Prospects for X-Ray Polarimetry and its Potential Use for Understanding Neutron Stars

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- M. C. Weisskopf (NASA/MSFC)
- D. Hanna (McGill U)
- S. L. O'Dell (NASA/MSFC)
- B. D. Ramsey (NASA/MSFC)
- R. F. Elsner (NASA/MSFC)
- V. M. Kaspi (McGill U)
- G. G. Pavlov (Penn State U)

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Outline

- Scientific case
- Brief history
- Techniques
- Statistics
- With X-ray telescopes
- Without X-ray telescopes
- Concluding remarks

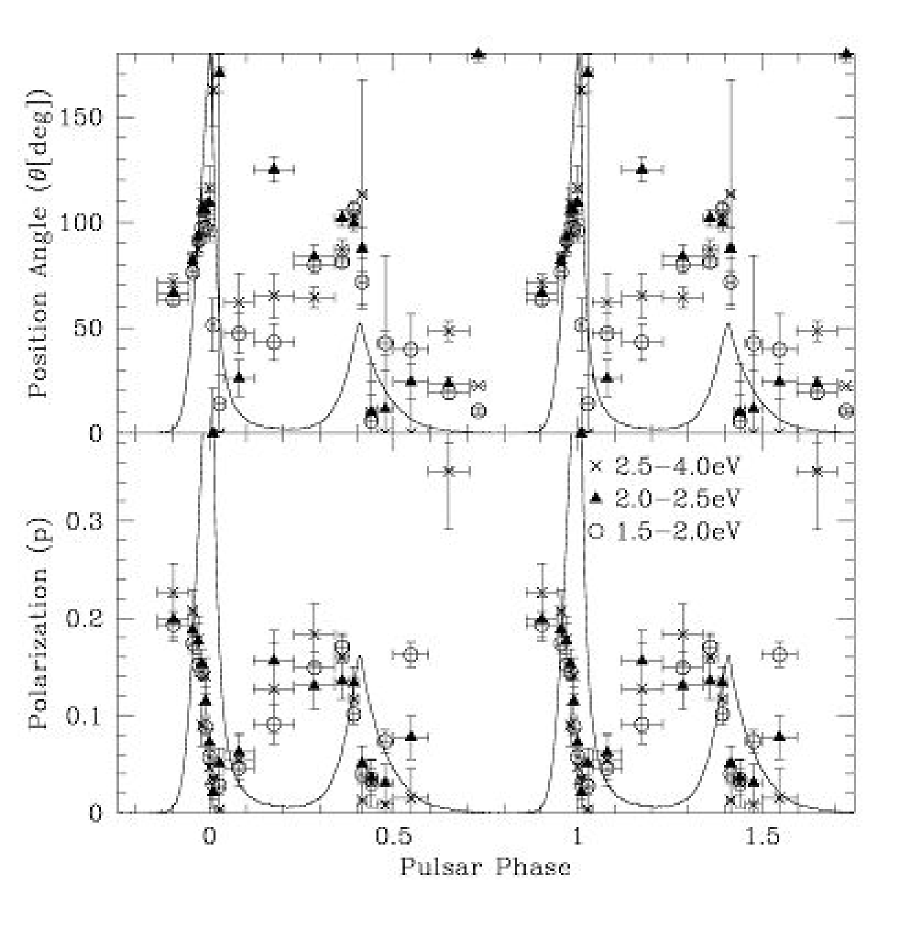
“Telescope” & “Polarization”

“telescope” implies the use of grazing-incidence, focusing optics.

“polarization” implies linear polarization

Radio Pulsars

Radio Pulsars convert rotational energy to ultrarelativistic-particle energy and radiation. Electromagnetic cascades in the very strong magnetic fields result in a rotating beam of relativistic particles and radiation.



Romani et al. (2001)

Magnetars & DINS

AXPs and **SGRs** convert magnetic stress ultimately into high-energy radiation and outflow. Interesting QED effects occur in the extremely strong magnetic fields thought to be present.

- Vacuum birefringence ⇒ "vacuum resonance"

$$n_{\|}(B,\vartheta) \approx 1 + \frac{\alpha}{4\pi}\sin^2\vartheta \langle \frac{14}{45}(\frac{B}{B_{cr}})^2 - \frac{13}{315}(\frac{B}{B_{cr}})^4 \rangle$$

$$n_{\perp}(B,\vartheta) \approx 1 + \frac{\alpha}{4\pi}\sin^2\vartheta \langle \frac{8}{45}(\frac{B}{B_{cr}})^2 - \frac{379}{5040}(\frac{B}{B_{cr}})^4 \rangle$$

$$B_{cr} = m^2c^3 / e\hbar \approx 4.4 \times 10^{13} G$$

"Dim" Isolated Neutron Stars (DINS) are radio-quiet and non-accreting, exhibiting predominantly thermal emission from the neutron-star surface.

Binaries

Pulsating X-Ray Binaries channel and convert kinetic energy into X-ray emission at the stellar surface. Rotation and accretion-flow anisotropy in strong magnetic fields modulate the X radiation.

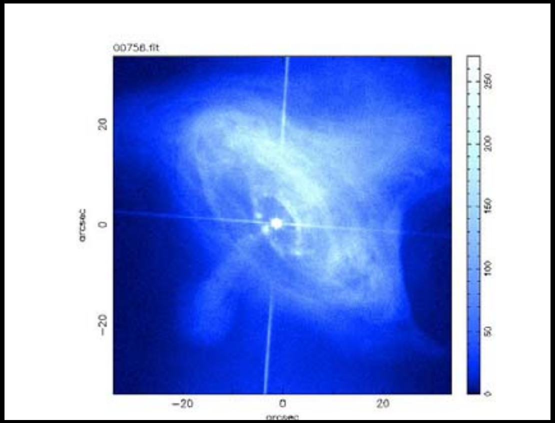
Accretion-Disk Systems convert kinetic energy into X-ray emission in the disk around the neutron star (or black hole). Here polarization results mainly from scattering.

Brief History: Rocket Experiments

- 1968 Aerobee 150
  - Sco X-1 upper limit
- 1969 Aerobee 150
  - Crab upper limit
- 1971 Aerobee 350
  - Crab detection!
    - $P = 15\% \pm 5\%$
    - $\varphi = 156° \pm 10°$

Brief History: Satellite Experiment

- 1975 OSO-8 satellite
  - Precision measurement of Crab Nebula
    - $\Pi = 19\% \pm 1\%$
    - $\varphi = 156° \pm 2°$ (NNE)



  - Limit for Crab Pulsar
  - Limits for Her X-1 & Cen X-3
  - Various upper limits in the several-% range

Why Such a Brief History?

- Observatory Model—the Einstein Legacy
    - Part of original payload
    - "Descoped"
- Observatory Model—the Spectrum-X Legacy
    - 11 days of observation per year

Polarimetry is Difficult

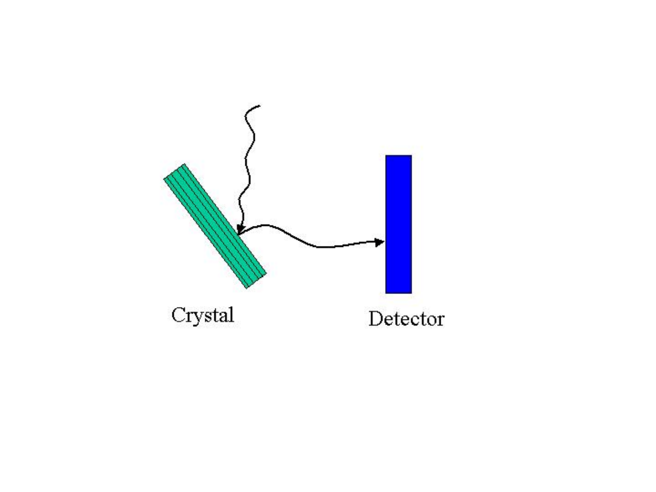
- One does not expect all astrophysical systems to be strongly polarized.
- Instruments not fully sensitive to polarization
- Measured parameter is positive definite

Crystal Polarimeter: Theory

$$\frac{N}{T} = \int_0^\infty \frac{I(E')}{E'} R(E',\vartheta) A(\vartheta) dE' = I(E) A(\vartheta_B) \Delta\vartheta(E) \cot(\vartheta_B)$$

