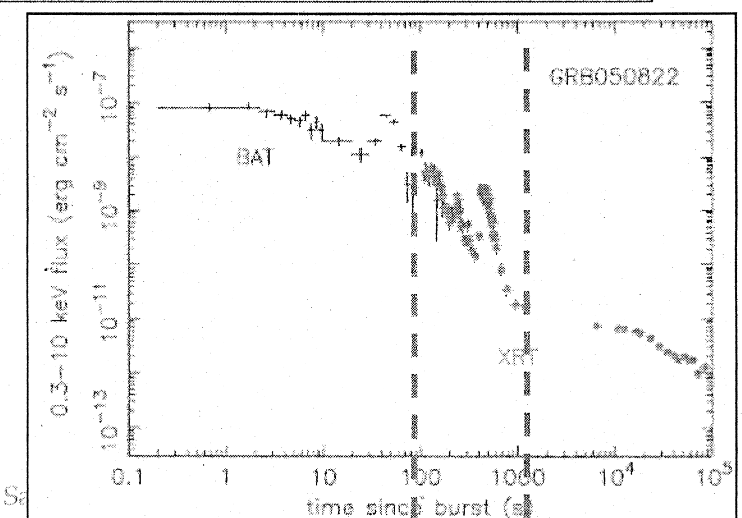
GRB Science - from Polarimetry

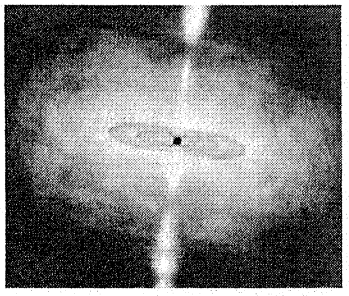
- Discriminating between emission models
- Discriminating between central engine models
- Understanding XRFs, XRR and GRBs
- Understanding
- Determine origin of X-ray flares
- Proof of technology concept for larger missions



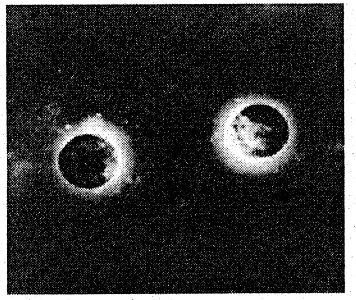
Waxman, Nature, 2003

2007, Sa

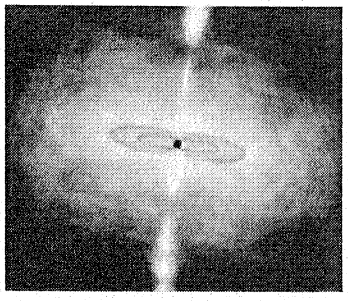


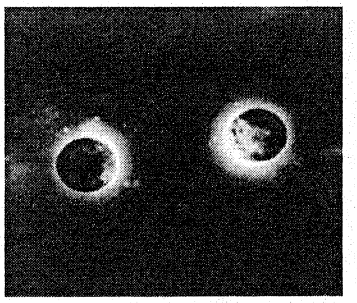


GRB Polarization



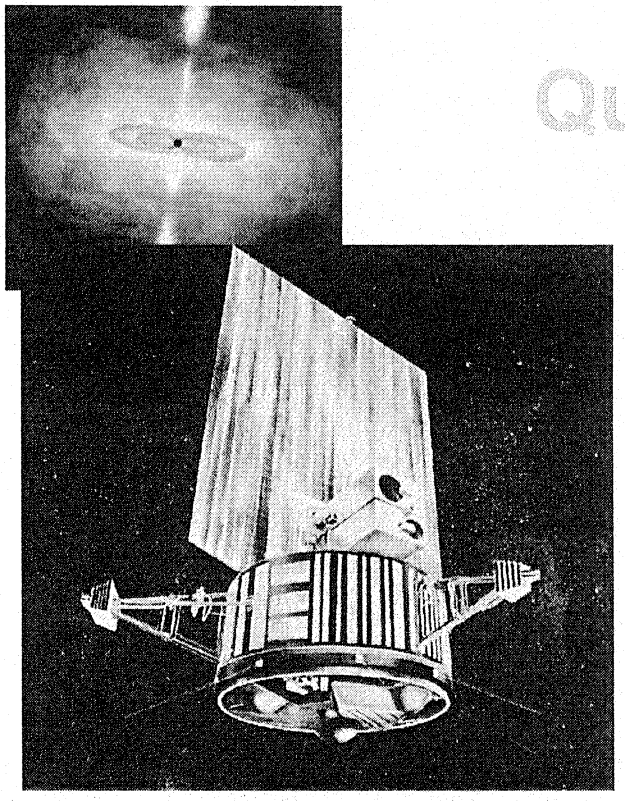
- The theories on the GRB production mechanism can be constrained by different degrees of linear polarization (P):
  - P>80% IC with optimum view
  - P~80% shock accelerated synchrotron emission or a tuned Compton-drag model
  - 20%<P<60% implies synchrotron emission as the dominant source of radiation 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

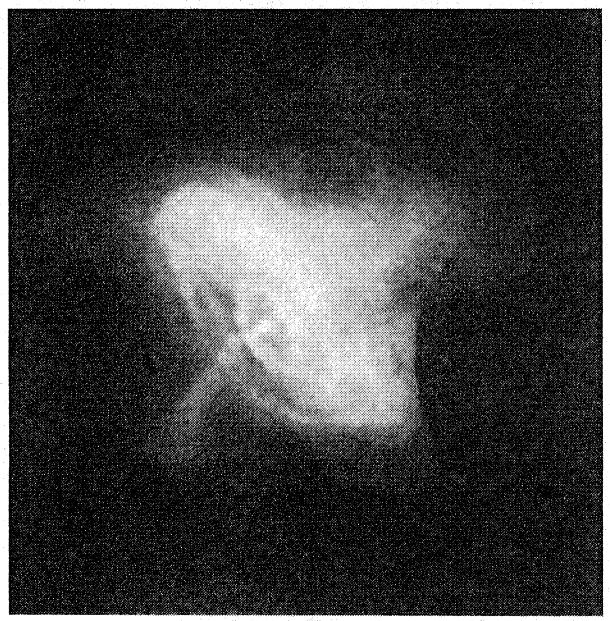




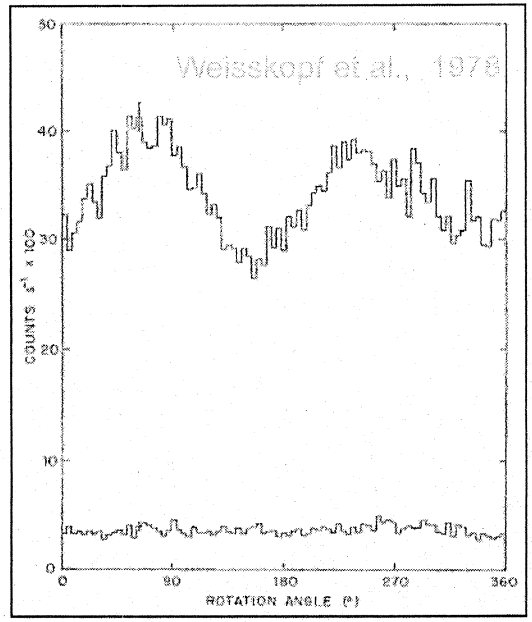
How do we measure it….?

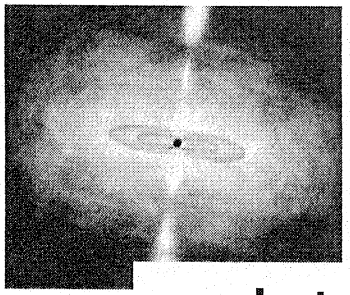
Quest for the holy grail



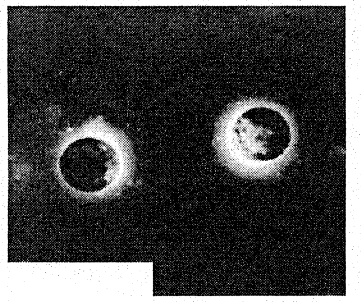


- X-ray polarimetry will be a valuable diagnostic of high magnetic field geometry and strong gravity…..
- One definitive astrophysical measurement (1978) at two energies
  - Weisskopf et al.
  - P=19.2% ±1.0%
  - @ 156°

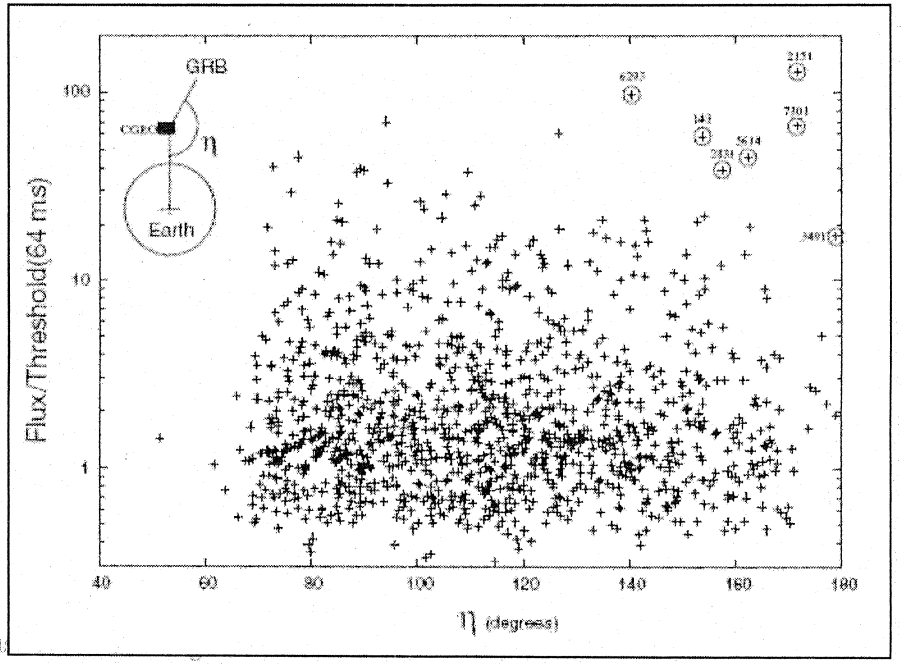


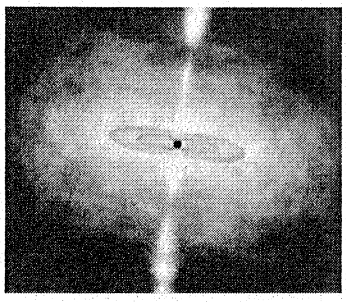


Other Measurements

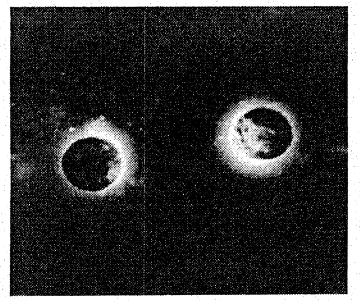


- Intercosmos (Tindo)
  - Solar Flares
- Rhessi (Coburn & Boggs)
  - GRB 021206
- BATSE Albedo Polarimetry System (Willis)
  - GRB 930131 P > 35%
  - GRB 960924 P > 50%
- INTEGRAL (2 groups)
  - 2σ result
  - 98 ± 33%



