X-ray Polarimetry
— a new window about to open

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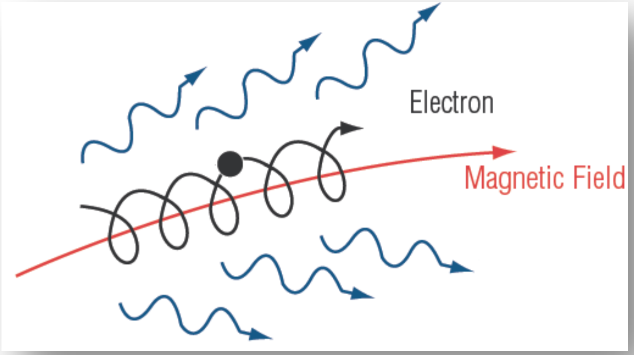
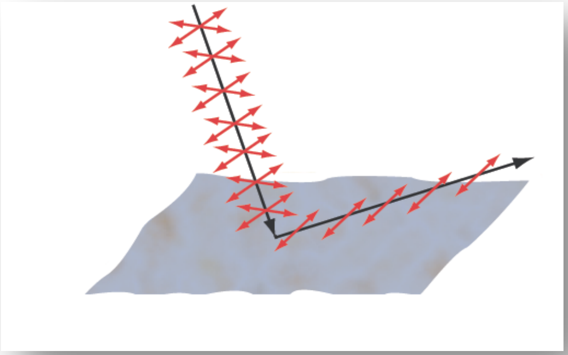
Outline □

- Science with X-ray polarimetry
  - Jet structure
  - Black hole spin measurement
  - Thermal emission from pulsar
- How to measure X-ray polarization
  - History
  - Breakthroughs in technology
  - Future missions in China: XTP and LAMP

What can we learn from X-ray polarization?

- Information about magnetic field
  - Synchrotron emission (Jets, SNR, PWN)
  - Plasma polarization (pulsars)
  - Vacuum polarization (neutron stars & magnetars)
- Information about geometry
  - Thomson/Compton/InverseCompton scattering
  - Symmetry (accretion flow; BHBs & AGN)
- X-rays are not subject to Faraday rotation





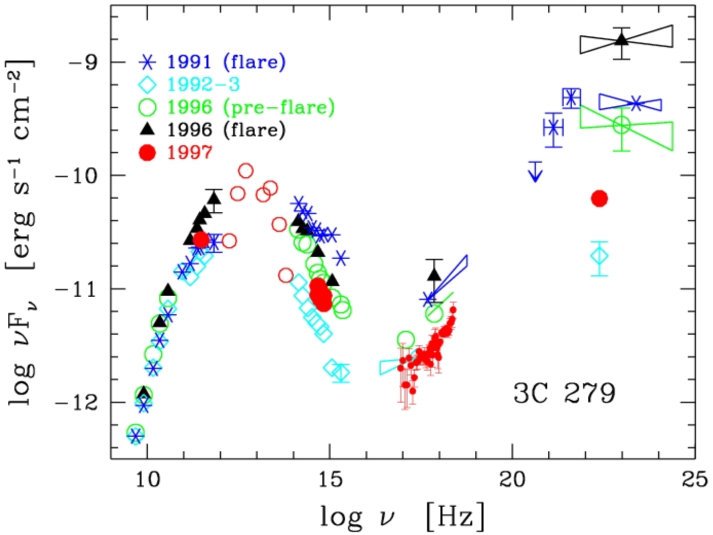
Science with X-ray polarimetry

- ✓ Magnetic fields in relativistic jets
- ✓ Black hole spin measurement
- ✓ Thermal emission from the surface of neutron stars

Case A

Relativistic jets

- Blazar
  - Radio-loud AGN with jets pointing to our line of sight
  - Optical and radio polarization as high as 40% (Ghisellini et al. 1992)
  - SED: double peaks, synchrotron + Comptonization