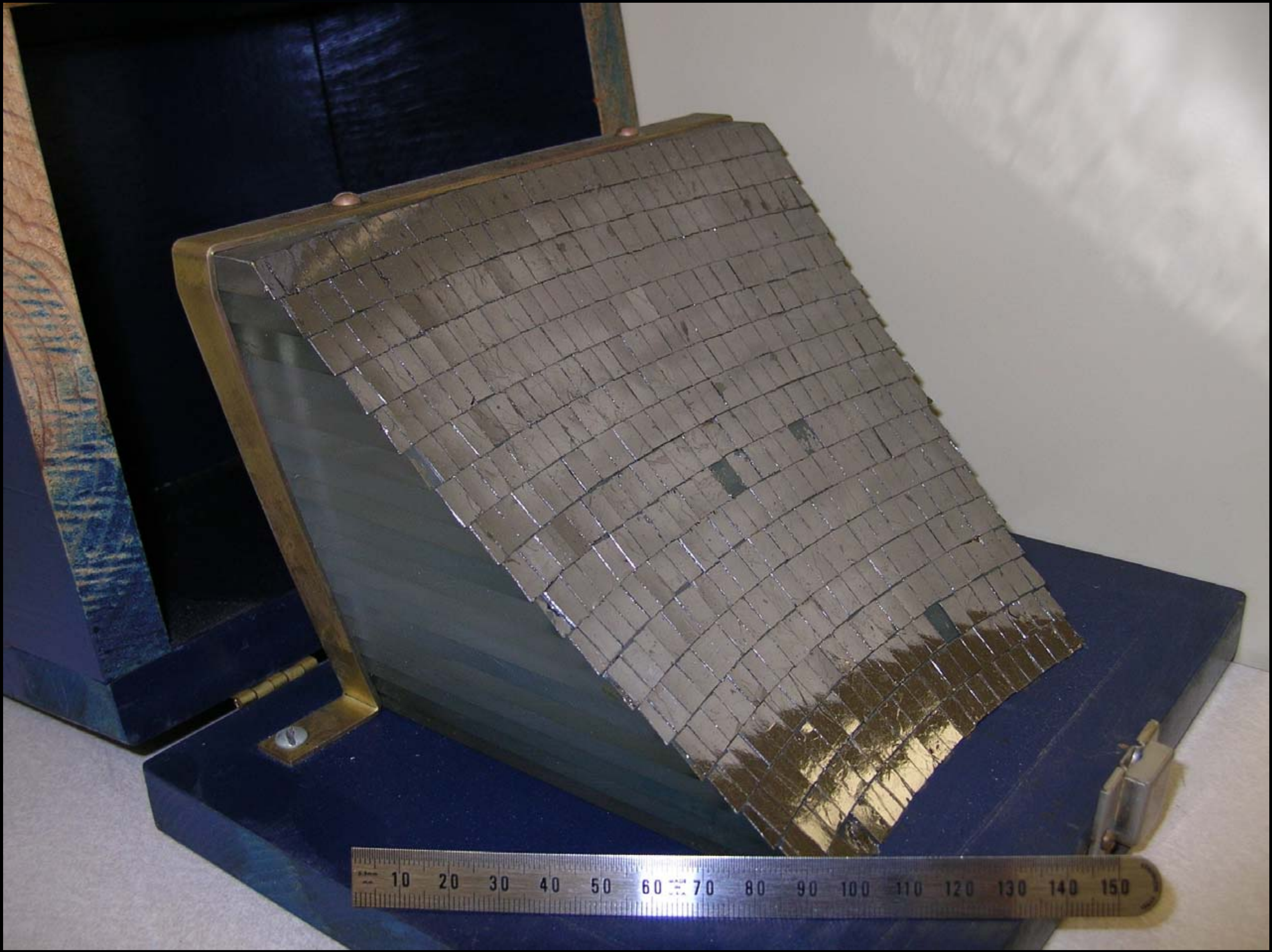
where

$$E = \frac{nhc}{2d \sin(\vartheta_B)}$$



$$\Delta\vartheta(E) = \frac{N_S^2 F^2 r_0^2}{2\mu(E)} \left(\frac{hc}{En} \right)^3 \left[\frac{1}{\sin 2\vartheta_B} - \frac{\sin 2\vartheta_B}{2} (1 + \Pi \cos 2\varphi) \right]$$

Crystal Polarimeter: OSO-8 Panel



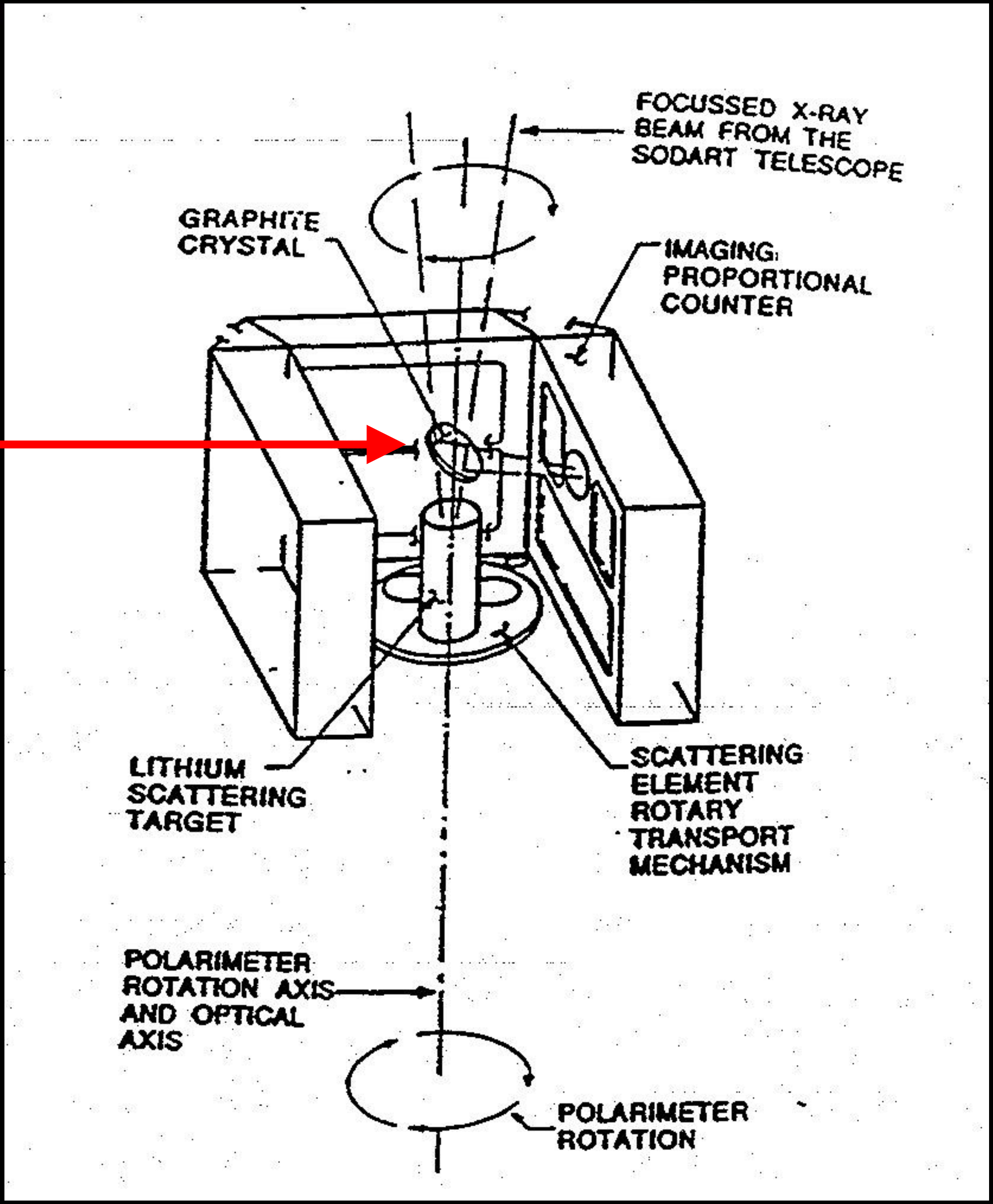
Crystal Polarimeter: Flight history

- Graphite crystal on sounding rocket in 1971
  - 2.62 keV
- Graphite crystal on OSO-8 in 1975
- Graphite crystal for Spectrum-X mission
  - Calibrated but not flown

Crystal Polarimeter: Spectrum-X

Configuration

Graphite crystal



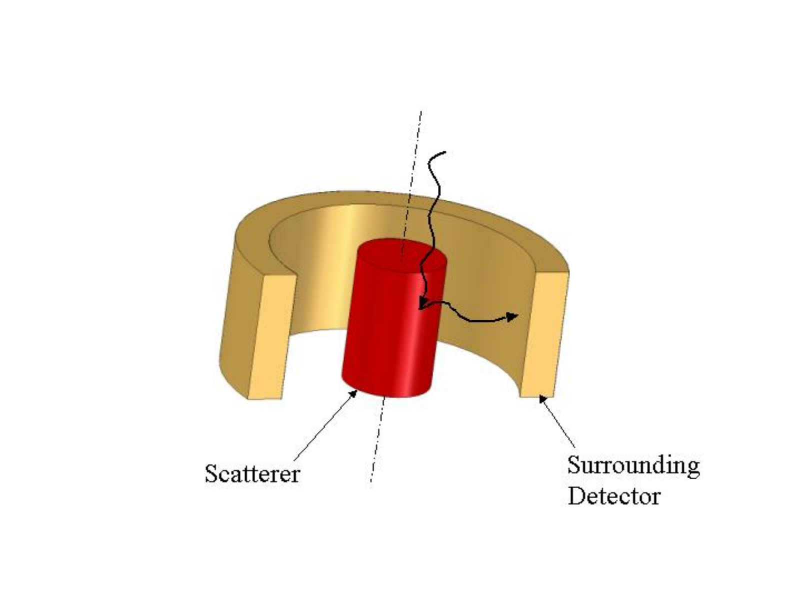
Crystal Polarimeter: Issues

- Modulation factor close to unity (+)
- Energy somewhat selectable (+)
- Narrow energy response (-)
- Low efficiency (-)
- May be used with or without a telescope (+)