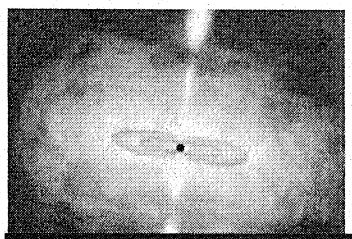


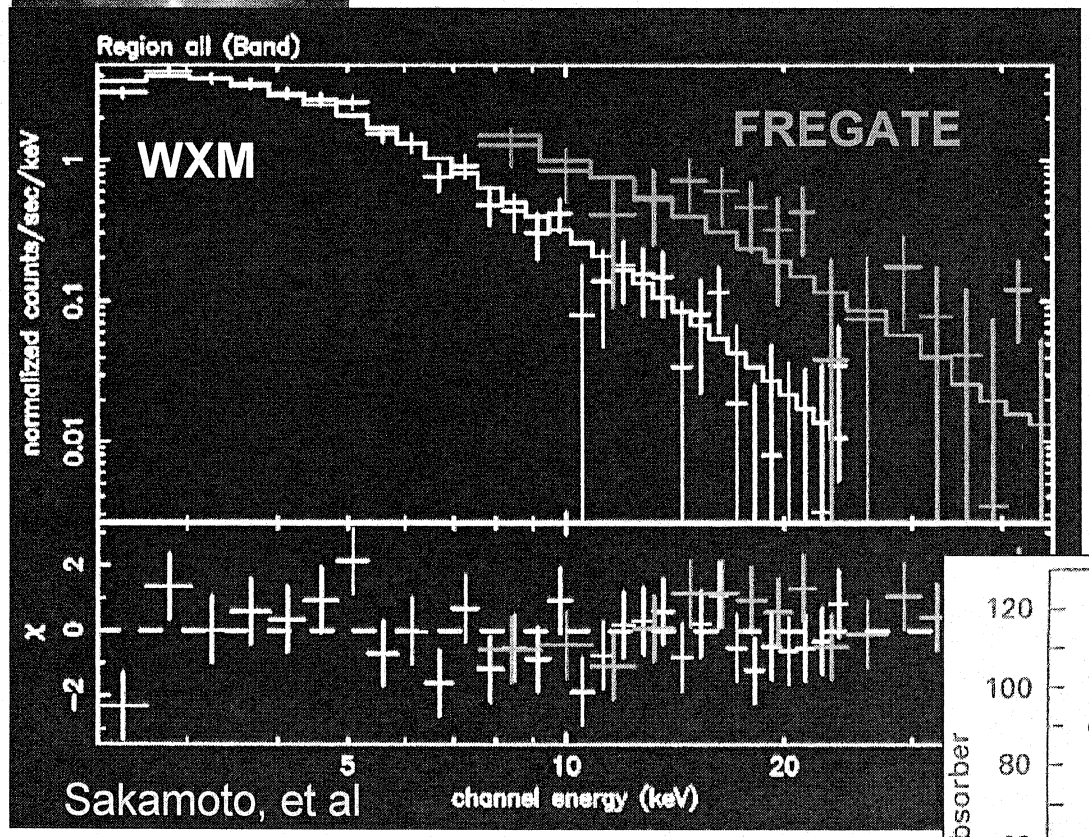
Current Polarimetry Status

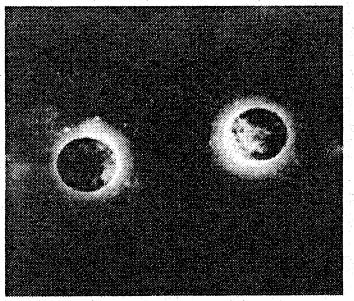


- Recent instruments have not been optimised for polarimetry…
  - …or never launched
- Gazillion papers describing the importance
- Need a way to break the cycle
  - new techniques are lowering the technical barriers

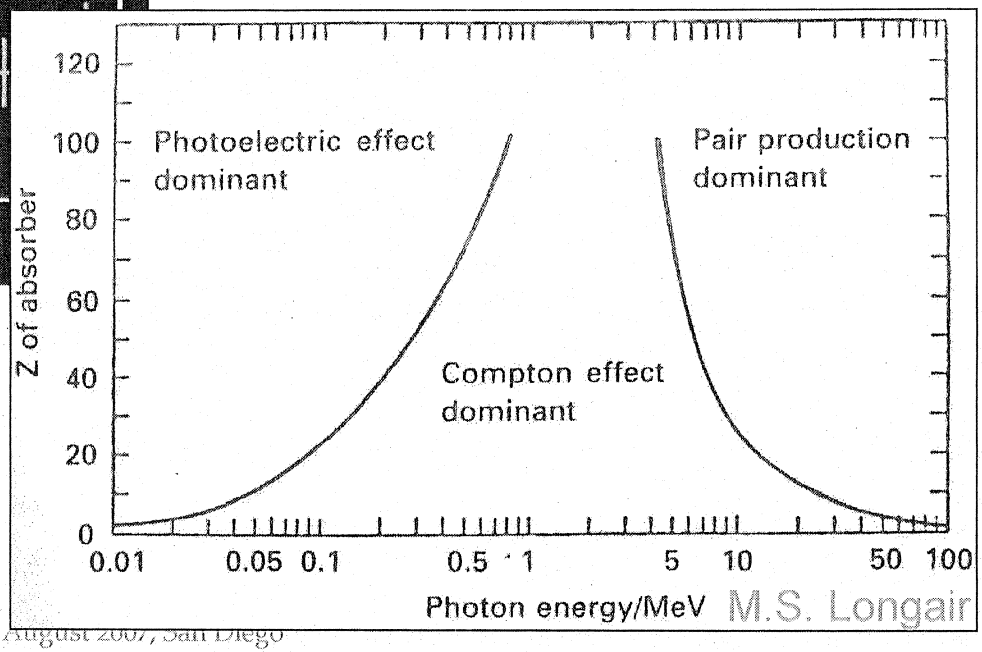
GRB X-ray Emission

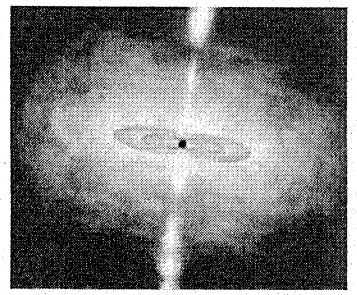






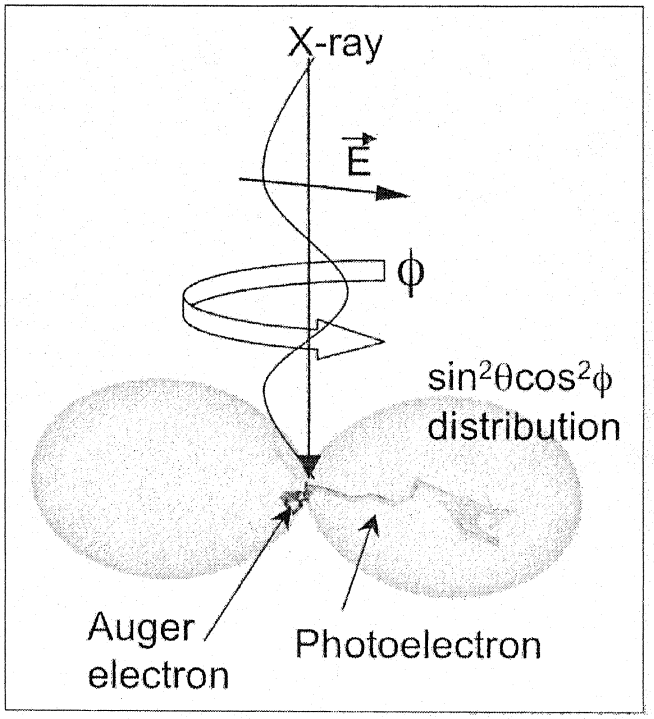
- X-ray is where the photons are!
- Photoelectric effect is dominant process

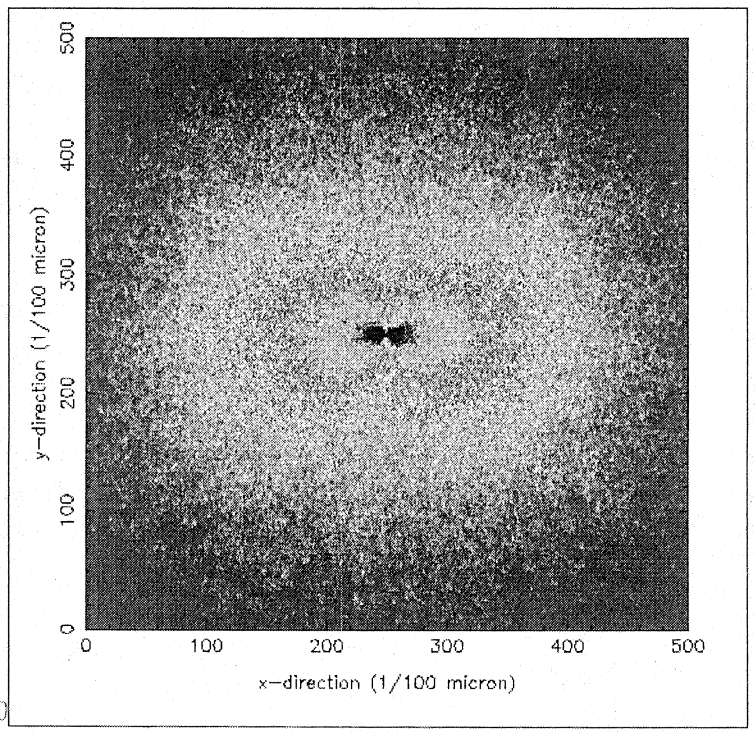


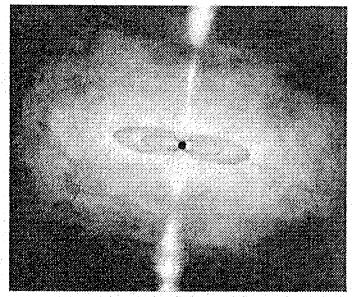


The Photoelectric Effect

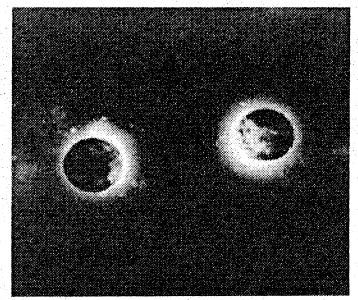
- The photoelectron is ejected with a $\sin^2\theta\cos^2\phi$ distribution aligned with the E-field of the incident X-ray
- The photoelectron looses its energy with elastic and inelastic collisions creating small charge clouds