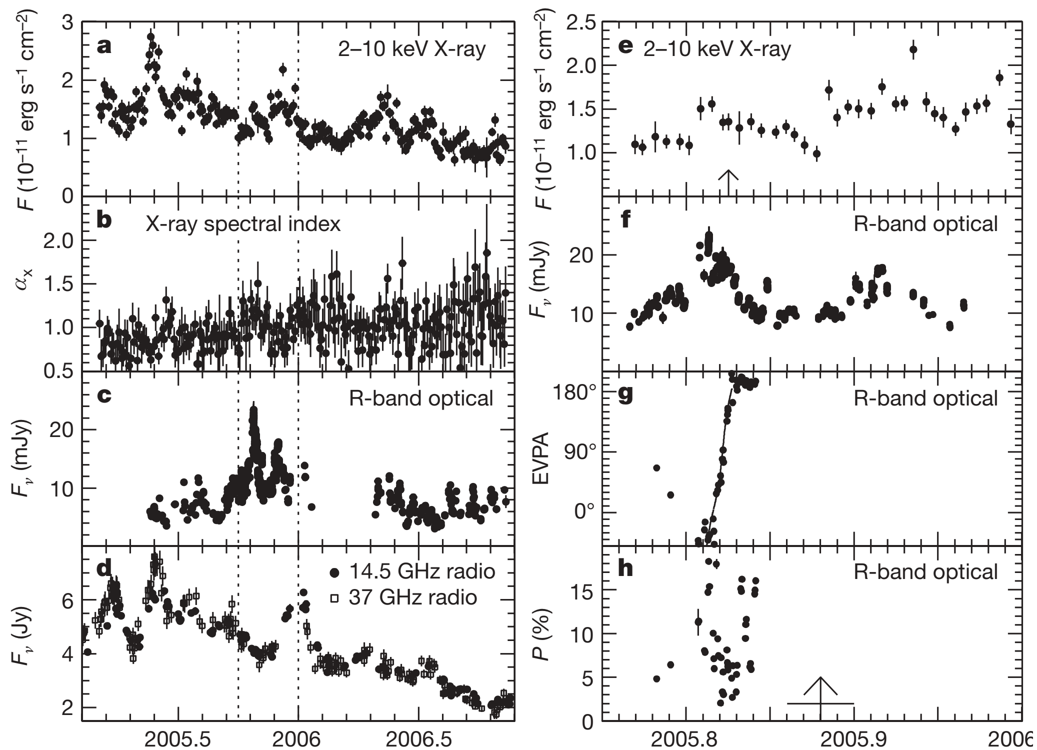


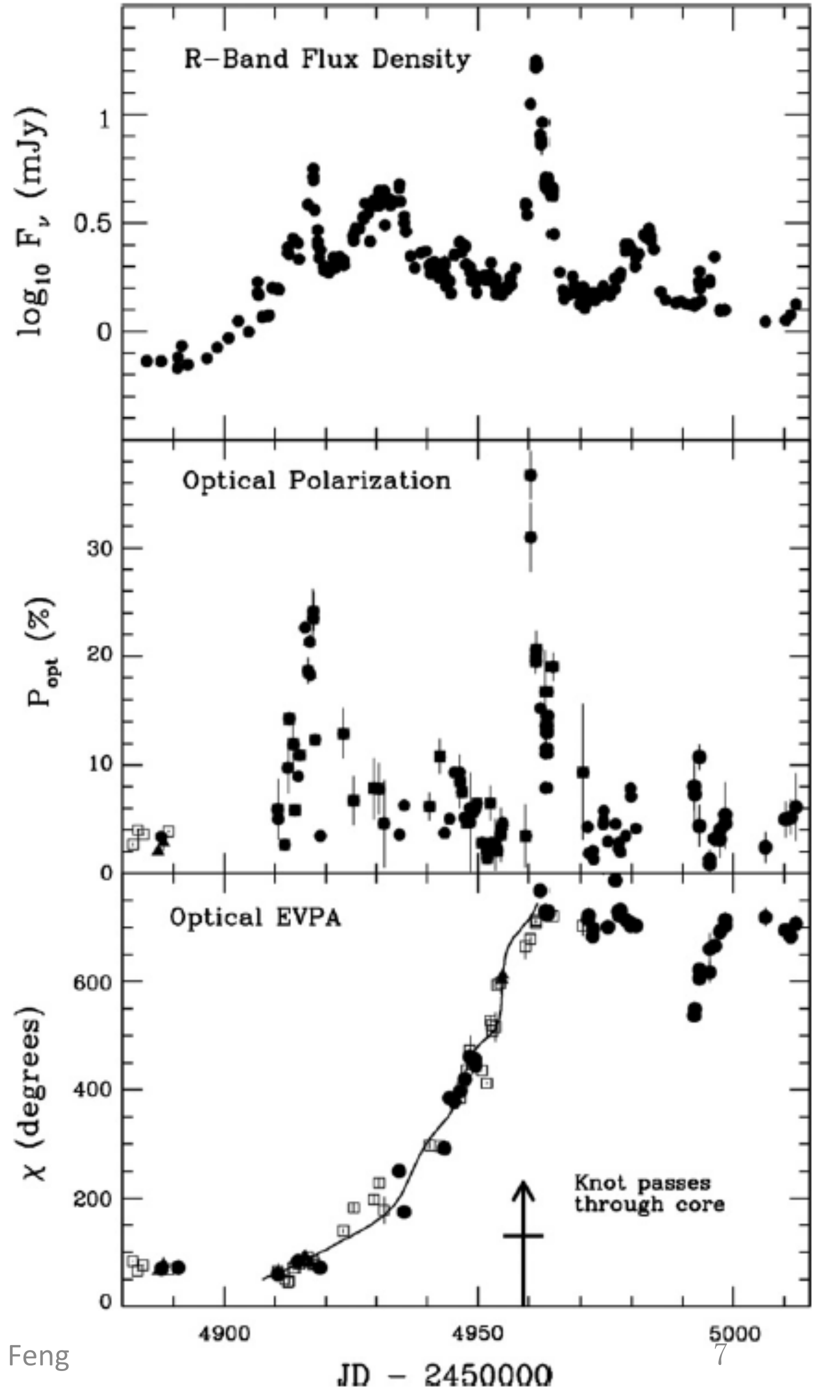
Structure of the magnetic fields in jets

- How are the jets launched?
- Role of magnetic fields in jets collimation and acceleration
- The local B-filed orientation can be measured by synchrotron emission in the jets
- Objects: High Synchrotron Peaked Blazars whose Synchrotron emission peaks in the X-ray band

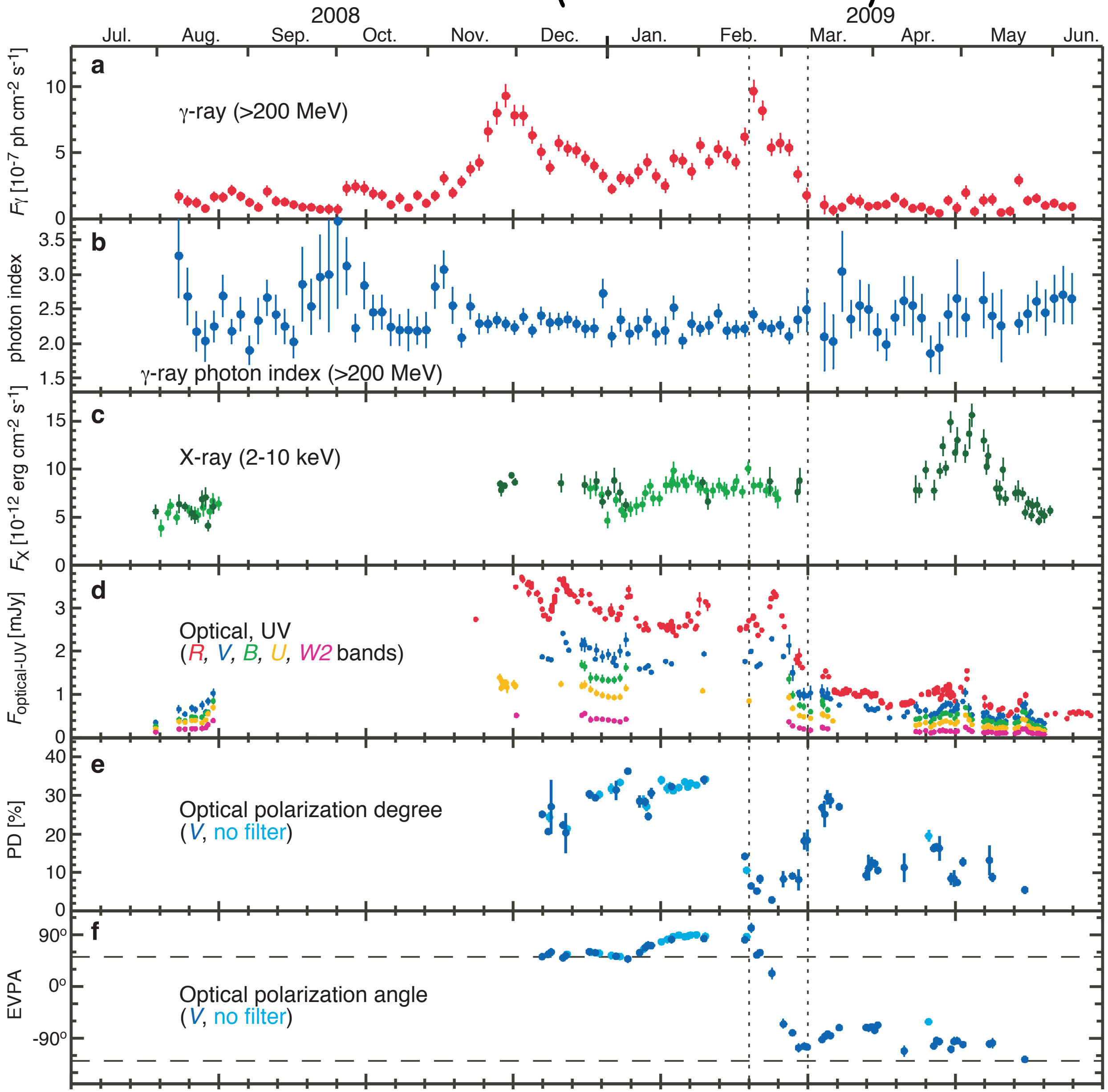
Polarization position angle changed during flares

- BL Lac (Marscher et al. 2008)
- PKS 1510-089 (Marscher et al. 2010)
- 3C 279 (Abdo+2010)