Scattering Polarimeter: Theory

$$\frac{d\sigma_{\mathrm{coh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi \rangle |F|^2$$

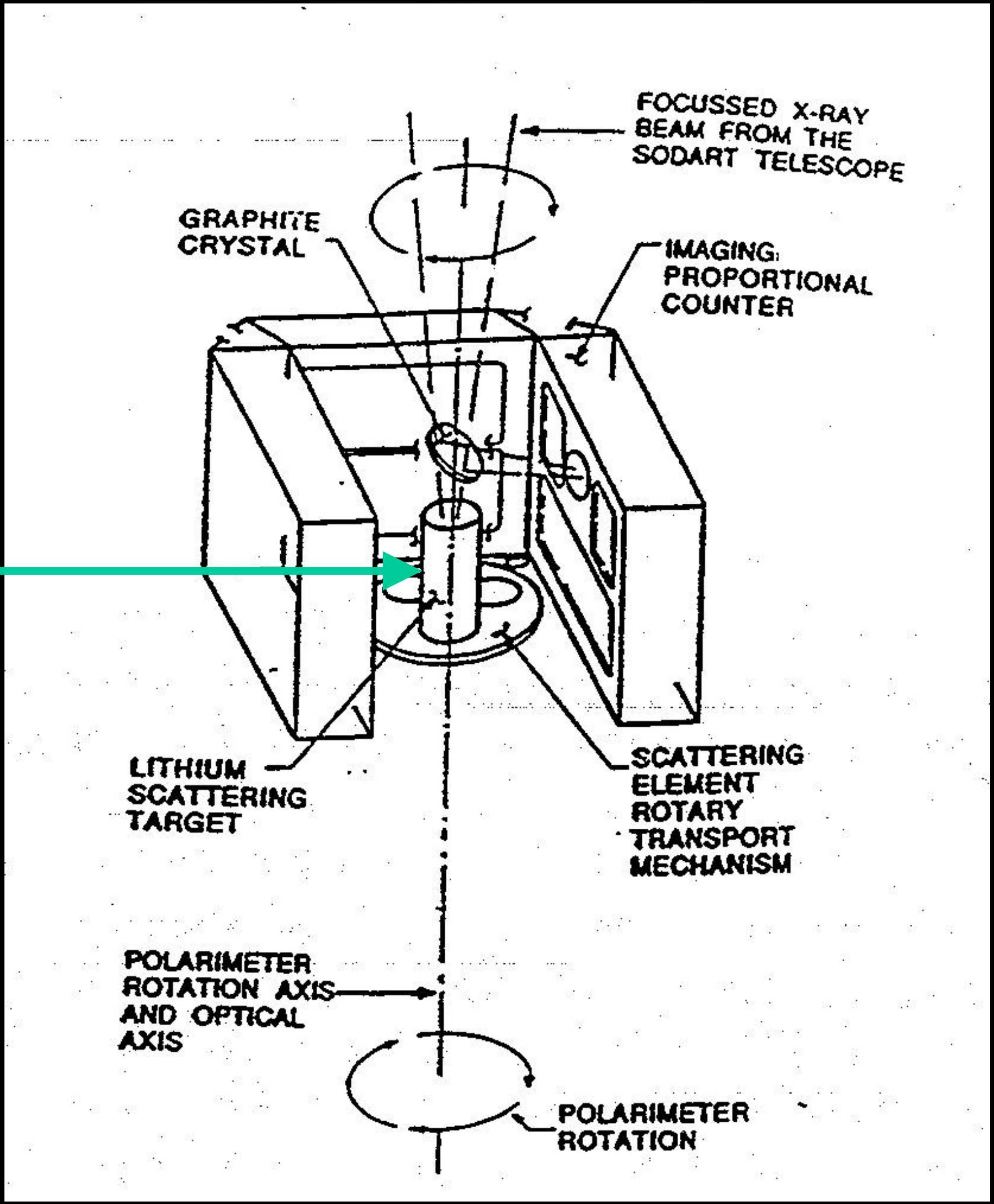
$$\frac{d\sigma_{\mathrm{incoh}}}{d\Omega} = r_0^2 \langle \cos^2 \vartheta \cos^2 \varphi + \sin^2 \varphi \rangle I$$