Polarimeter Figure of Merit



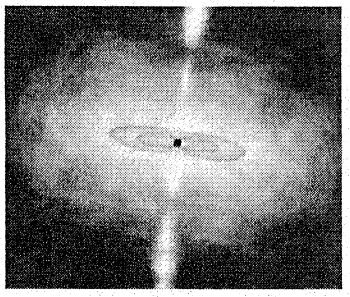
- Polarimeter Minimum Detectable Polarization (apparent polarization arising from statistical fluctuations in unpolarized data):

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

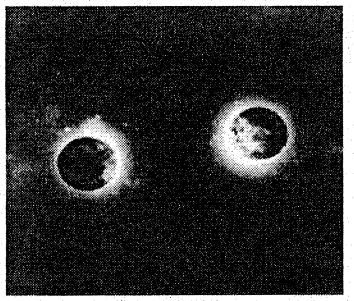
- Polarimeter Figure of Merit (in the signal dominated case):

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

Challenge: High modulation AND high QE

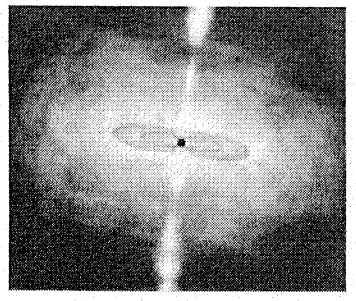


Polarimeter Requirements

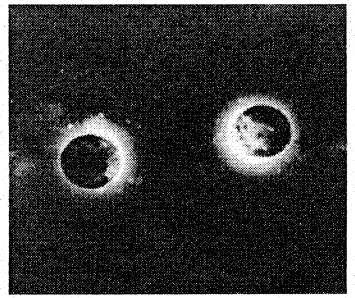


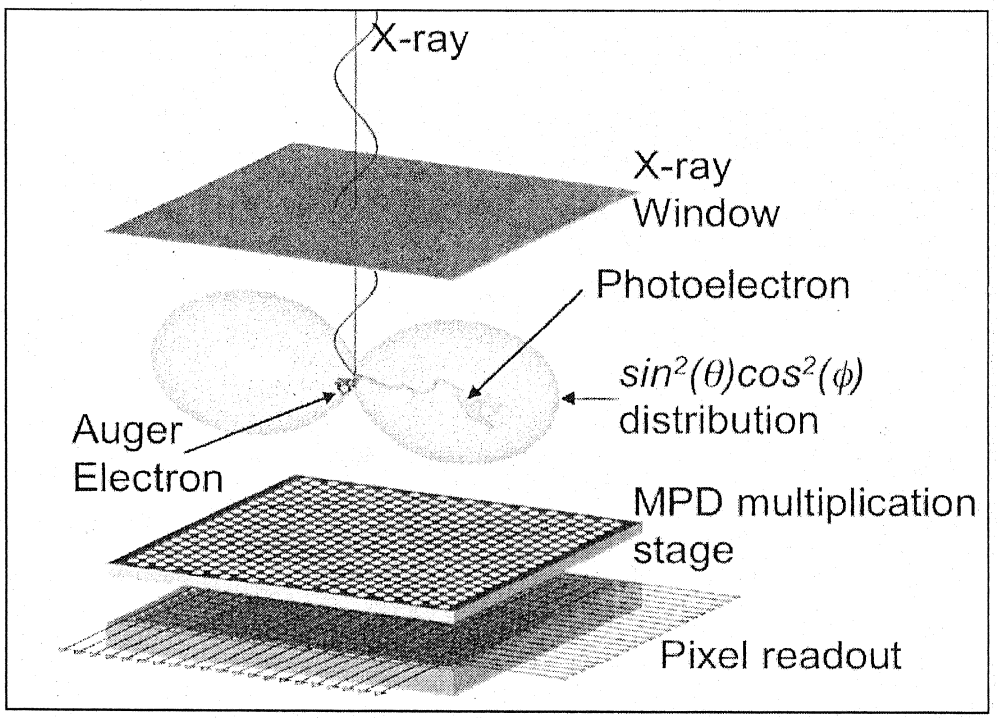
- Challenge: both good modulation and high QE

- Ideal polarimeter is an electron track imager:
  - resolution elements < mean free path
    - **Can only begin to approach this in a gas detector**

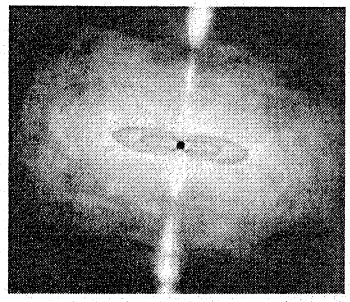


Micropattern Gas Polarimeter

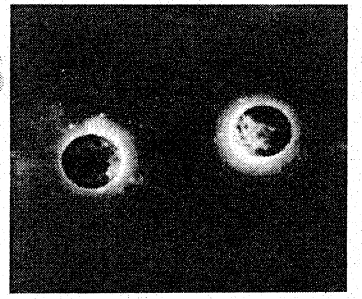




- X-ray interacts in the gas
- K-shell photoelectron ejected
- Photoelectron creates electron cloud
- Electron cloud drifts to cathode
- Electron multiplication occurs between cathode and anode
- Charge collected at the pixel readout

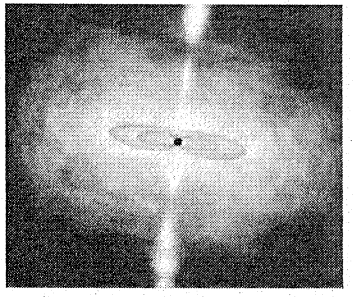


Polarimeter Requirements

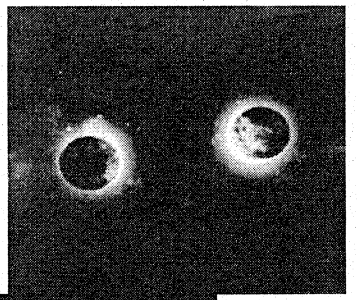


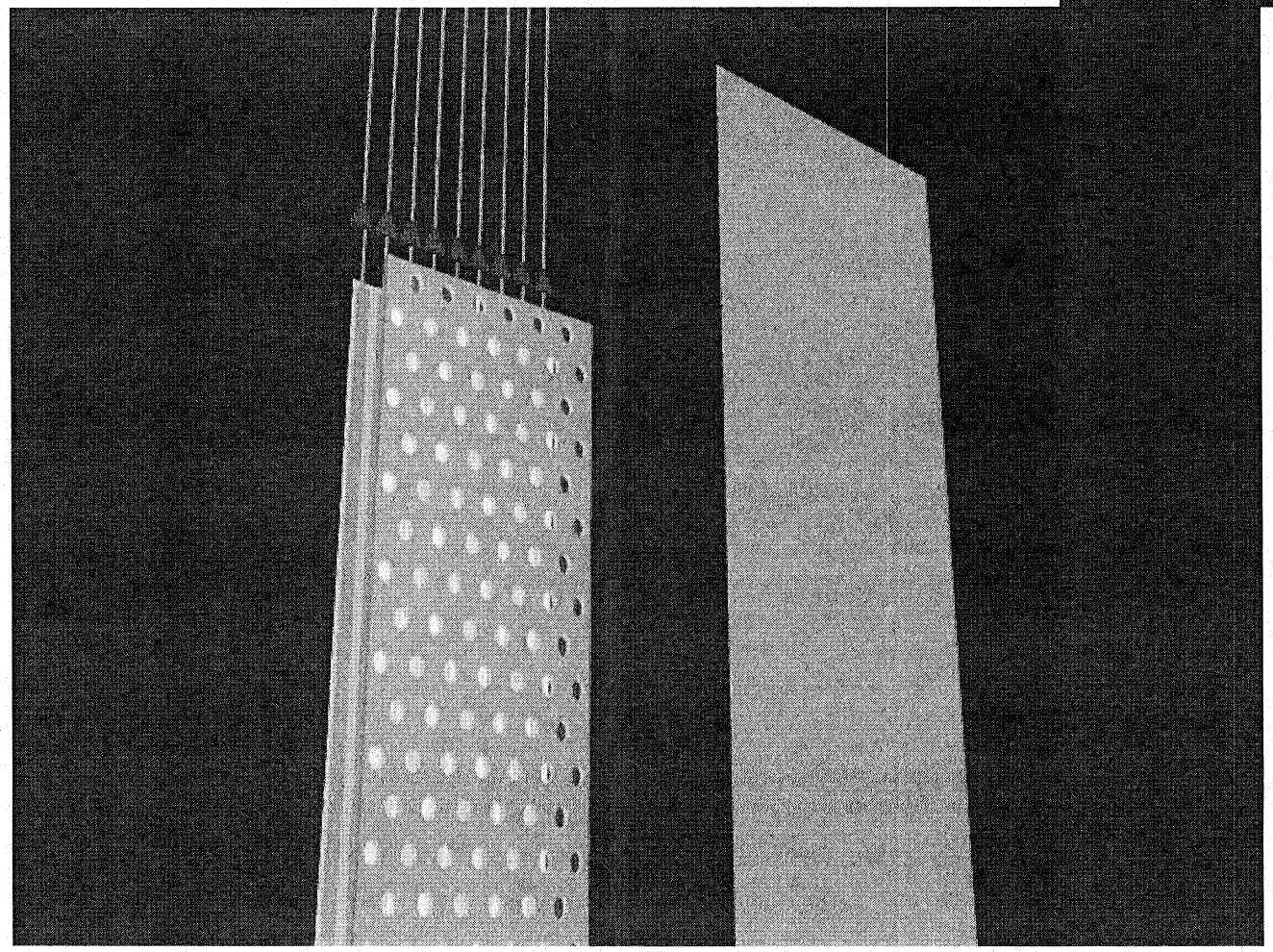
- Challenge: both good modulation and high QE
  - Scattering mean free path ~ 0.1% X-ray absorption depth
  - Electron diffusion in the drift region creates a tradeoff between QE, modulation
- Ideal polarimeter is an electron track imager with:
  - Resolution elements < mean free path
    - => Gas Detector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