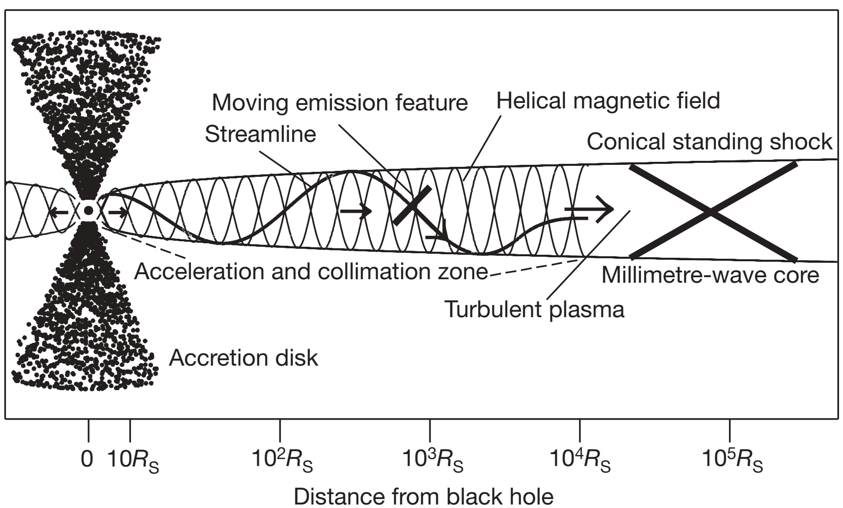


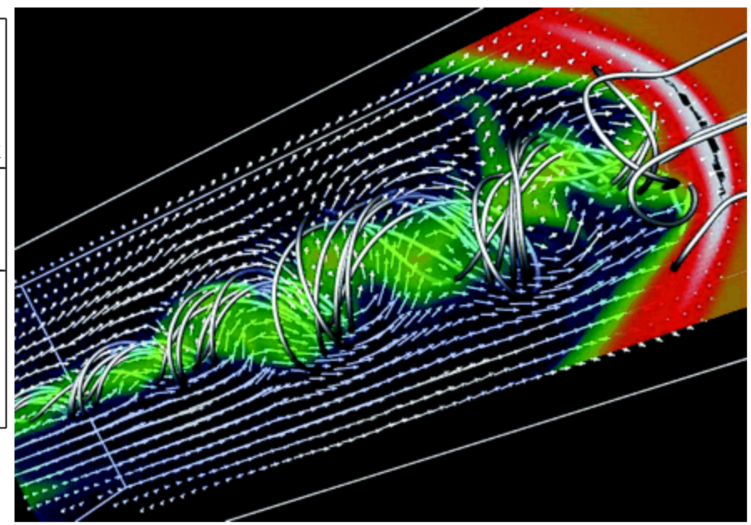
3C 279 (Abdo+2010)



Structure of the magnetic fields in jets

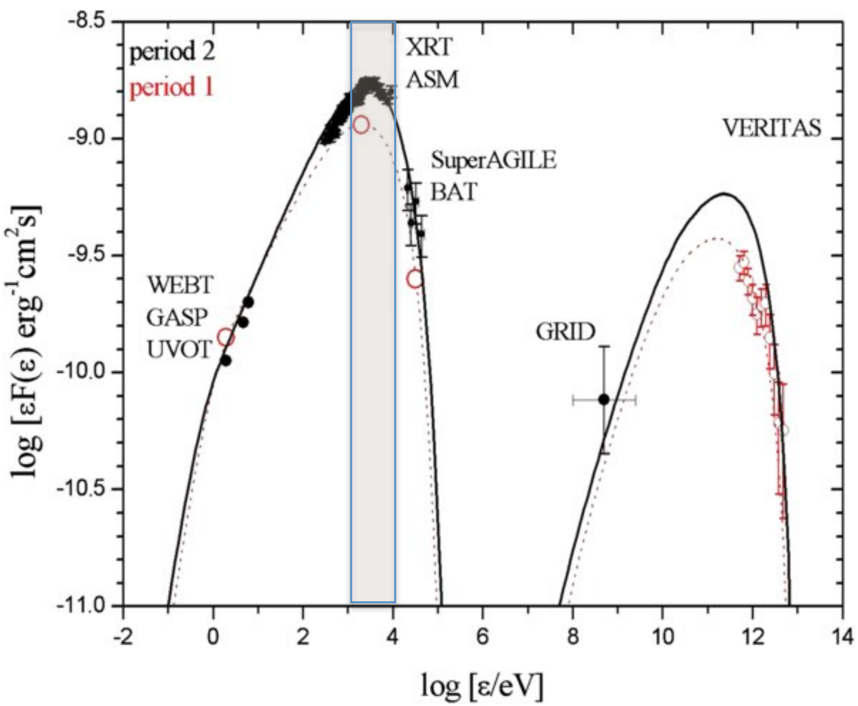
- Propagation of shocks trace the local magnetic fields
  - Helical magnetic fields
- X-ray polarimetry
  - Emission region may be more compact
  - In the accelerating region
  - Easy for continual monitoring in the space



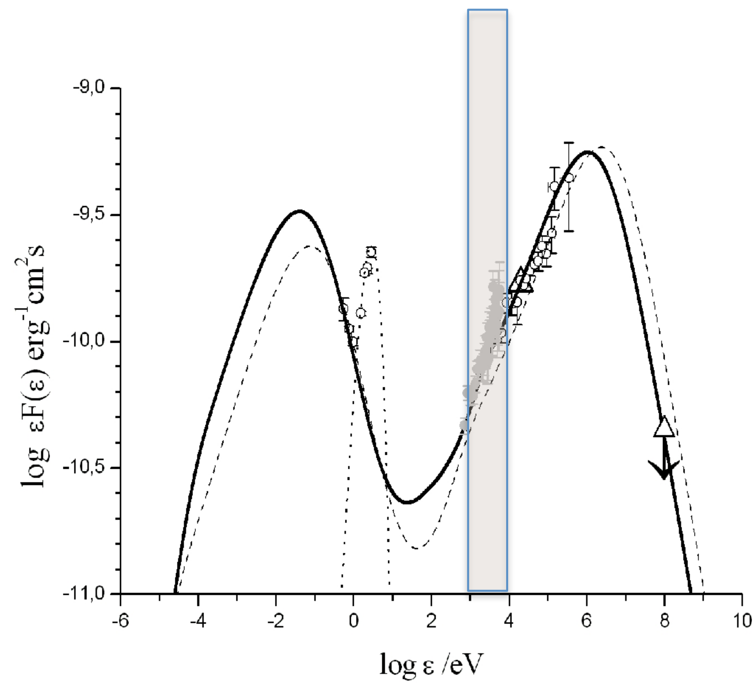


Low Synchrotron Peaked Blazars

- Seed of the Comptonization?
  - Synchrotron self or external photons?



Mrk 421 (HSP)

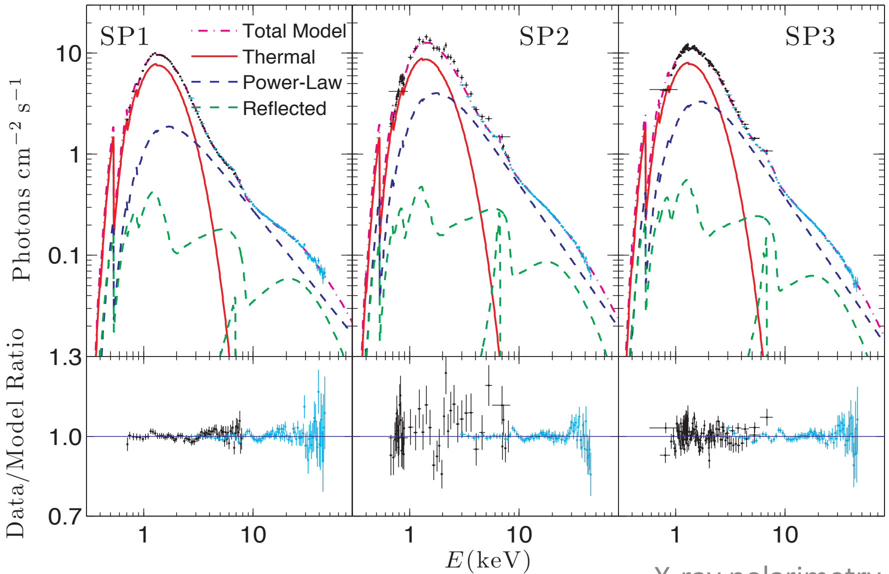


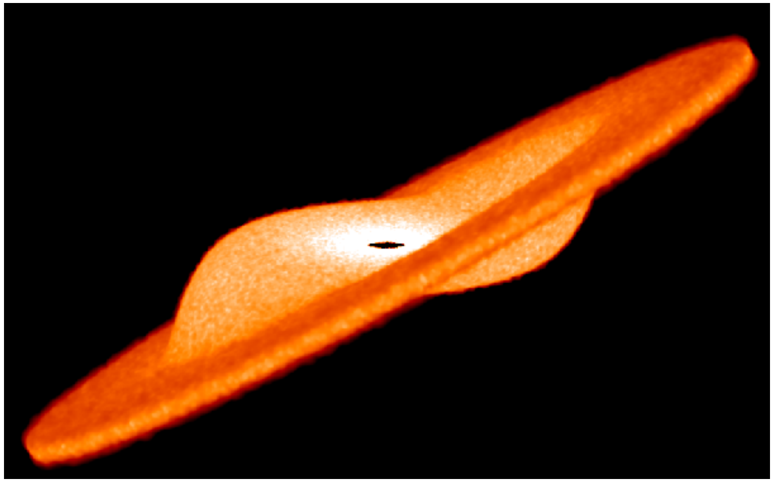
3C 273 (LSP)