Scattering Polarimeter: Spectrum-X

Configuration

Scattering target

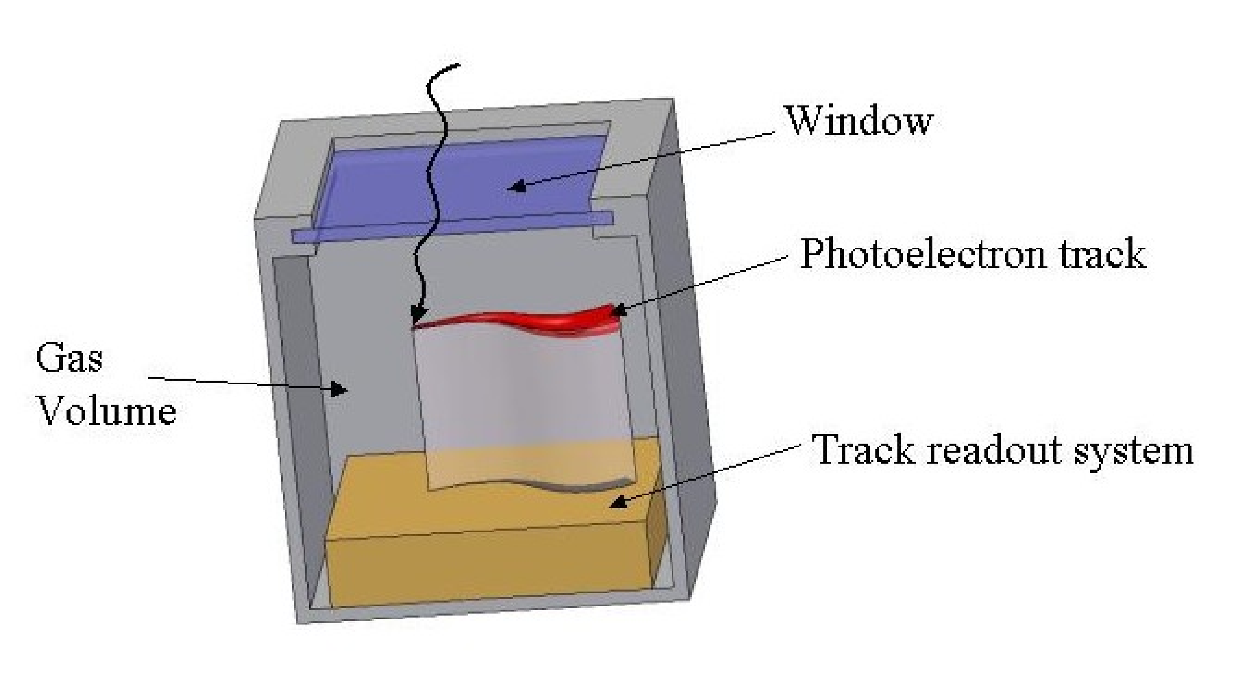


Scattering Polarimeter: Issues

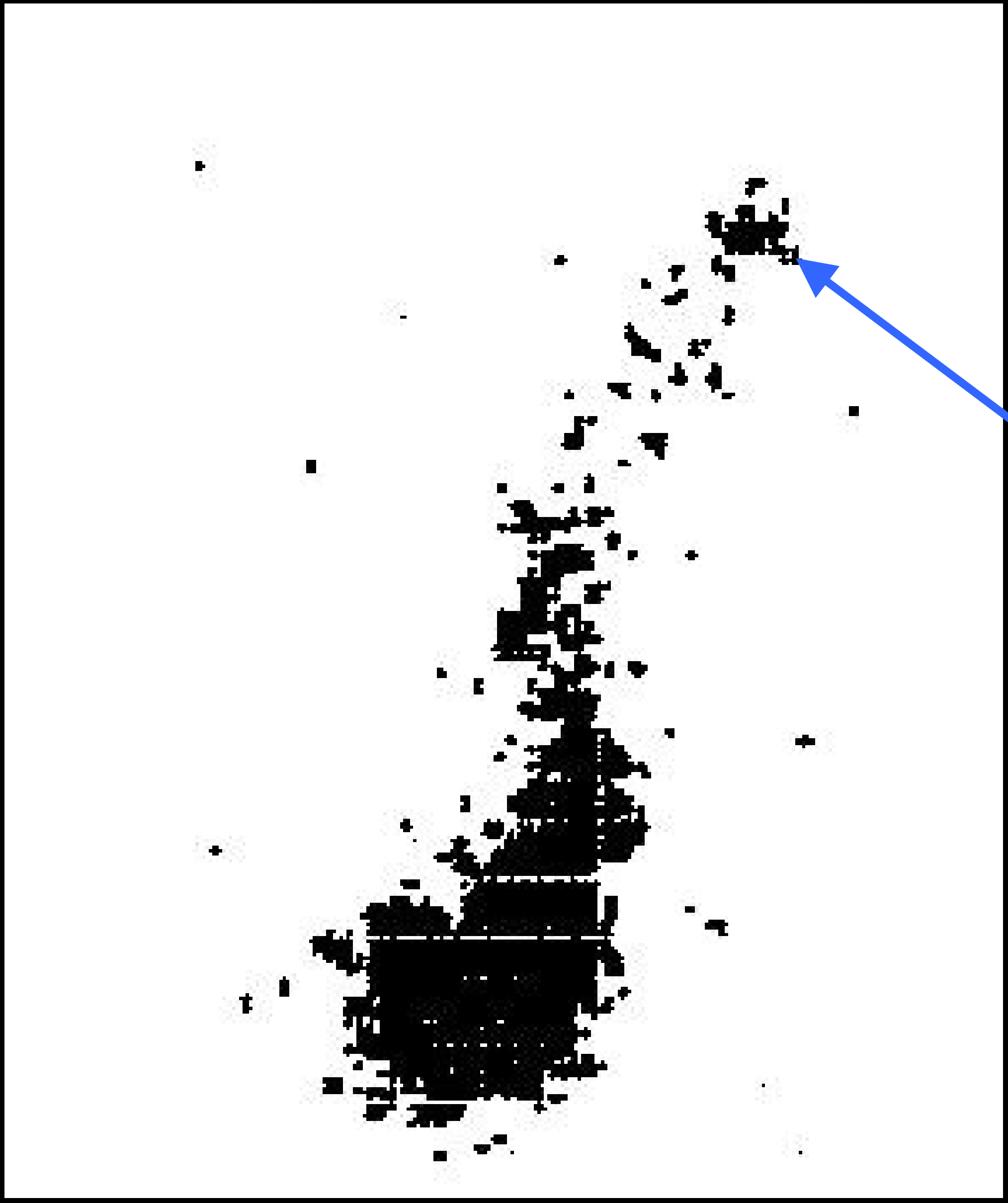
- May be used with or without a telescope (+)
  - With telescope, modulation factor high (+)
  - Lower without a telescope (-)
- Central energy somewhat selectable (+/-)
- Broad energy response (++)
- Moderate efficiency (-)

Electron-Tracking Polarimeter: Theory

$$\frac{d\sigma}{d\Omega} = f(\zeta) r_0^2 Z^5 \alpha_0^4 \left(\frac{1}{\beta}\right)^{7/2} 4\sqrt{2} \sin^2\theta \cos^2\varphi$$



Electron-Tracking Polarimeter: Tracks

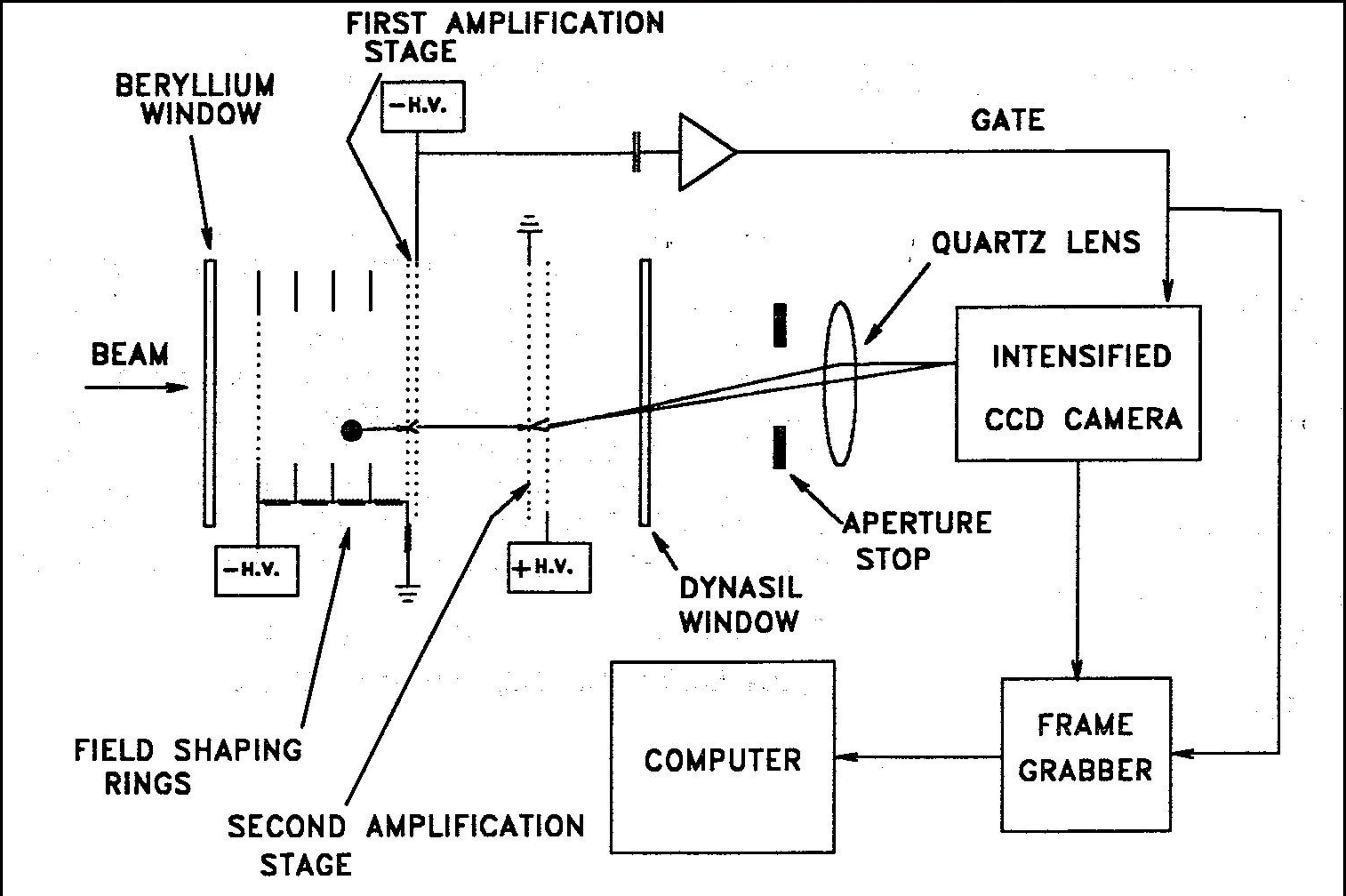


Site of initial ionization and Auger electron cloud

Electron-Tracking Polarimeter: Methods

- Optical Imaging Chamber
  - Austin & Ramsey 1992
- Pixilated Gas Multiplication
  - Costa et al. 2001

Electron-Tracking Polarimeter: Scheme



Electron-Tracking Polarimeter: Issues

- Moderate modulation factors (-)
- Central energy somewhat selectable (+/-)
- Broad energy response (++)
- Moderate efficiency (-)
- Problematic without a telescope (-)
- Unproven in laboratory over operating range (!?)