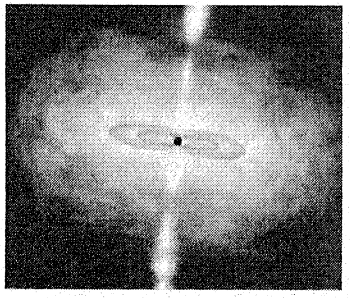
One Solution is TPC Polarimeter



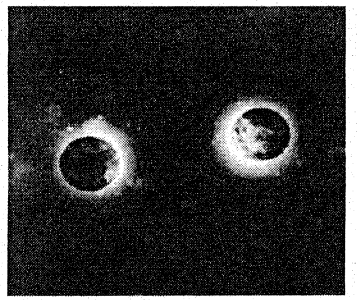
A Time-Projection Chamber (TPC) X-ray polarimeter

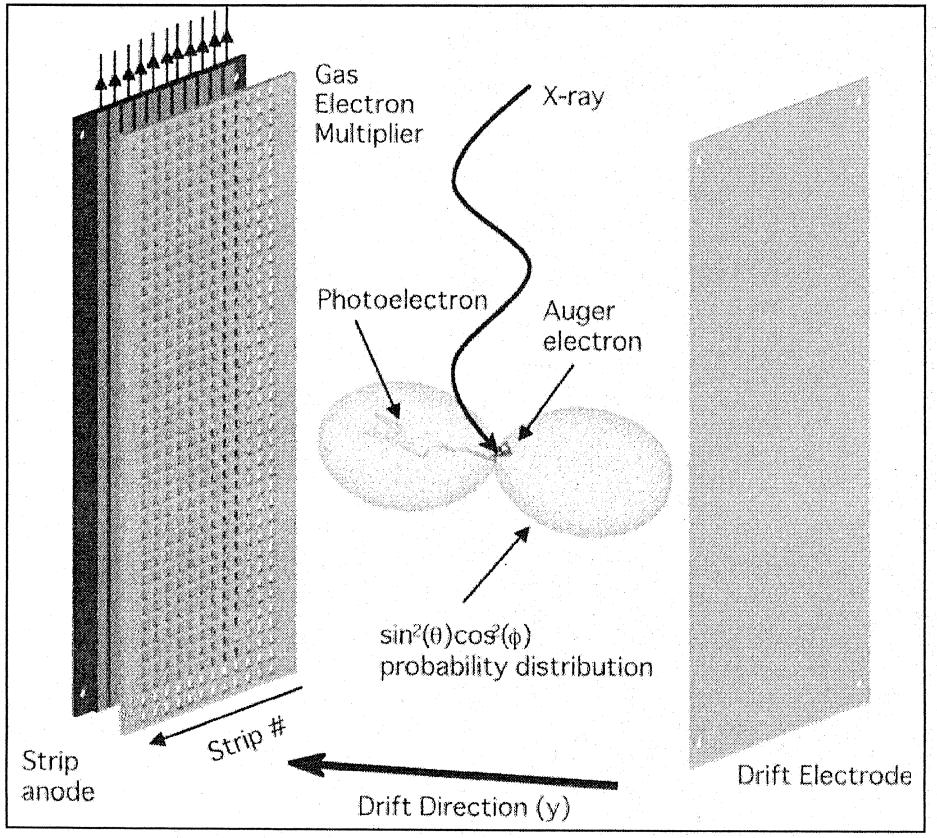




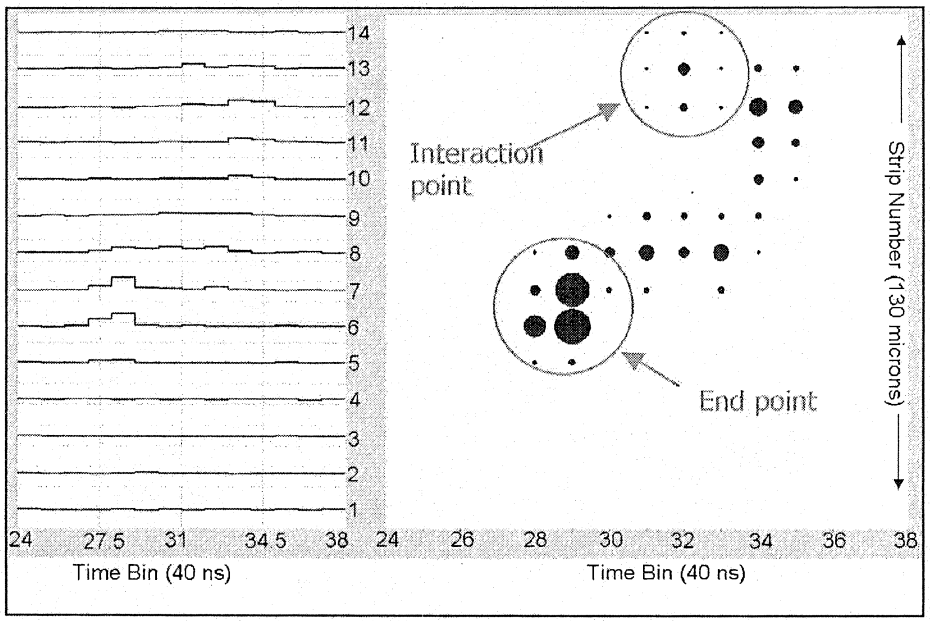


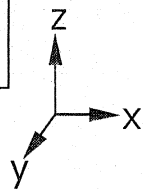
Time-Projection Chamber Polarimeter

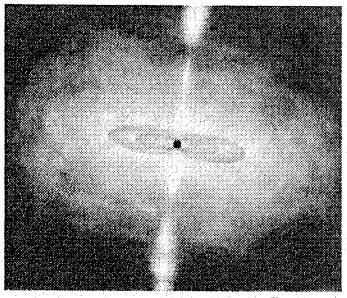




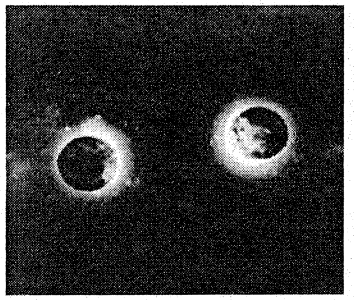
Charge pulses arriving at the strips



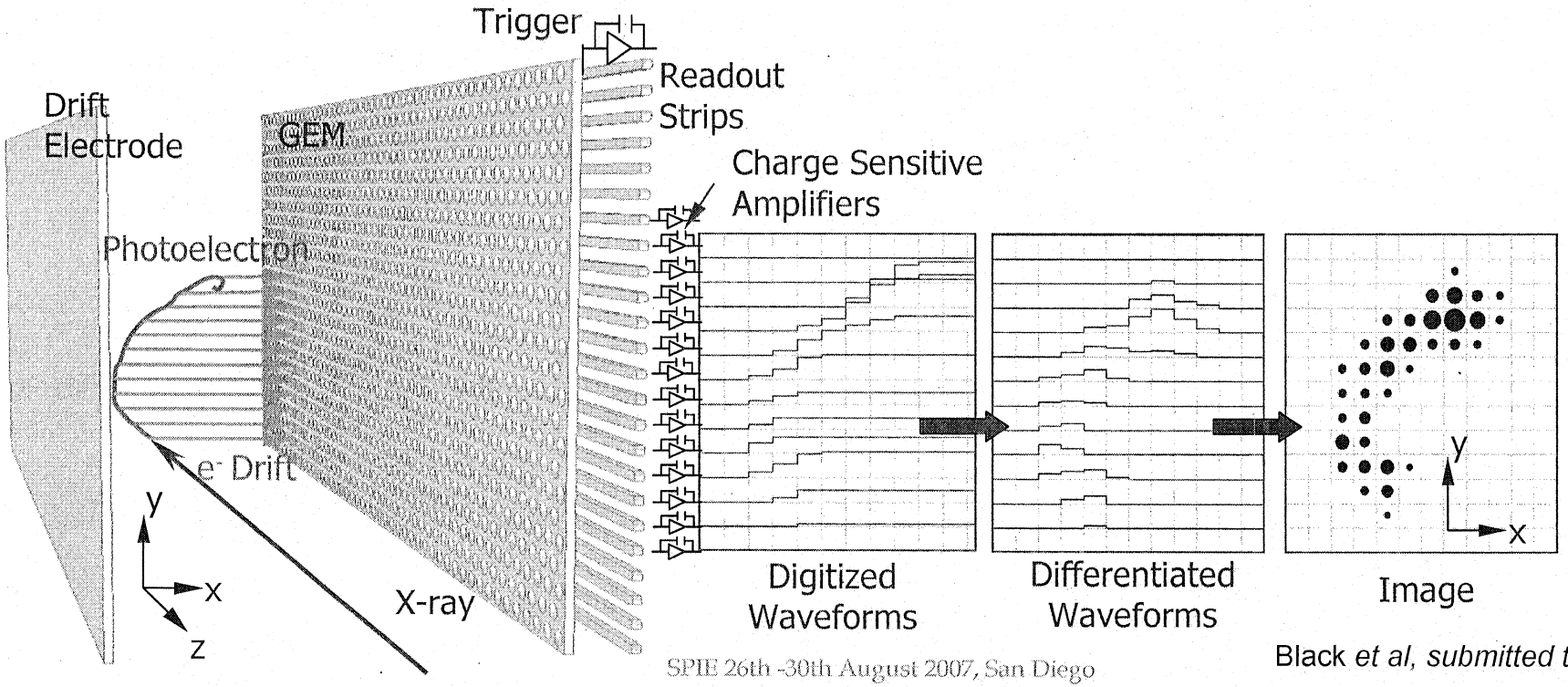




The TPC Polarimeter



- 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



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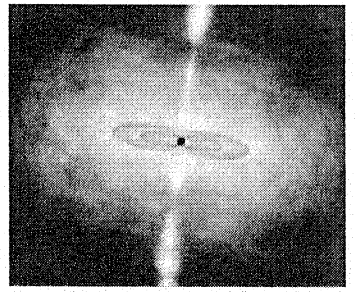
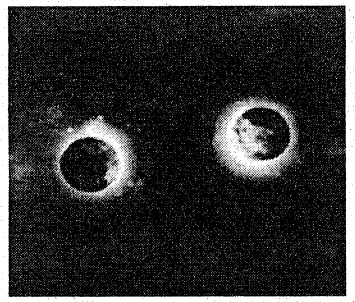