Case B

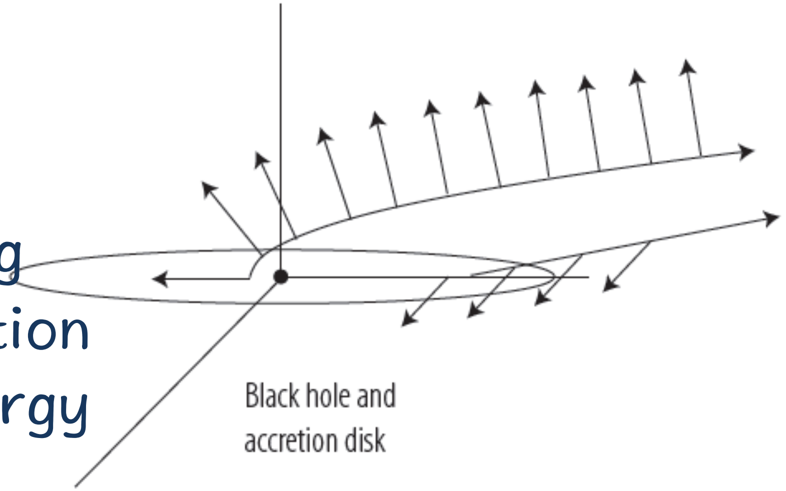
Black Hole Spin Measurement

- Spin measurement of BHs in binaries
  - basic property of a BH, GR, accretion physics, jet formation
  - Spin measure via continuum fit: measure the size of the innermost stable circular orbit (ISCO) (Zhang et al. 1997; McClintock et al. 2006-2013)
  - Problem: couple of disk inclination and spin

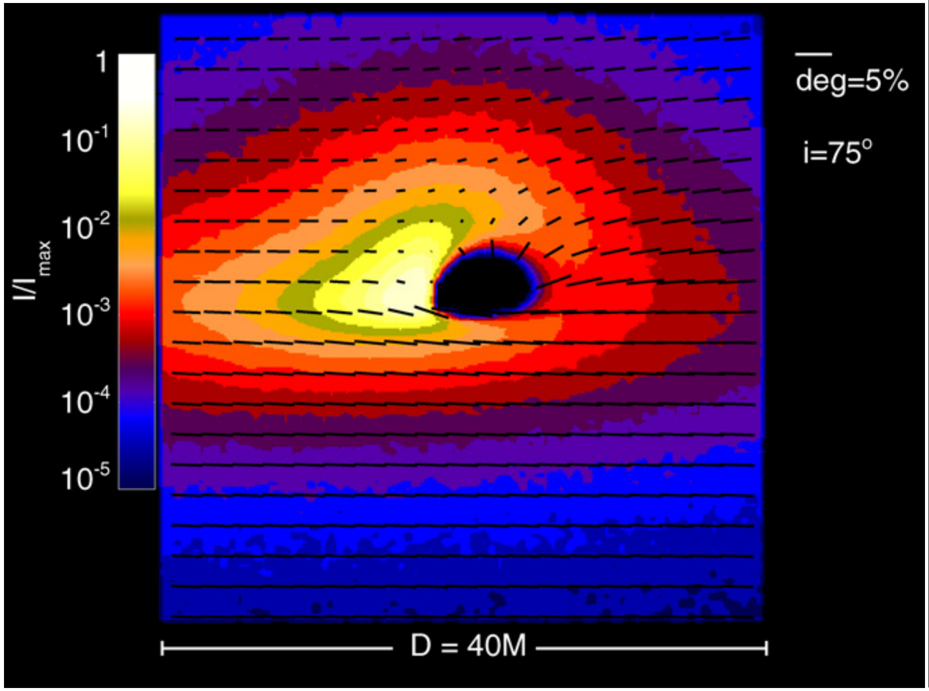




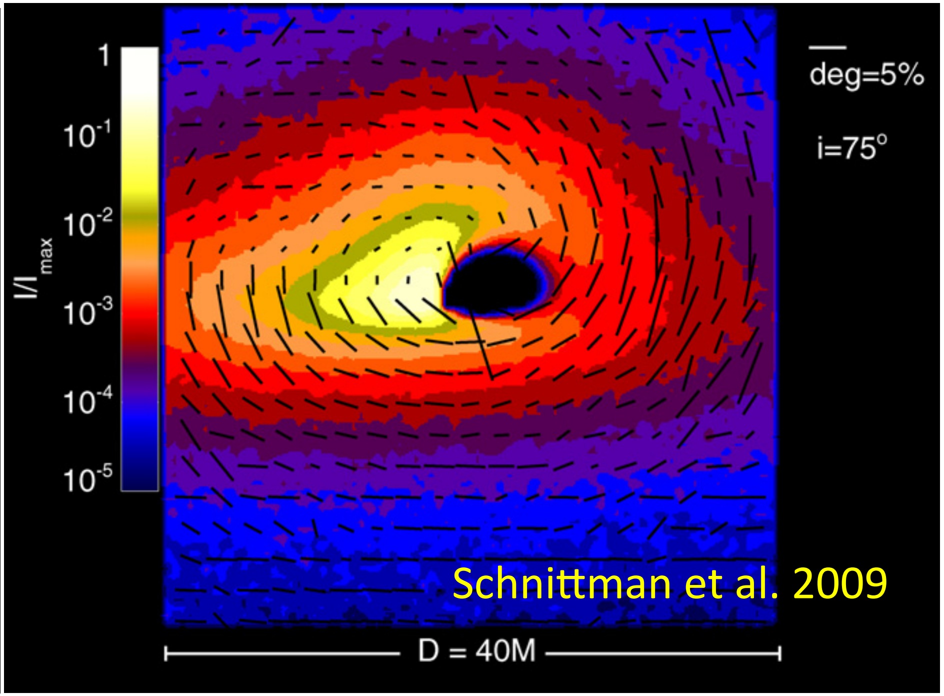
- Polarized due to scattering in disk atmosphere
- GR effects (light bending, returning radiation) will reduce net polarization degree, depending on spin and energy