Statistics

$$p(a,\varphi) = \frac{N\overline{S}^2 a}{4\pi\sigma^2} \exp\left[-\frac{N\overline{S}^2}{4\sigma^2} (a^2 + a_0^2 - 2aa_0 \cos\Delta\varphi) \right]$$

a_0 = true amplitude of modulation

φ_0 = true phase of modulation

$\Delta\varphi = \varphi - \varphi_o$

N = number of data points

$\overline{S}$ = mean number of counts per data bin

σ^2 = variance of the distribution

Statistics

$$p(a) = \frac{N\bar{S}^2 a}{2\sigma^2} \exp\left[-\frac{N\bar{S}^2}{4\sigma^2}(a^2 + a_0^2) \right] I_0\left(\frac{N\bar{S}^2 a a_0}{2\sigma^2}\right)$$

If underlying data satisfy these conditions:

- Unmodulated
- Poisson distributed

$$p(a' \geq a) = \int_a^\infty p(a')da' = \exp\left(-\frac{N\bar{S}a^2}{4}\right)$$

Statistics

$$a_{1\%} = 4.29 / \sqrt{N\bar{S}}$$

$$a_s = \frac{4.29}{R_s}\sqrt{\frac{R_s + R_b}{T}}$$

$$MDP_{99} = \frac{a_s}{M} = \frac{4.29}{MR_s}\sqrt{\frac{R_s + R_b}{T}}$$

MDP is the "Minimal Detectable Polarization"

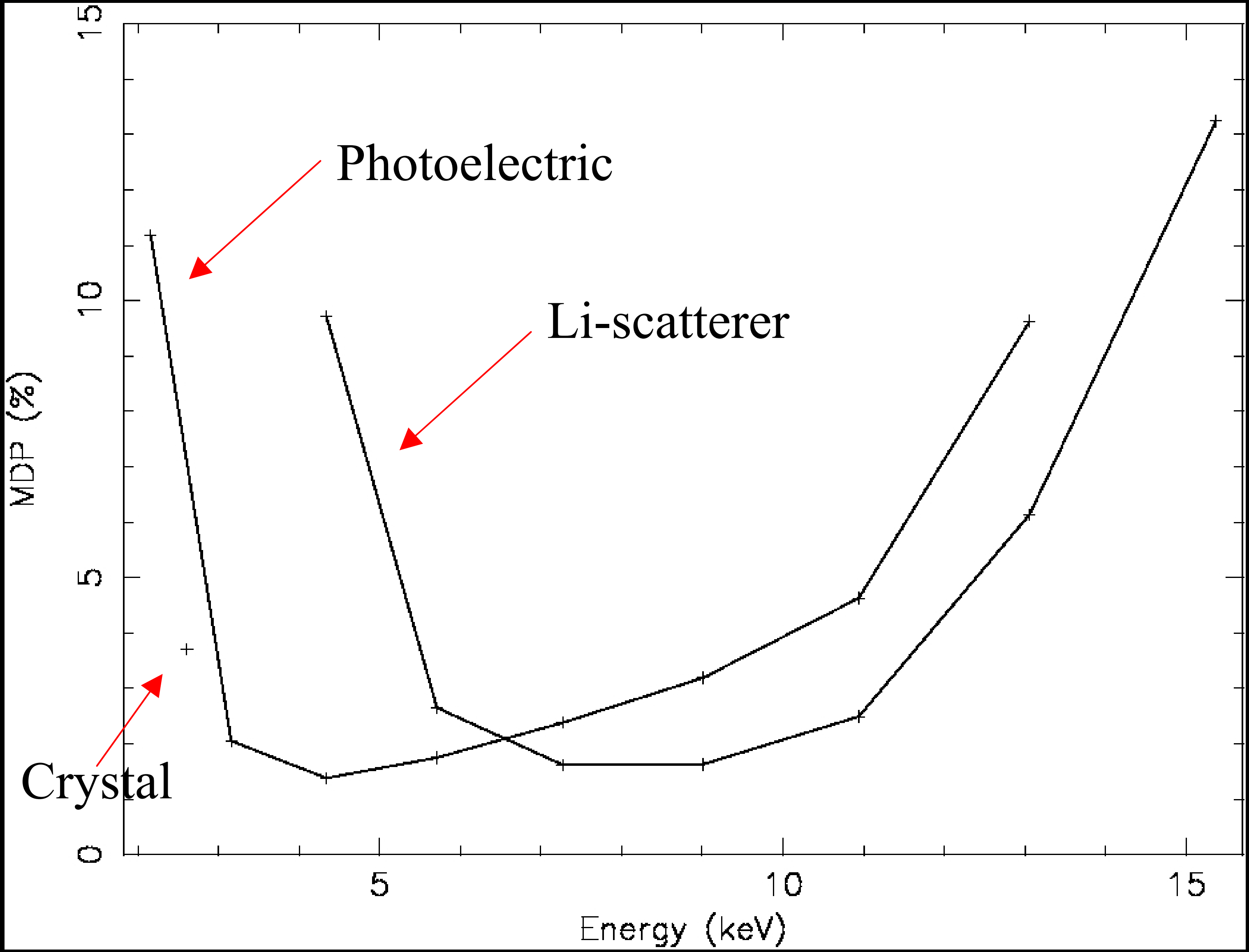
At the Focus of a Telescope

- SODART (foil) telescope
  - 60-cm diameter, 6-m focal length
  - 1000 cm^2@ 3.0 keV
- Spectrum-X Crystal
- Spectrum-X Lithium Scatterer
- Electron tracking (80%Ne/20%DME)
  - Pacciani et al. 2003

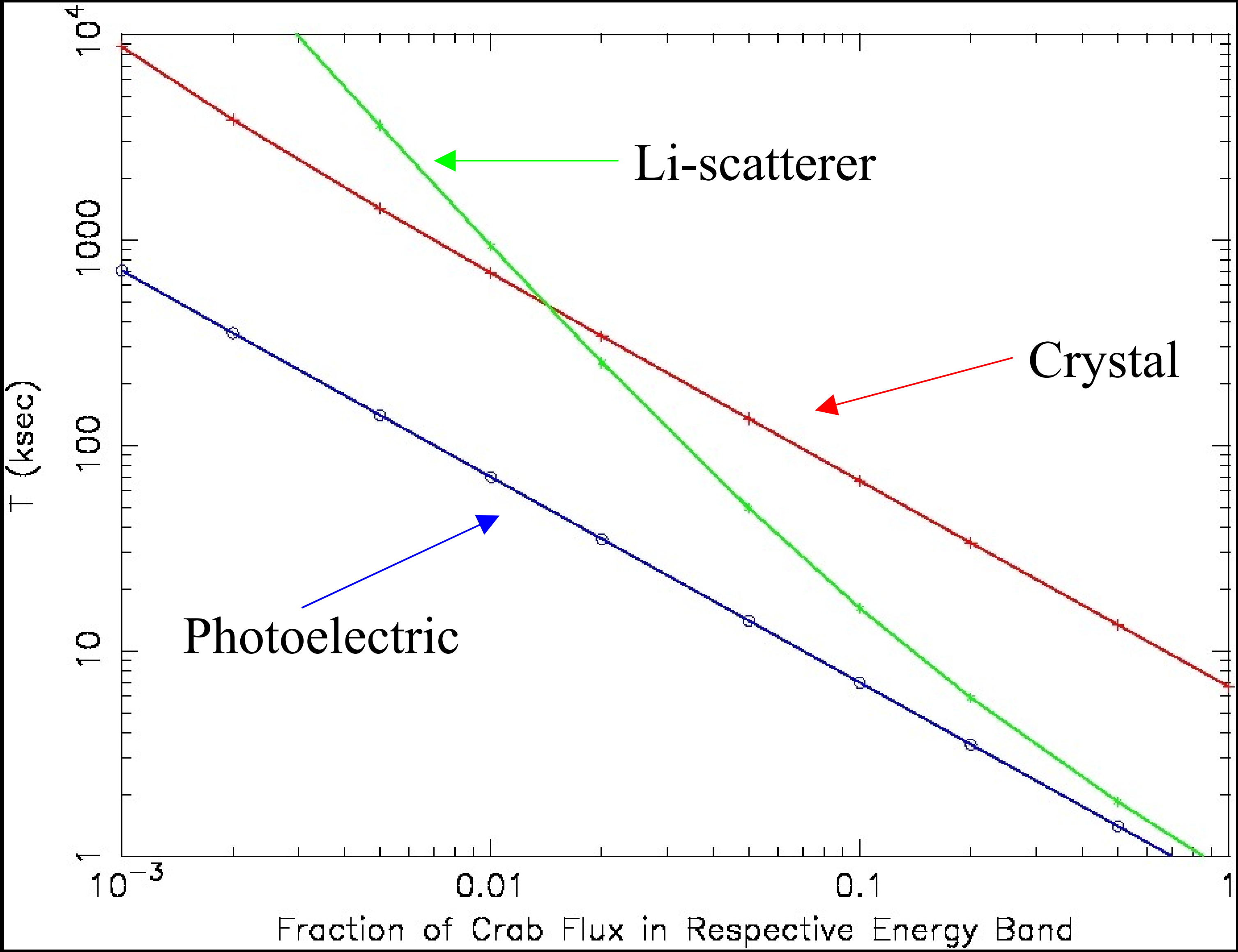
Background at Focus of a Telescope

- Low for crystal polarimeter
  - Determined by resolution of telescope
- High for scattering polarimeter
  - Determined by area of surrounding detector
- Low for electron-tracking polarimeter
  - Determined by the size of the ionization blob