TPC Trade-offs

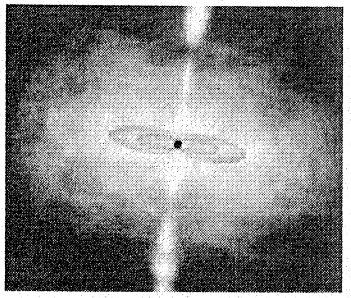


Pros

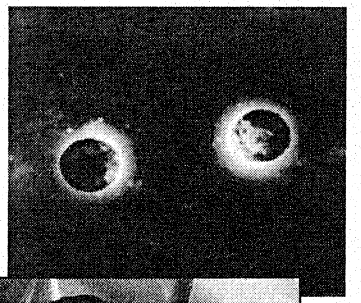
1. Potential for 100% quantum efficiency
2. Simplicity of construction
3. Geometry enables multiple instrument concepts

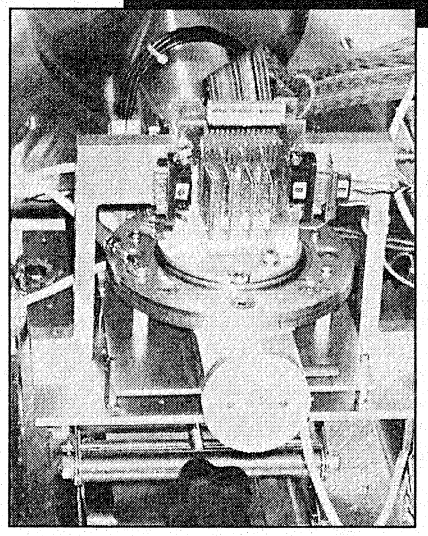
Cons

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

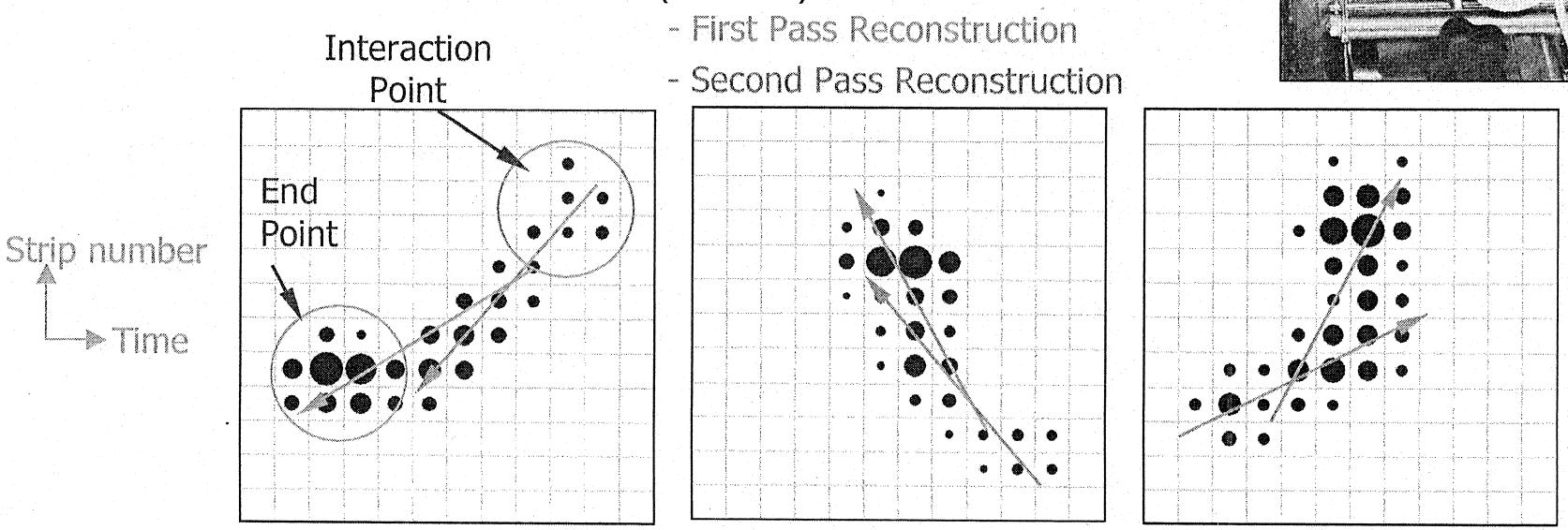


Prototype TPC polarimeter

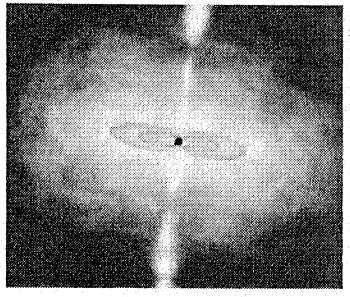




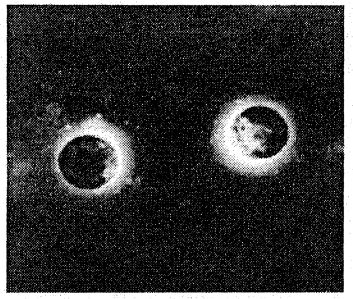
- Made from off-the-shelf components:
  - 130 μm pitch
  - 13mm(w) x 30mm(d) active area
  - 24-channel ADC
  - Drift velocity: 40 nsec bin = 130 μm
  - 460 Torr Ne:DME (50:50)