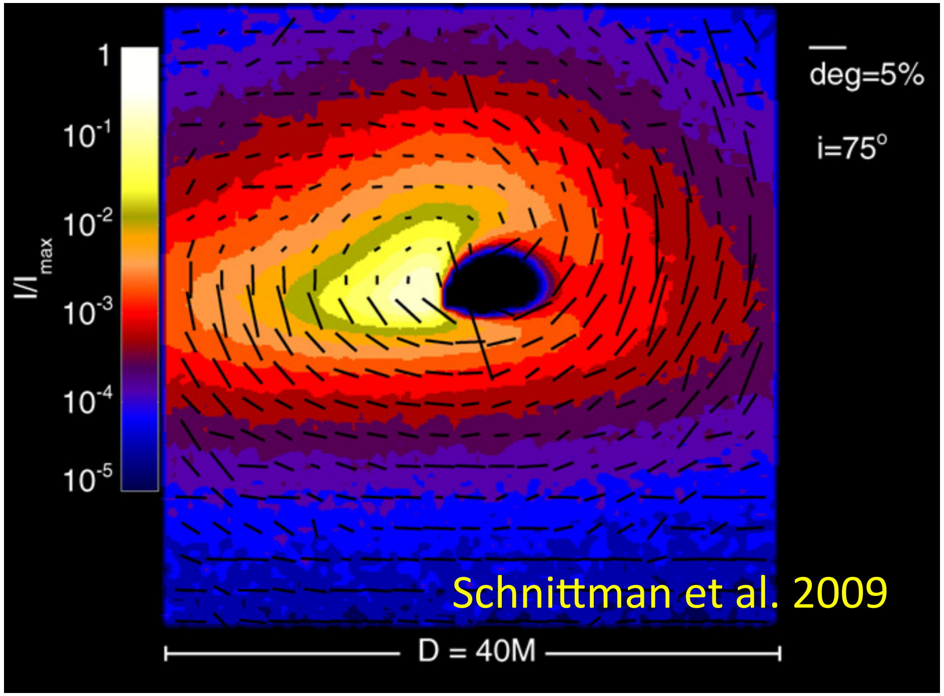
Direct emission of the thermal disk



With returning radiation



- Energy dependent polarimetry



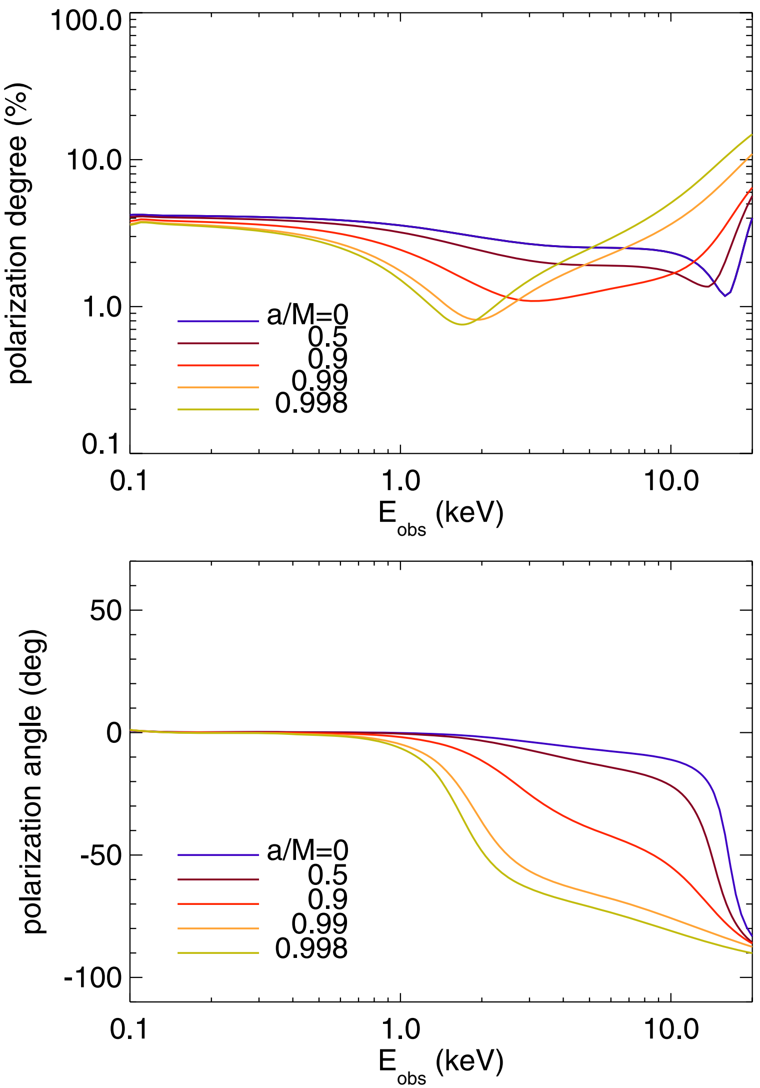
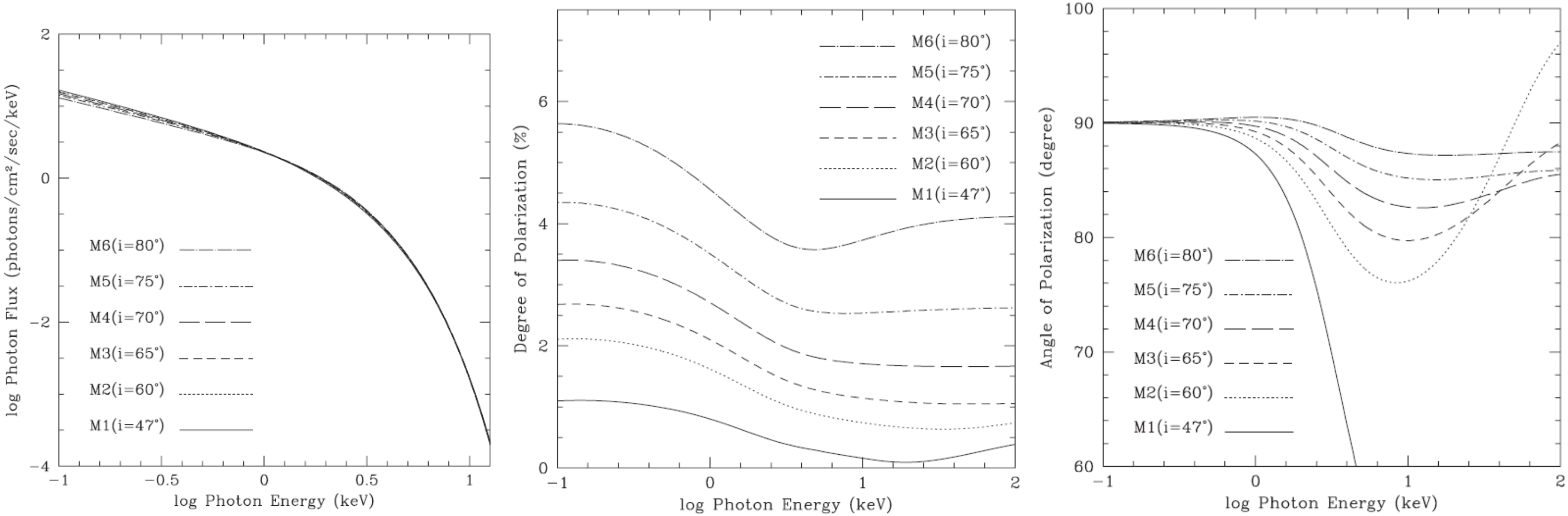


Figure 7. Polarization degree and angle for a range of BH spin parameters. All systems have inclination $i = 75°$, BH mass 10 $M_{\odot}$, luminosity $L/L_{\rm Edd} = 0.1$, and Novikov–Thorne radial emission profiles.

(A color version of this figure is available in the online journal.)