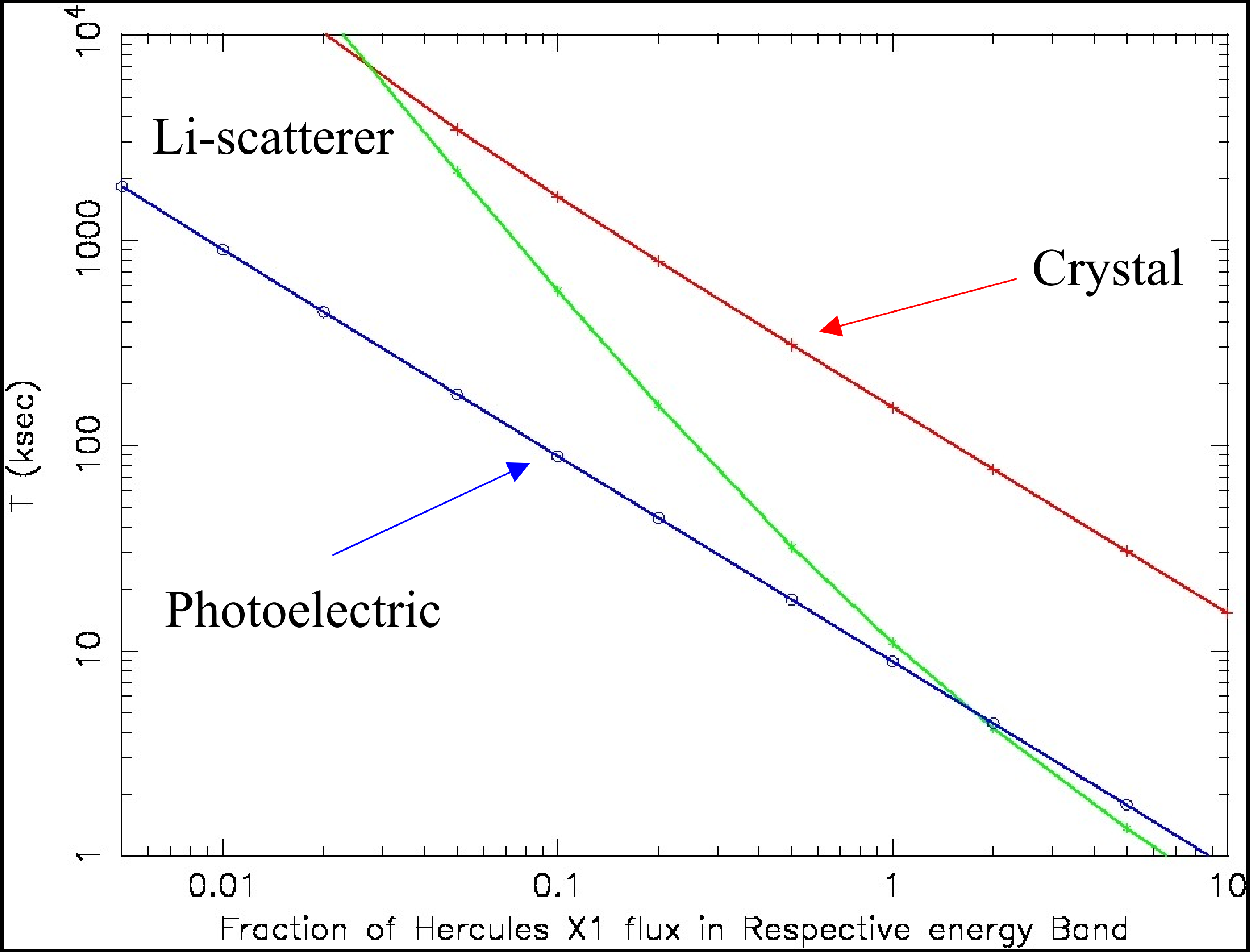
MDP(E) with Telescope: Her X-1



3%-MDP Time with Telescope: Crab



3%-MDP Time with Telescope: Her X-1



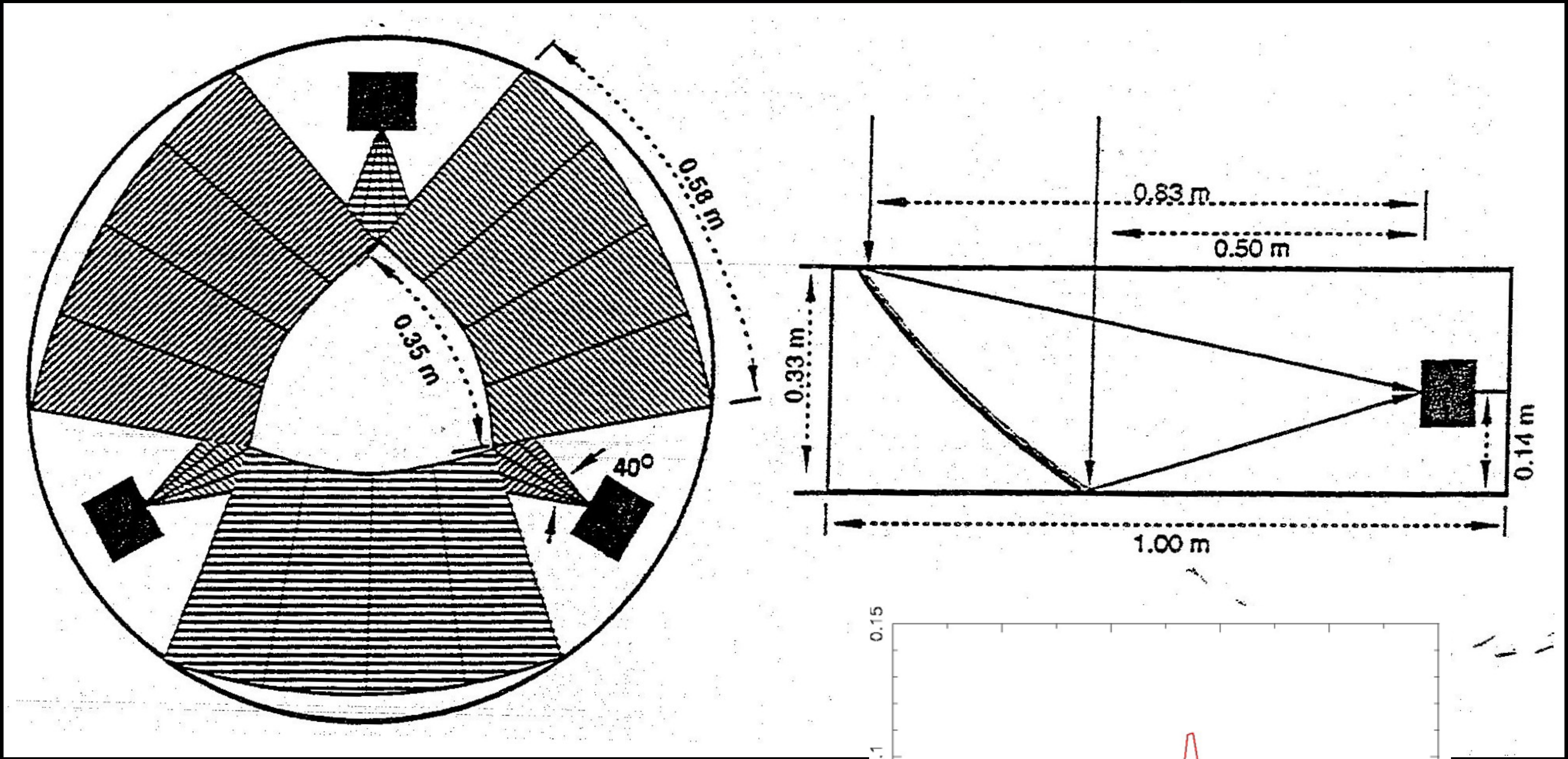
No Telescope

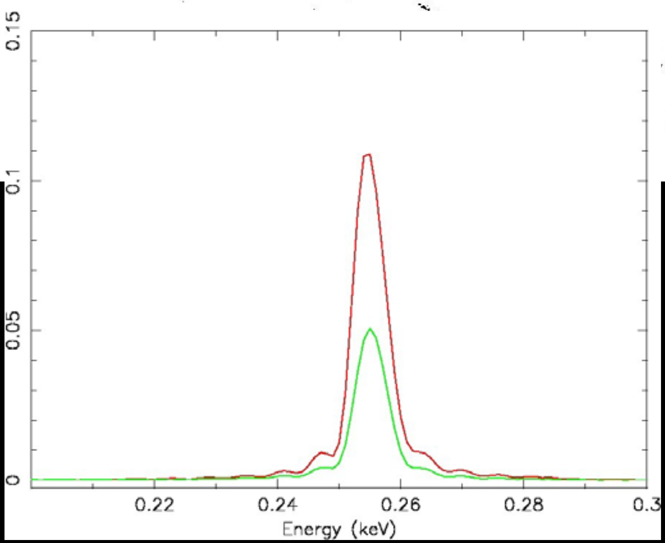
- Crystal polarimeter
- Scattering polarimeter
- Electron-tracking polarimeter is problematic.
  - Power requirement

Background without a Telescope

- Lower for crystal polarimeter
  - Determined by crystal geometry
- Higher for scattering polarimeter
  - Determined by area of surrounding detector