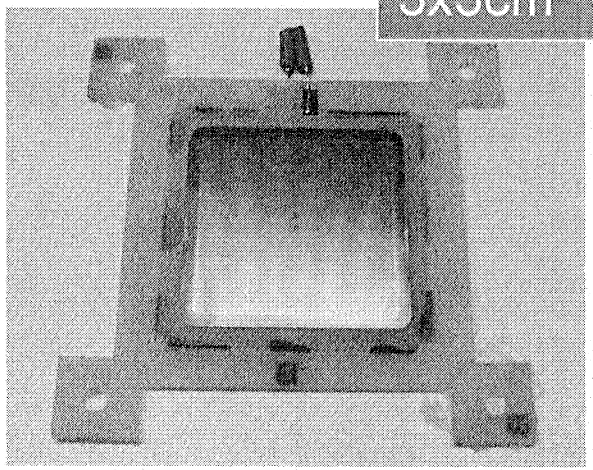
Reconstructed 6.4 keV track images



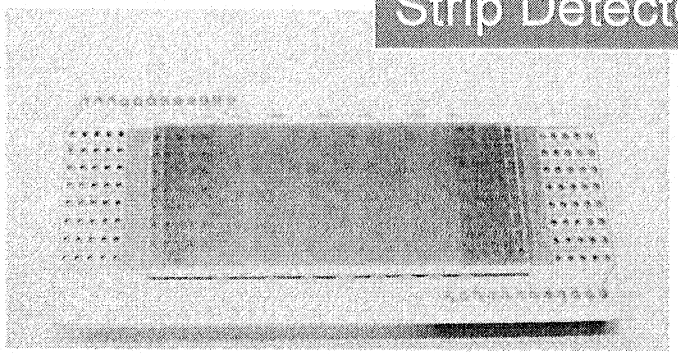
Prototype TPC polarimeter

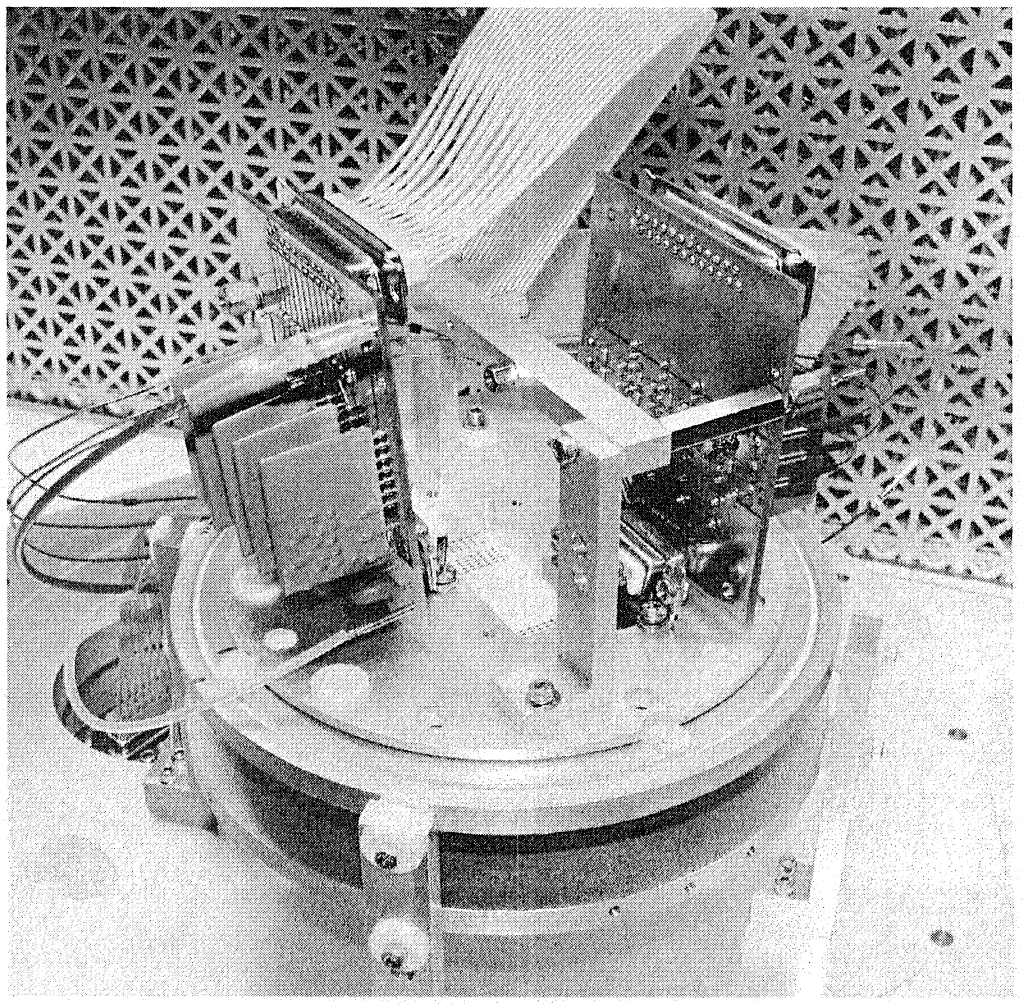


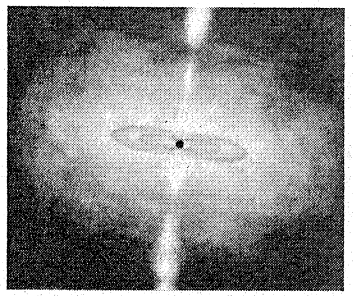
3x3cm^2 GEM



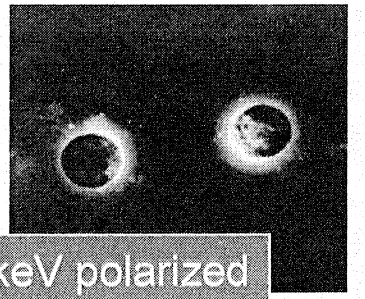
Strip Detector





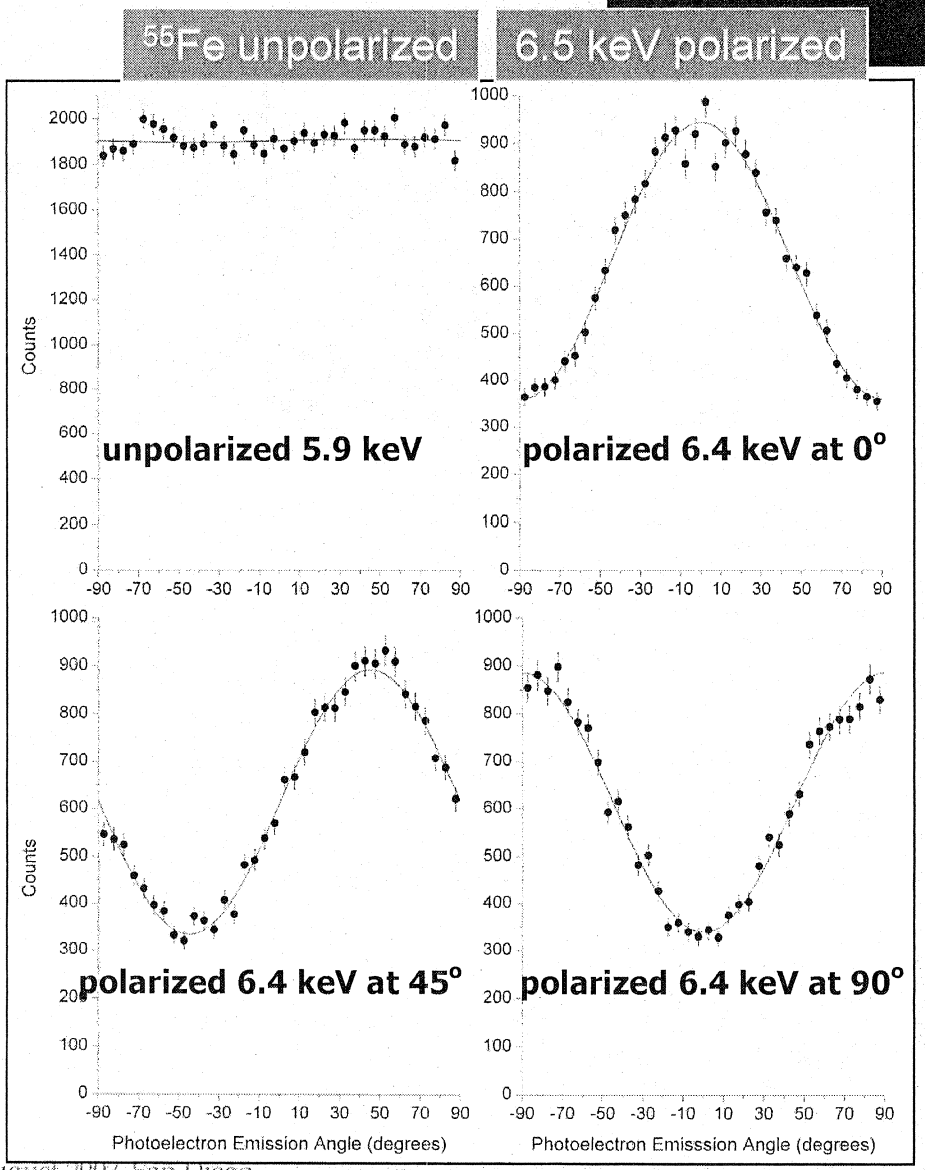


Prototype TPC Polarimeter Results



Polarization Phase	Measured Parameters		
	Modulation (%)	Phase (degrees)	χ_ν^2
unpolarized	0.49 ± 0.54	44.6 ± 28.7	1.2
0°	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 consistent with gas pixel detectors
- Unit QE possible



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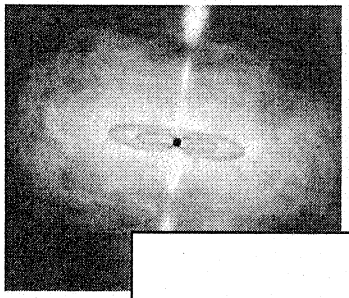
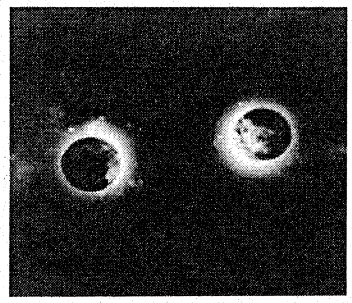
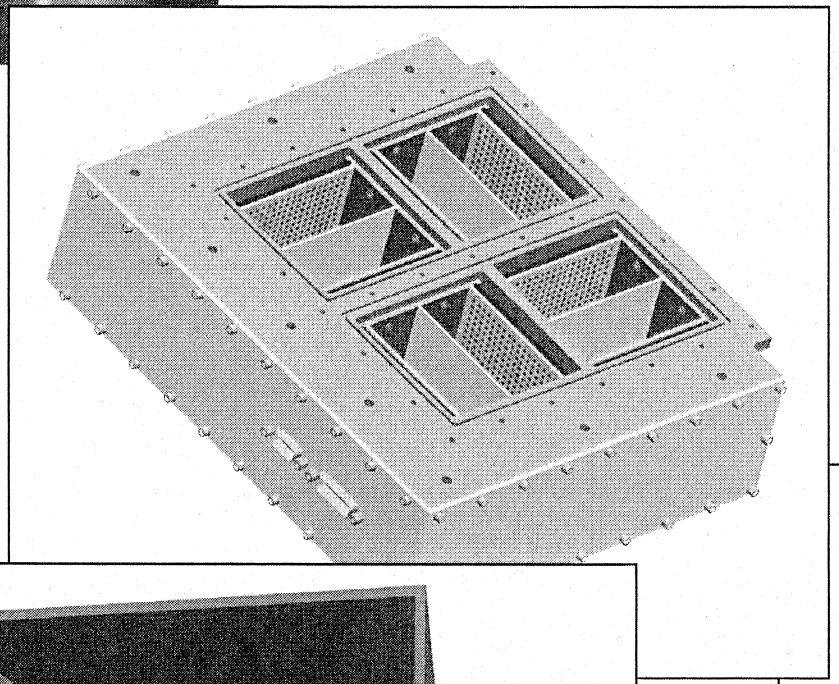
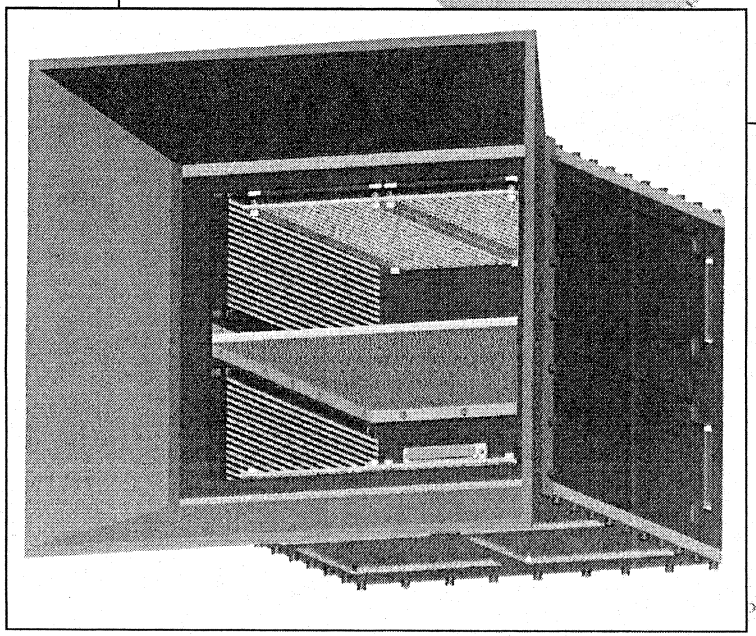


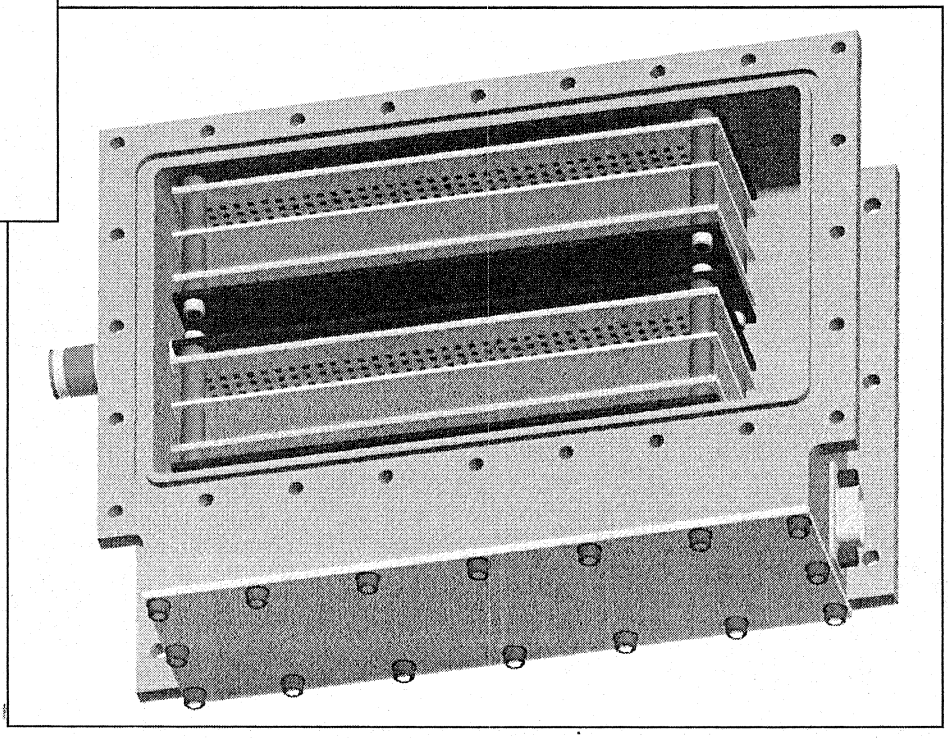
Wide field-of-view GRB polarimeter

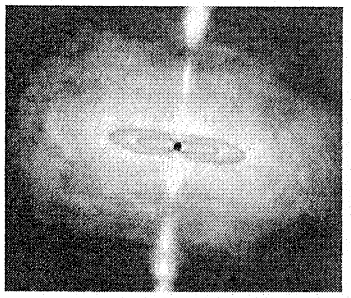




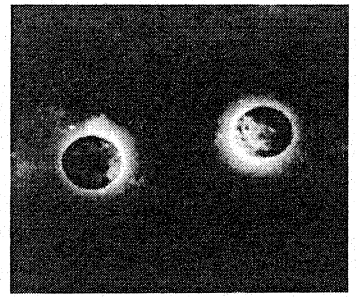
Enables large volume detectors with wide of view