Decoupling spin and inclination

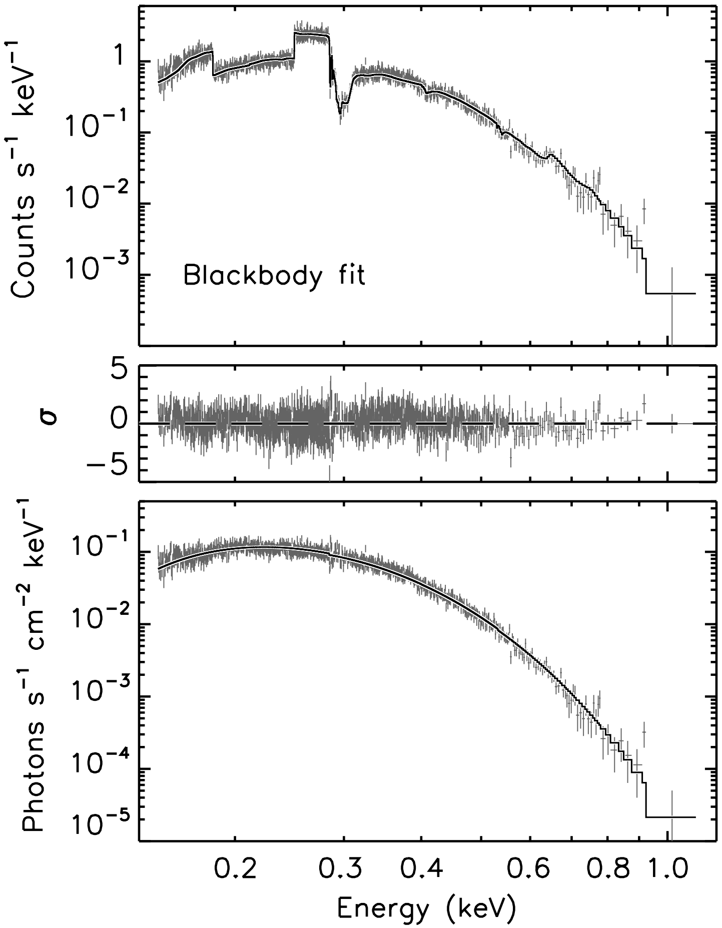
Model	a_*	$i_{\rm disk}$	$\dot{M}$
M1	0.998	47.0	0.48
M2	0.900	60.0	1.00
M3	0.830	65.0	1.40
M4	0.750	70.0	2.00
M5	0.630	75.0	3.20
M6	0.450	80.0	5.80



(Li et al. 2009)

Case C

Thermal emission from the surface of NSs

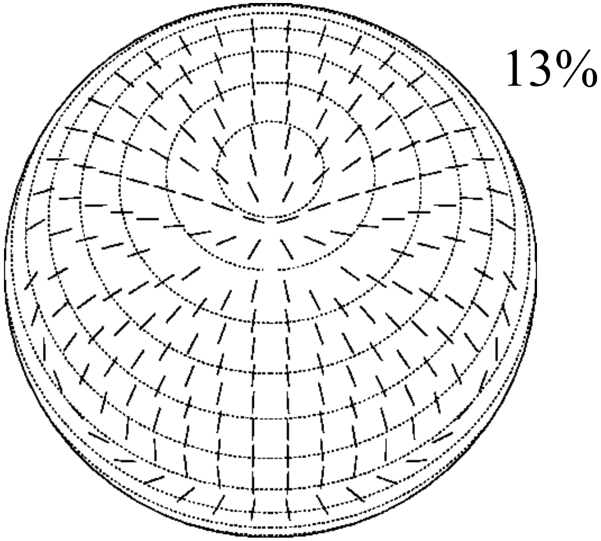


RX J1856.5-3754 (Burwitz et al. 2003)

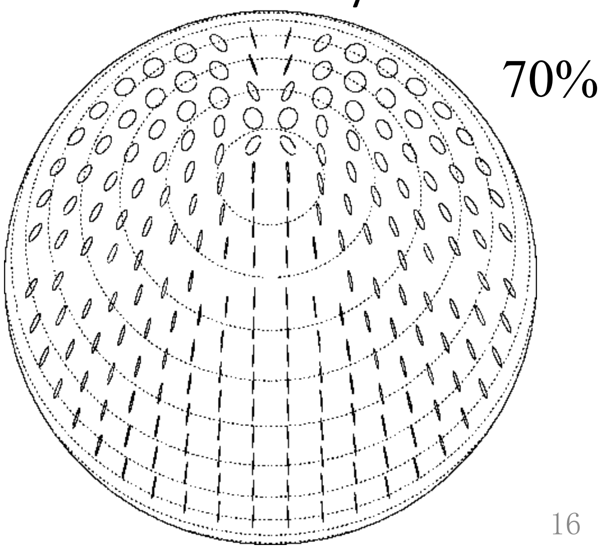
- Low temperature blackbody component
- X-ray dim isolated neutron stars (XDINS)
  - Pure, featureless blackbody spectrum
- Better probe to NS interior
  - Close to the NS body
  - Well known radiation mechanism

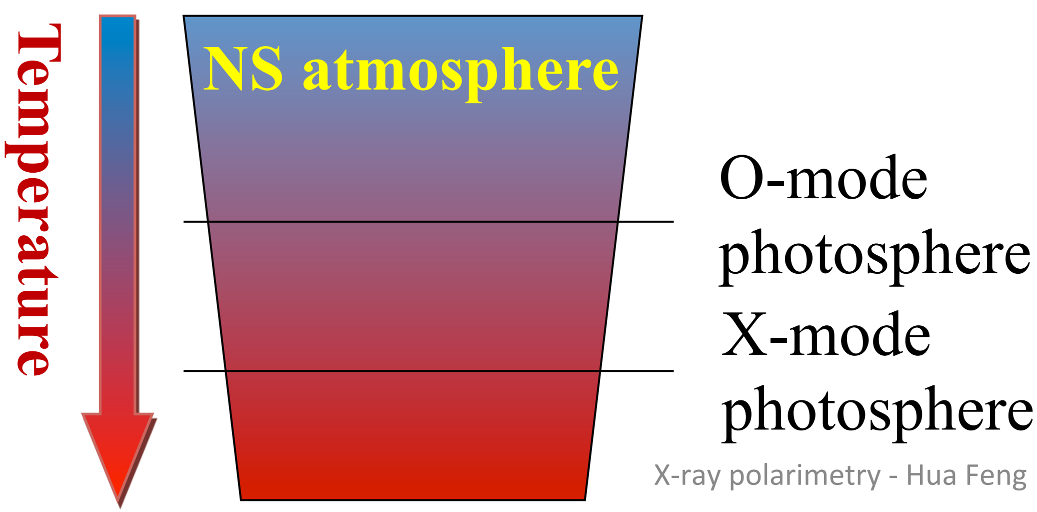
Thermal emission from the surface of NSs

- Magnetized plasma act as polarizer
  - Different scattering cross-section for O-mode & X-mode photons
- QED effect: vacuum birefringence
  - Different indices of refraction for O-mode and X-mode
  - Adiabatic walking (mode conservation): direction of the polarization follows the B-field

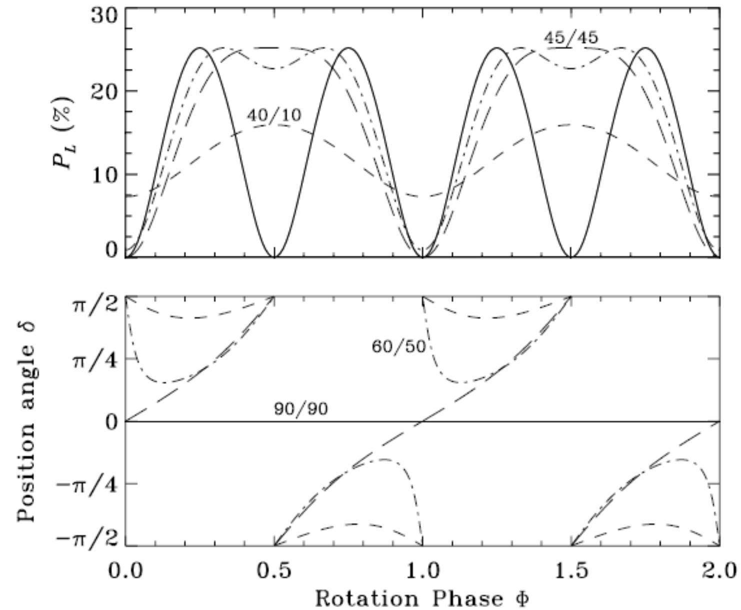


Heyl & Shaviv 2000





- Phase resolved polarimetry
  - B-field (dipole component) strength & orientation
- Neutron Stars
  - High polarization P > 10-30%
- Quark Stars
  - self-bound, no atmosphere (bare)
  - Low temperature gradient
  - $T_{\text{O-mode}} = T_{\text{X-mode}}$
  - Zero polarization (Lu, Xu & Feng 2013)