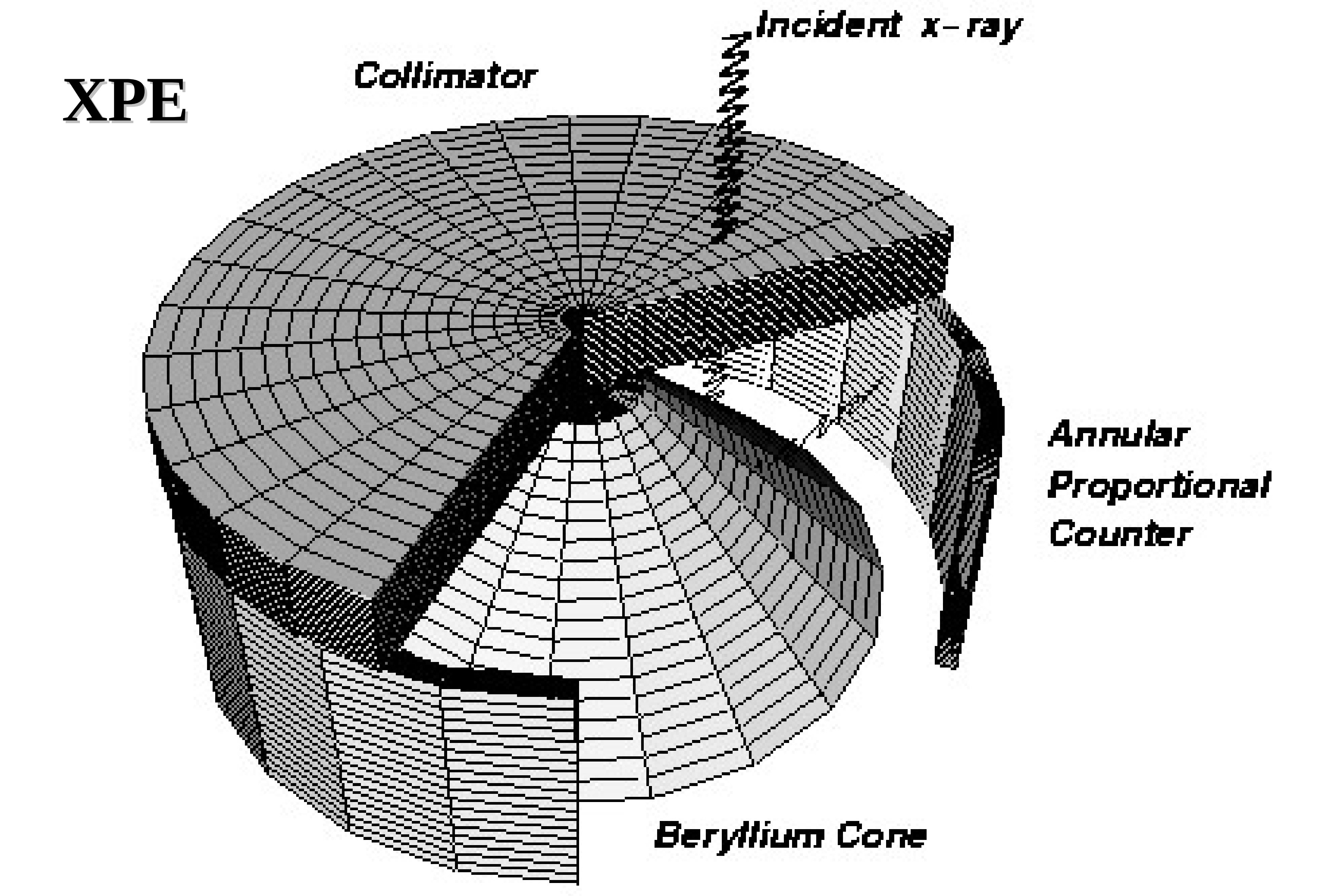
Crystal Polarimeter sans Telescope



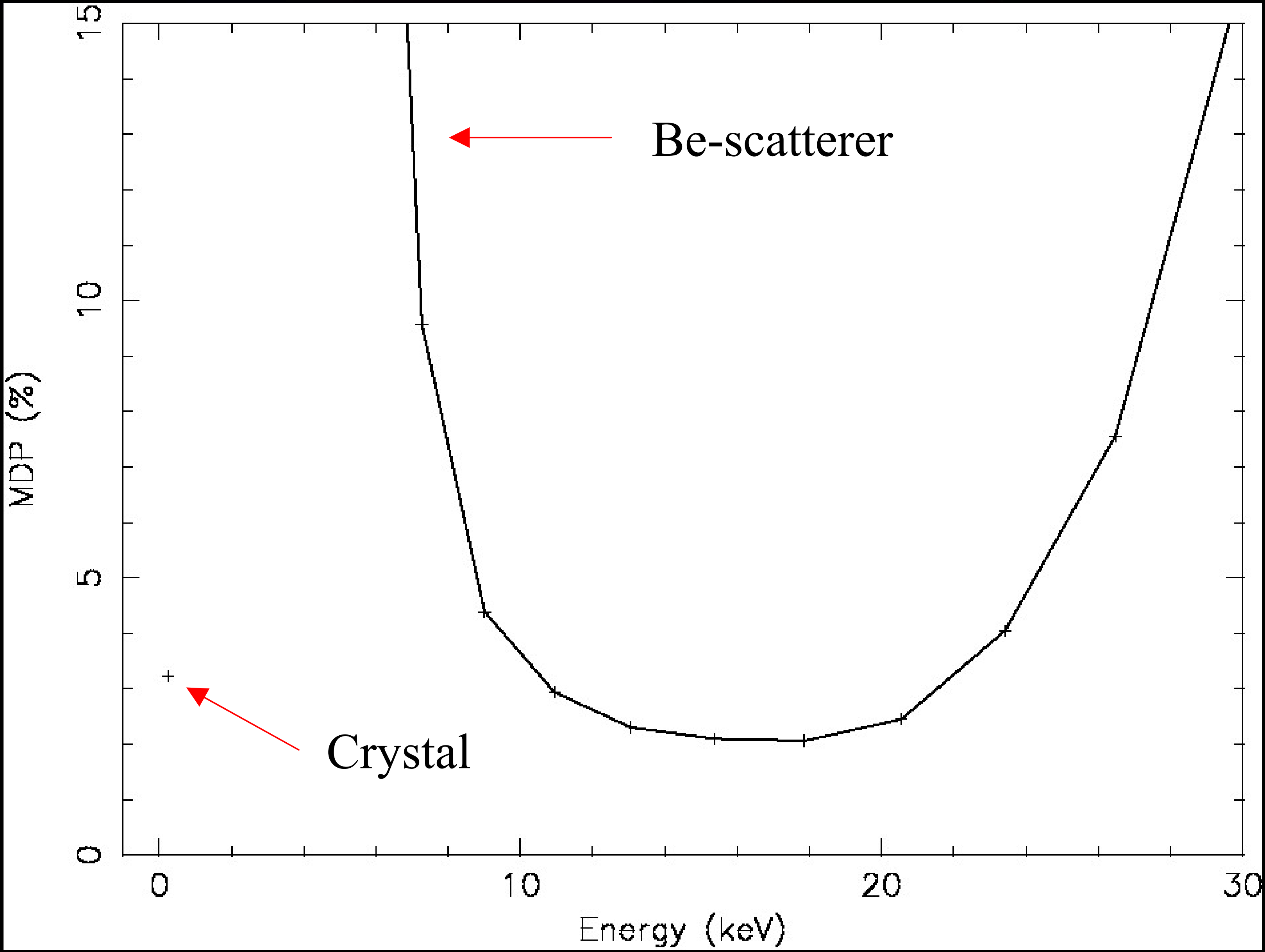


Marshall et al. (2003)