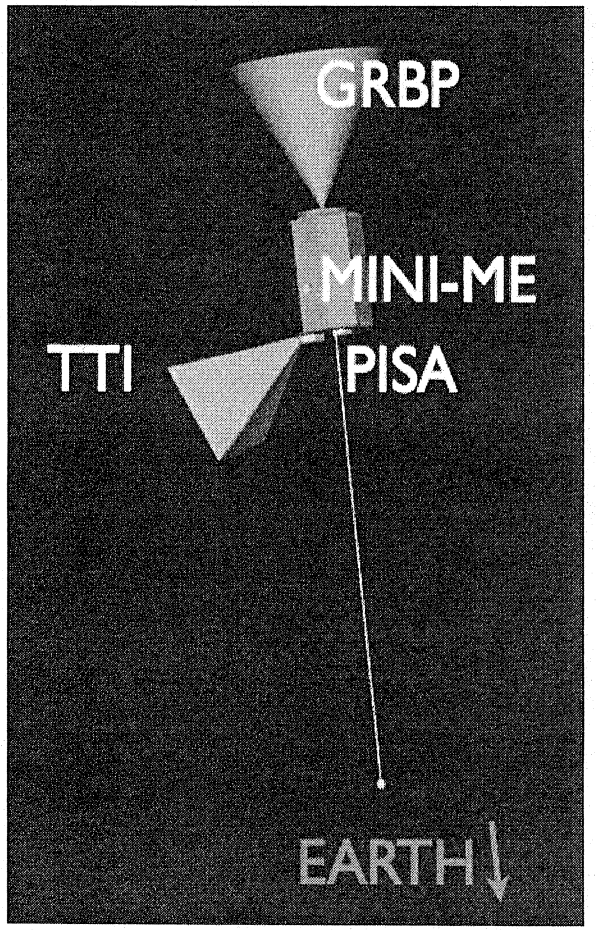


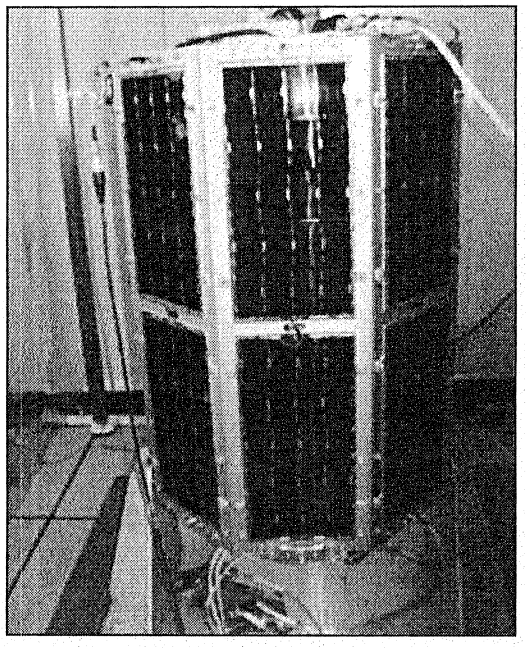


MidSTAR-2



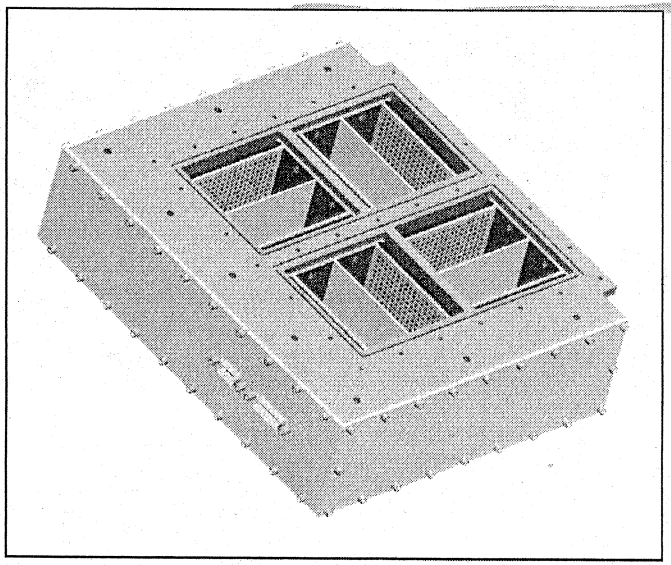
- USNA Project
- High risk Low-cost
- Make a scientific measurement
  - Several GRBs in 2 yr lifetime
- Low cost proof-of-concept
- Launch ~2011