- Pavlov & Zavlin 2000, ApJ, 529, 1011
- Heyl & Shaviv 2000, MNRAS, 311, 555
- Ho & Lai 2001, MNRAS, 327, 1081
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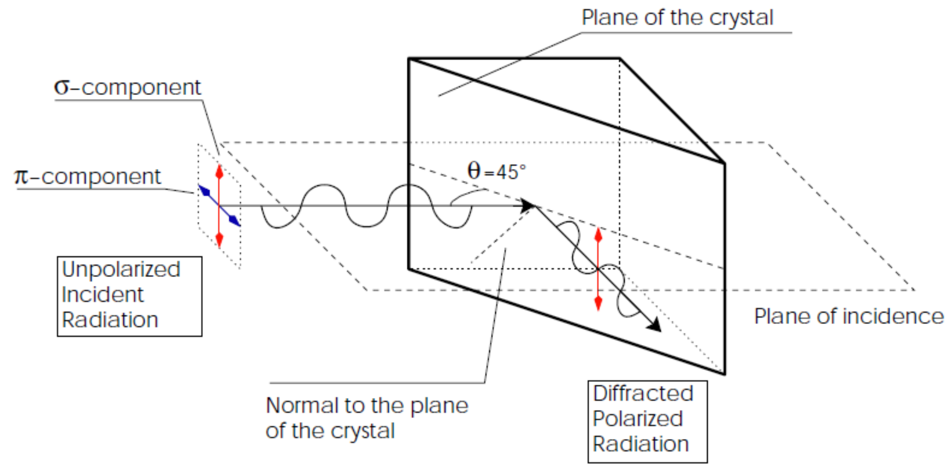
- Heyl, Shaviv, Lloyd 2003, MNRAS, 342, 134
- Lai & Ho 2003, PRL, 91, 1101
- van Adelsberg & Lai 2006, MNRAS, 373, 1495
- Wang & Lai 2009, MNRAS, 398, 515
- Fernandez & Davis 2011, ApJ, 730, 131

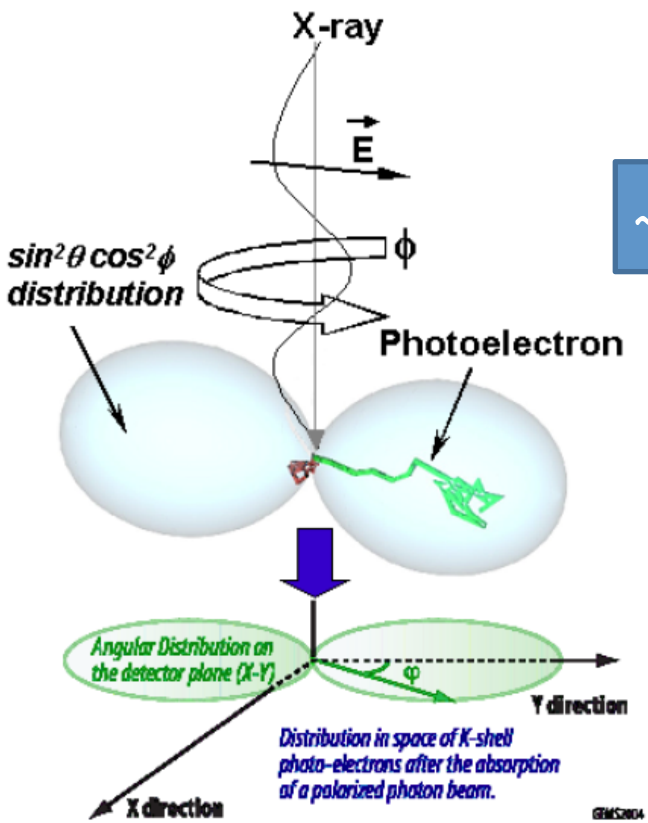
Science cases with X-ray polarimetry

- Neutron Stars
  - Rotation-powered pulsars: emission mechanism (polar cap/slot gap/outer gap)
  - Accretion-powered pulsars: pencil beam vs. fan beam
  - Millisecond pulsars: geometry
  - Thermal emission from the surface: B-field
- Black Holes
  - Black hole spin measurement
  - AGN: disk inclination & scattering geometry
  - Corona geometry
  - Sgr B2: history of activity of Sgr A*
- Relativistic Jets
  - Structure of magnetic fields
- Pulsar wind nebula
  - Magnetic fields
- Supernova remnants
  - synchrotron or non-thermal bremsstrahlung
  - magnetic fields and particle acceleration
- GRB prompt emission & afterglow
  - emission mechanism & B-fields
- Solar flares
  - Magnetic reconnection

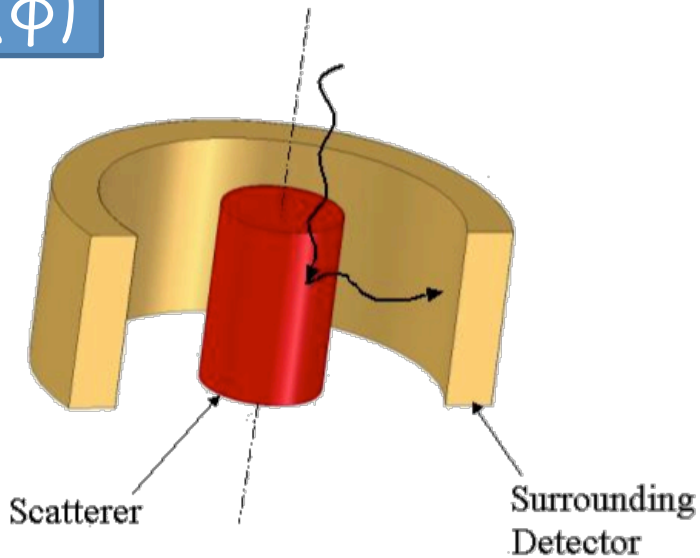
How to detect X-ray (0.1-30 keV) polarization

- Bragg diffraction
- Thomson Scattering
- Photoelectric effect





~ $\cos^2(\phi)$



History: Bragg polarimeters

WEISSKOPF *ET AL.*

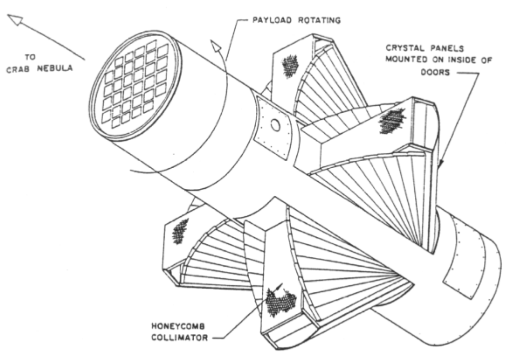
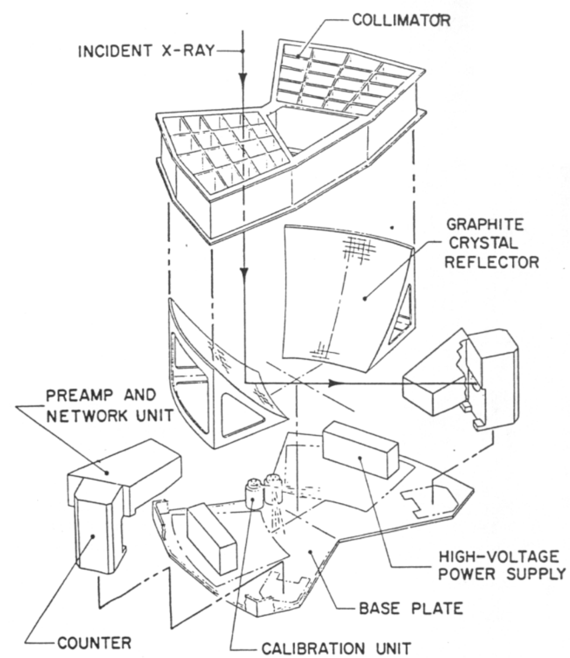


FIG. 1. Aerobee-350 x-ray polarimeter payload. The rocket is shown in flight configuration after target acquisition. The honeycomb collimator and flaps on the sides of the doors were used as an rf shield and to prevent direct illumination of the proportional counter by the diffuse x-ray background.