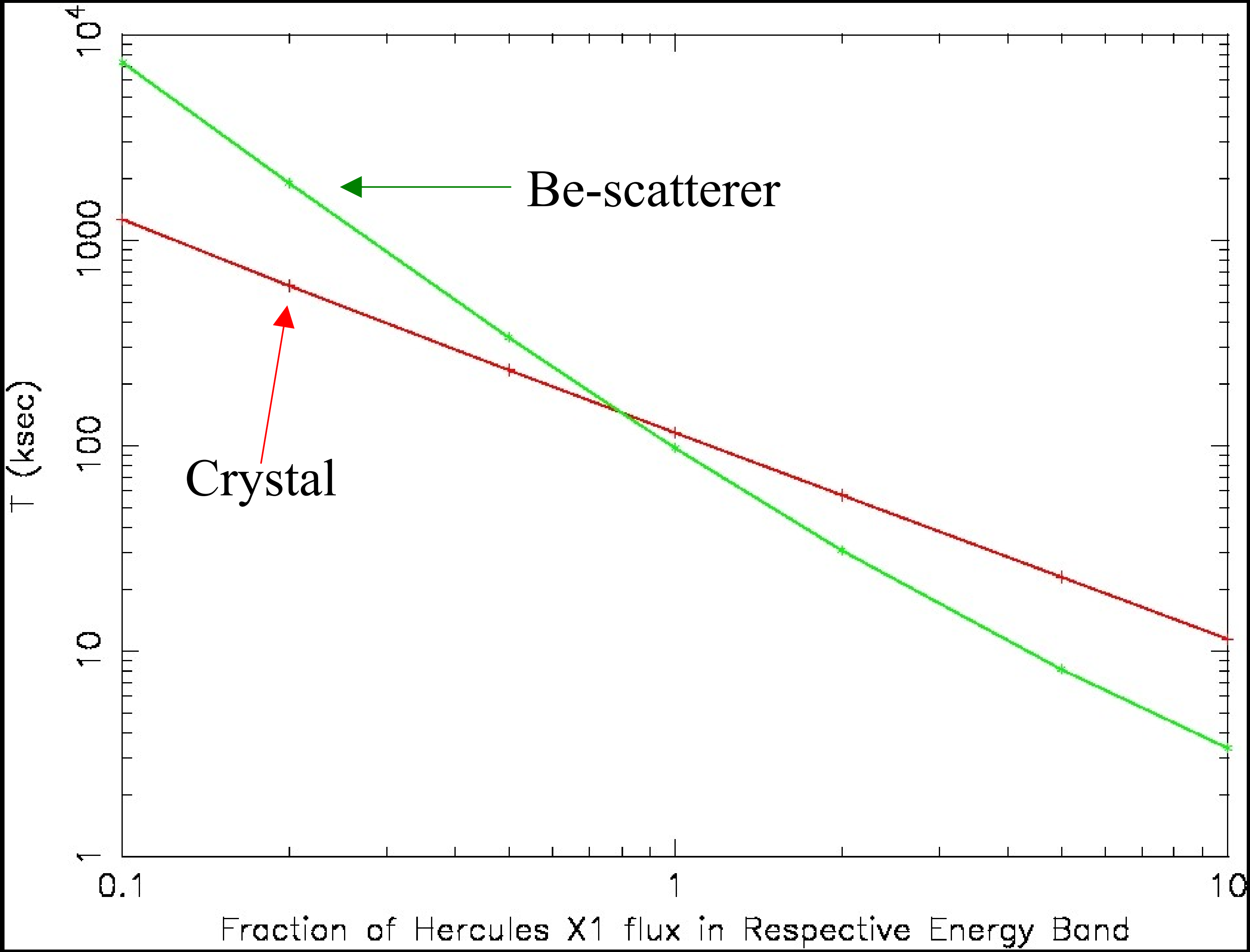
Scattering Polarimeter sans Telescope



MDP(E) sans Telescope: Her X-1



3%-MDP Time sans Telescope: Her X-1



No Telescope: Why Bother?

- Polarimeter with telescope on Observatory-class mission is improbable at best.
  - Lesson of history
- Unlikely to survive (e.g.) SMEX-type considerations
  - Best science for the dollar
- Expensive for a stand-alone mission
  - Need an inexpensive pathfinder to blaze trail.

Observing Program

	Probability (>MDP) =	99% confidence			95% confidence			99% confidence			95% confidence		
	MDP =	3%	2%	1%	3%	2%	1%	3%	2%	1%	3%	2%	1%
Name	Type of X-ray source	Time[a] [d]						Time[a] [d] for 0.5-d minimum					
Crab Pulsar	radio pulsar [b]	29.6	66.6	266.4	19.3	43.3	173.3	29.6	66.6	266.4	19.3	43.3	173.3
Crab Nebula	supernova remnant (SNR) [c]	0.0	0.1	0.3	0.0	0.0	0.2	0.5	0.5	0.5	0.5	0.5	0.5
SGR 1900+14	soft gamma-ray repeater (SGR):	1.0	2.3	9.0	0.7	1.5	5.9	1.0	2.3	9.0	0.7	1.5	5.9
4U1636-53	burster	9.0	20.3	81.0	5.9	13.2	52.7	9.0	20.3	81.0	5.9	13.2	52.7
J1808.4-3658	accreting millisecond pulsar (MSP)	9.1	20.5	81.9	5.9	13.3	53.3	9.1	20.5	81.9	5.9	13.3	53.3
J1751-305	accreting millisecond pulsar (MSP)	10.3	23.2	92.7	6.7	15.1	60.3	10.3	23.2	92.7	6.7	15.1	60.3
Her X-1	accreting pulsar	0.2	0.5	1.8	0.1	0.3	1.2	0.5	0.5	1.8	0.5	0.5	1.2
Cen X-3	accreting pulsar	0.1	0.2	0.8	0.1	0.1	0.5	0.5	0.5	0.8	0.5	0.5	0.5
4U0900-40	accreting pulsar	0.3	0.7	2.9	0.2	0.5	1.9	0.5	0.7	2.9	0.5	0.5	1.9
GX 1+4	accreting pulsar	0.3	0.6	2.3	0.2	0.4	1.5	0.5	0.6	2.3	0.5	0.5	1.5
SMC X-1	accreting pulsar	3.2	7.2	28.8	2.1	4.7	18.7	3.2	7.2	28.8	2.1	4.7	18.7
4U1538-58	accreting pulsar	10.4	23.4	93.6	6.8	15.2	60.9	10.4	23.4	93.6	6.8	15.2	60.9
4U0115+63	accreting pulsar: high state	0.3	0.7	3.0	0.2	0.5	1.9	0.5	0.7	3.0	0.5	0.5	1.9
OAO1657-41	accreting pulsar	4.0	9.0	36.0	2.6	5.9	23.4	4.0	9.0	36.0	2.6	5.9	23.4
4U1626-67	accreting pulsar	1.3	2.9	11.7	0.8	1.9	7.6	1.3	2.9	11.7	0.8	1.9	7.6
Cyg X-3	binary	1.0	2.2	8.7	0.6	1.4	5.7	1.0	2.2	8.7	0.6	1.4	5.7
4U1822-37	accretion-disk corona	8.3	18.7	74.7	5.4	12.1	48.6	8.3	18.7	74.7	5.4	12.1	48.6
Sco X-1	quasi-periodic oscillator (QPO)	0.0	0.0	0.2	0.0	0.0	0.1	0.5	0.5	0.5	0.5	0.5	0.5
Cyg X-2	quasi-periodic oscillator (QPO)	0.4	1.0	4.0	0.3	0.6	2.6	0.5	1.0	4.0	0.5	0.6	2.6
GX 5-1	quasi-periodic oscillator (QPO)	0.2	0.5	2.1	0.1	0.3	1.3	0.5	0.5	2.1	0.5	0.5	1.3
Cir X-1	quasi-periodic oscillator (QPO)	0.2	0.5	2.1	0.1	0.3	1.3	0.5	0.5	2.1	0.5	0.5	1.3
Cyg X-1	black-hole binary	0.0	0.1	0.4	0.0	0.1	0.3	0.5	0.5	0.5	0.5	0.5	0.5
J1744-28	bursting pulsar: active	0.0	0.0	0.2	0.0	0.0	0.1	0.5	0.5	0.5	0.5	0.5	0.5
GRS	microquasar: high state	0.0	0.0	0.1	0.0	0.0	0.0	0.5	0.5	0.5	0.5	0.5	0.5
J1655-40	microquasar: high state	0.2	0.4	1.6	0.1	0.3	1.1	0.5	0.5	1.6	0.5	0.5	1.1
Cen A	active galactic nucleus (AGN)	16.2	36.5	145.8	10.5	23.7	94.8	16.2	36.5	145.8	10.5	23.7	94.8
NGC 4151	active galactic nucleus (AGN)	24.8	55.8	223.2	16.1	36.3	145.2	24.8	55.8	223.2	16.1	36.3	145.2
	All sources at stated MDP	131	294	1175	85	191	764	135	296	1176	90	194	766
B = Baseline	Leave Crab MDP=3%/bin in 10 bins	131	257	938	85	167	610	135	259	939	90	170	612
	B - 2 AGN	90	164	569	58	107	370	94	167	570	63	110	372
	B - 5 Galactic sources	83	151	514	54	98	334	88	153	515	59	101	336
	B - 2 AGN - 5 Galactic sources	42	58	145	28	38	94	47	61	146	33	41	96
	B - 1 AGN - 3 Galactic sources	85	154	528	55	100	344	89	157	530	60	104	345

a Stated times are observing time only. For an average efficiency of 0.65, required calendar time is 1.54 times longer.
b The time quoted is for reaching average minimum detectable polarization (MDP) of 3% in each of 10 phase bins.
c Integration time for Pulsar is much longer than needed for Nebula: Nebula's MDP << 3%, limited by systematic errors.

Conclusions

- Polarimetry is powerful and long overdue!
- Polarimetry needs to be done (now)!
  - Don’t rely on observatory-class mission
  - Don’t rely on SMEX-class mission
- Theorists start predicting!
- Need an innovative, low-cost mission
  - KISS!!