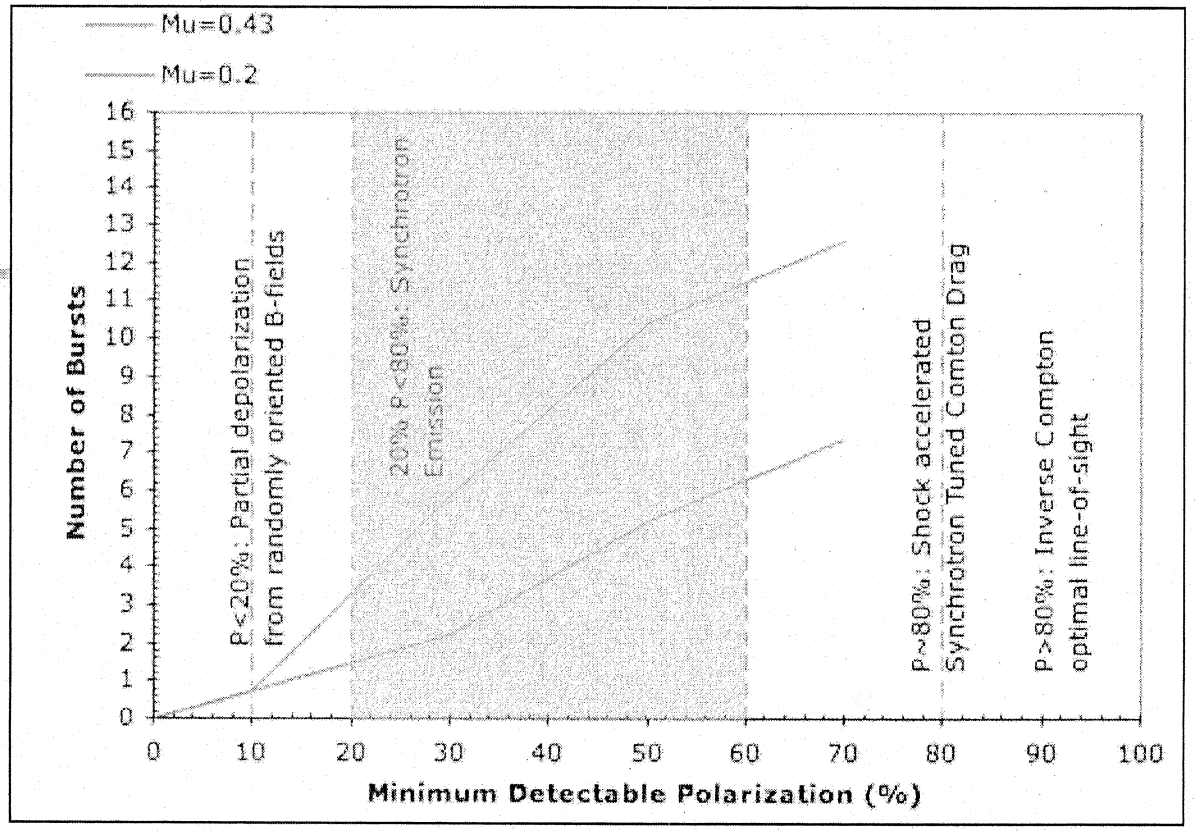


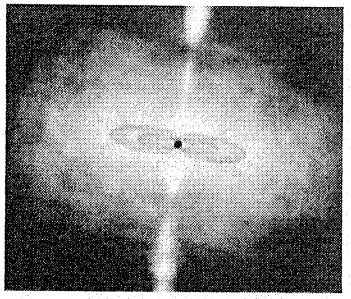
The GRBP: A payload for MidStar 2

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

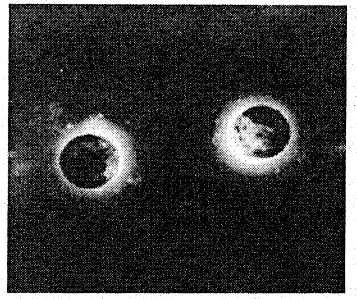


MDP averaged from 2 - 10 keV



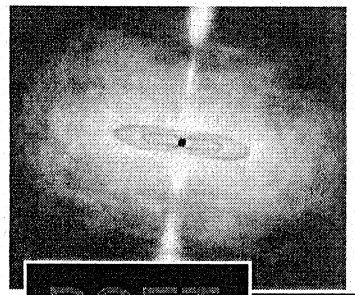


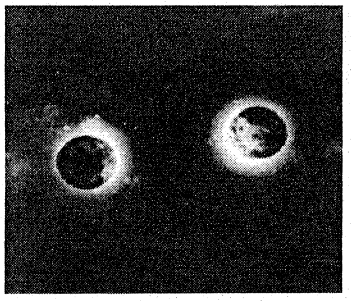
The GRBP: A payload for MidStar 2

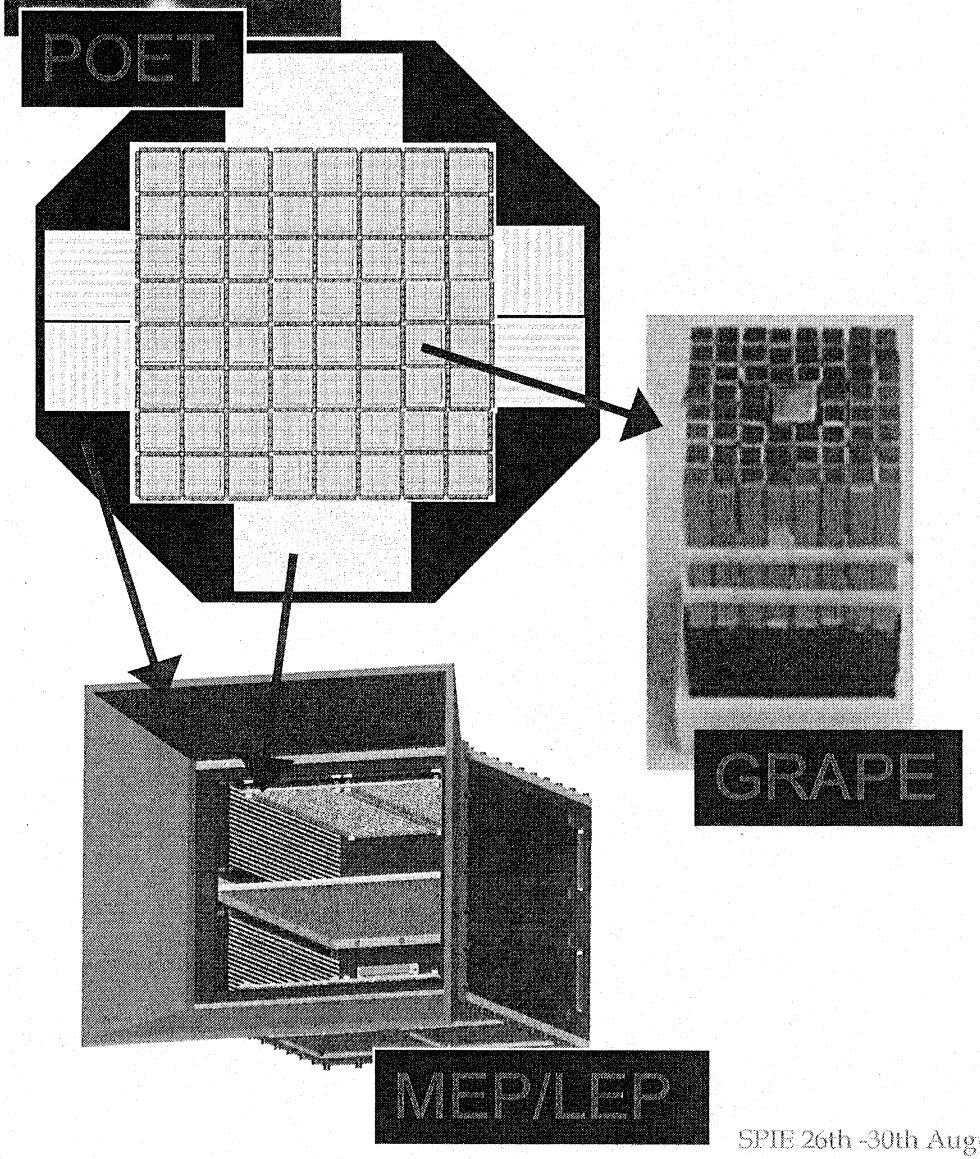


- MidStar offers dual opportunities:
  - Space qualify a new technology
  - Measure the polarization of several Gamma-Ray bursts
- Proposed experiment is sized:
  - To provide an excellent chance of qualifying technology
  - To provide reasonable chance of exciting scientific result

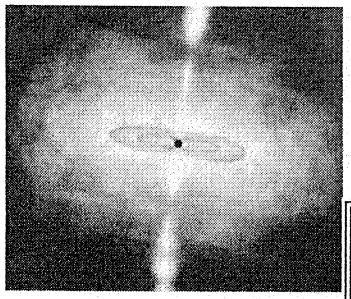
POET: POlarimeters for Energetic Transients



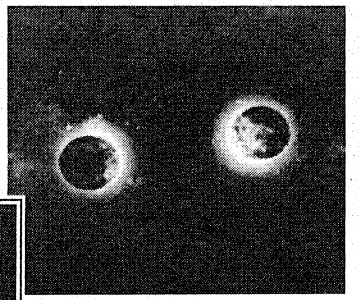




- UNH - PI Mark McConnell
- UNH - GRAPE:
  - 50-300 keV
  - Compton Scatter
- USRA/GSFC - LEP:
  - 2-10 keV
  - Photoelectric
- USRA/GSFC - MEP:
  - 15-30 keV
  - Photoelectric



POET: GRB Science



Mission Statement:

only

First definitive high E polarization measurements of transient sources.

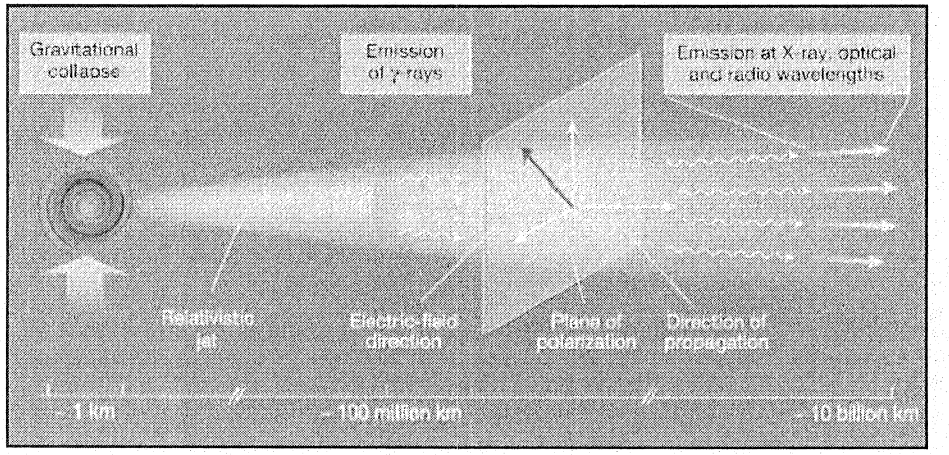
> 50 transient sources/year

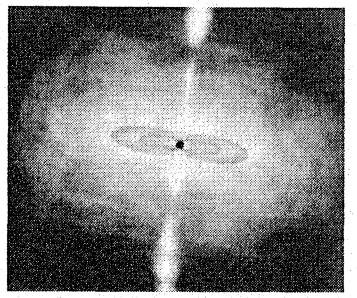
- Broadband Polarimetry
- Broadband Spectra: 2-300 keV
- Rapid Timing: msec
- Position: 3 deg

Sources: GRBs, Solar Flares, Magnetar Super Flares, SGRs.

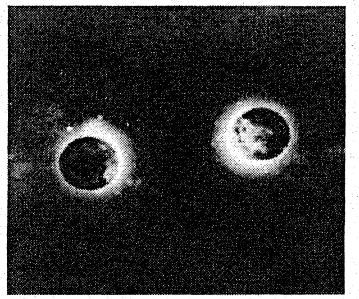
Dual band polarization measurements of bright persistent sources.

What is the composition of GRBs?
What is the prompt emission radiation mechanism?
What is the small-scale geometry of the prompt emission region?





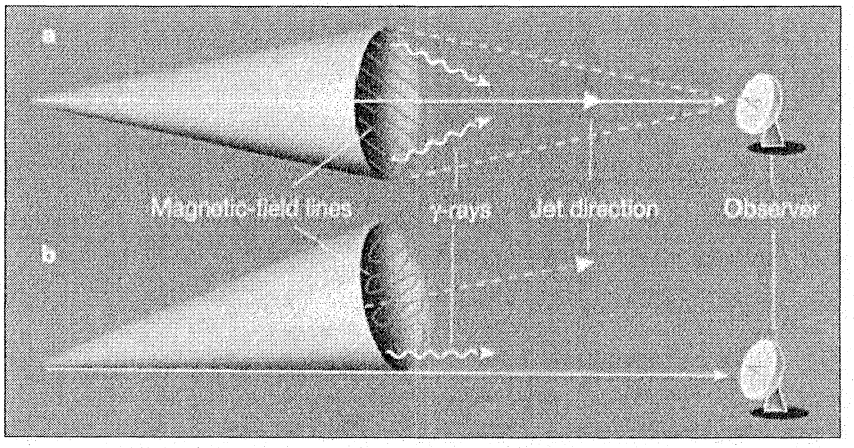
POET: GRB Science

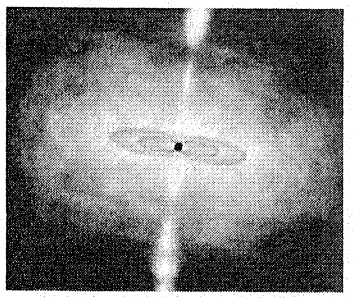


Theories on the GRB production mechanism can be constrained by different degrees of linear polarization (P):

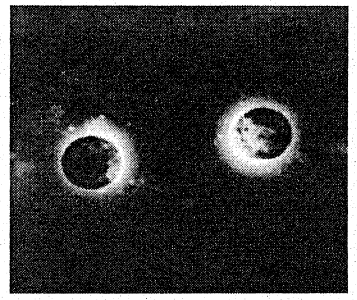
- P>80% IC with optimum view.
- P~80% shock accelerated synchrotron emission or a tuned Compton-drag model.
- 20%<P<60% synchrotron emission is the dominant source of radiation or viewing the burst from just out-side the edge of the jet.
- Low degrees of polarization: flux with a high degree of polarization experiencing partial depolarization, e.g. electrons in a randomly orientated magnetic field.

LEP		GRAPE	
GRBs	MDP	GRBs	MDP
21	10%	12	11%
60	30%	86	23%
72	50%	124	51%

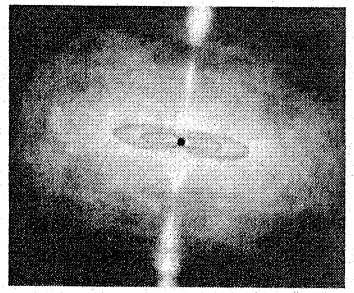


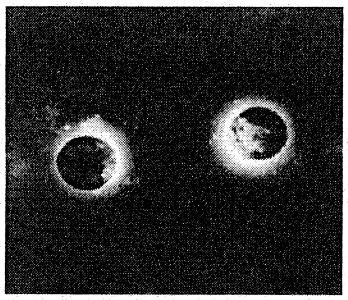


Further Work



- In-situ drift velocity calibration and monitoring
  - Feedback into algorithm
  - On-orbit
- Large area GEMs
- Background simulations
  - X-rays
  - Charged-particles
- http://astrophysics.gsfc.nasa.gov/xrays/inst/polarimetry/index.html





Future looks bright for X-ray Polarimetry!!!