Rocket, 1972, 247 s observation

Crab nebula $P = 15.4 \pm 5.2$



OSO-8, 1975-1978

450 R. E. Griffiths et al. Vol. 175

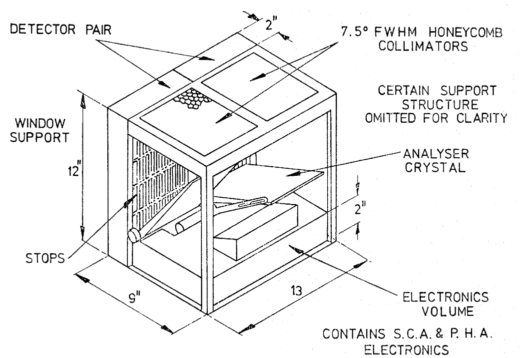


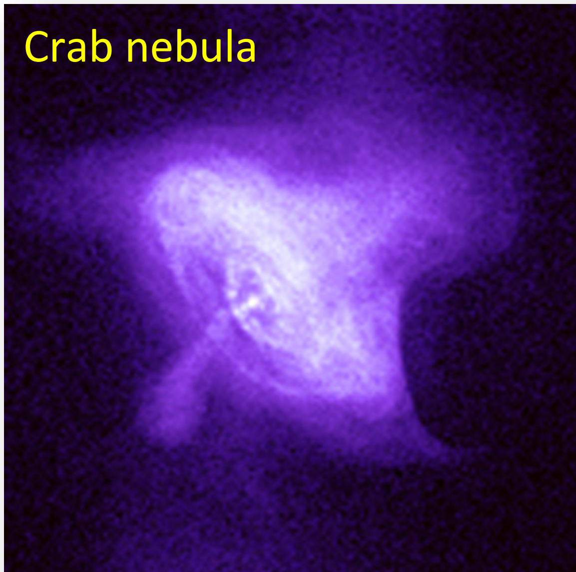
FIG. 1. *A schematic representation of the Leicester crystal spectrometer/polarimeter on Ariel V.*

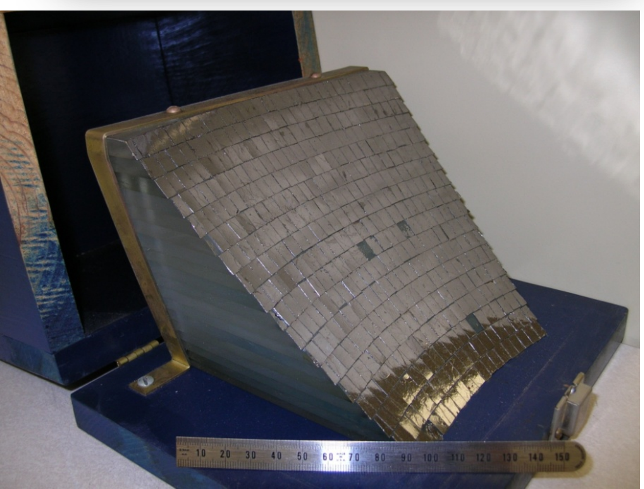
Ariel 5, 1974-1975,

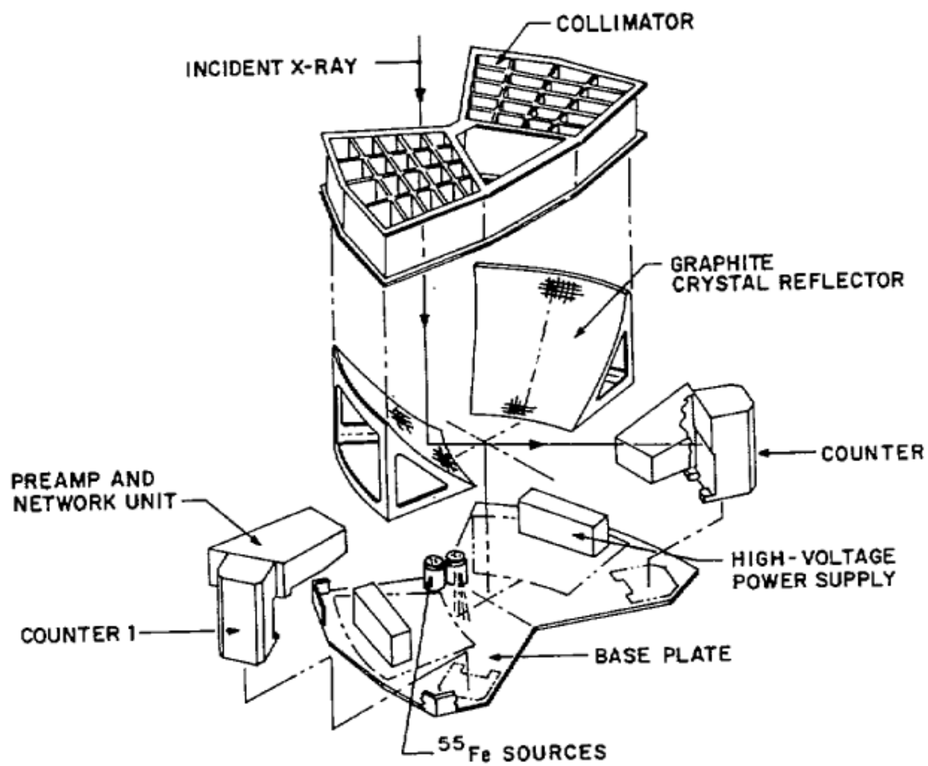
flat crystal, background too high

History: the only positive result so far

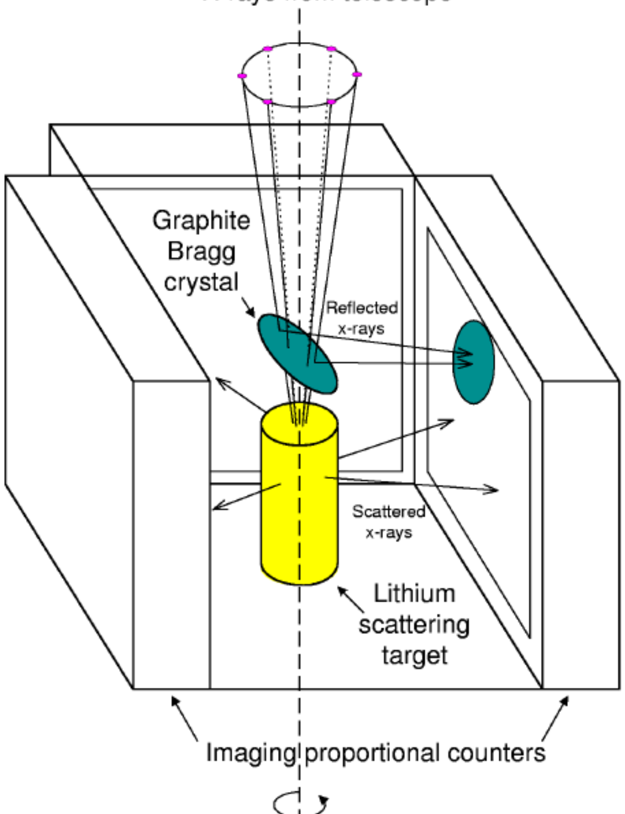
- 1975 OSO-8
  - Crab Nebula
  - $P = 19\% \pm 1\%$
  - $\varphi = 156° \pm 2°$
  - Weisskopf et al. (1976, 1978)

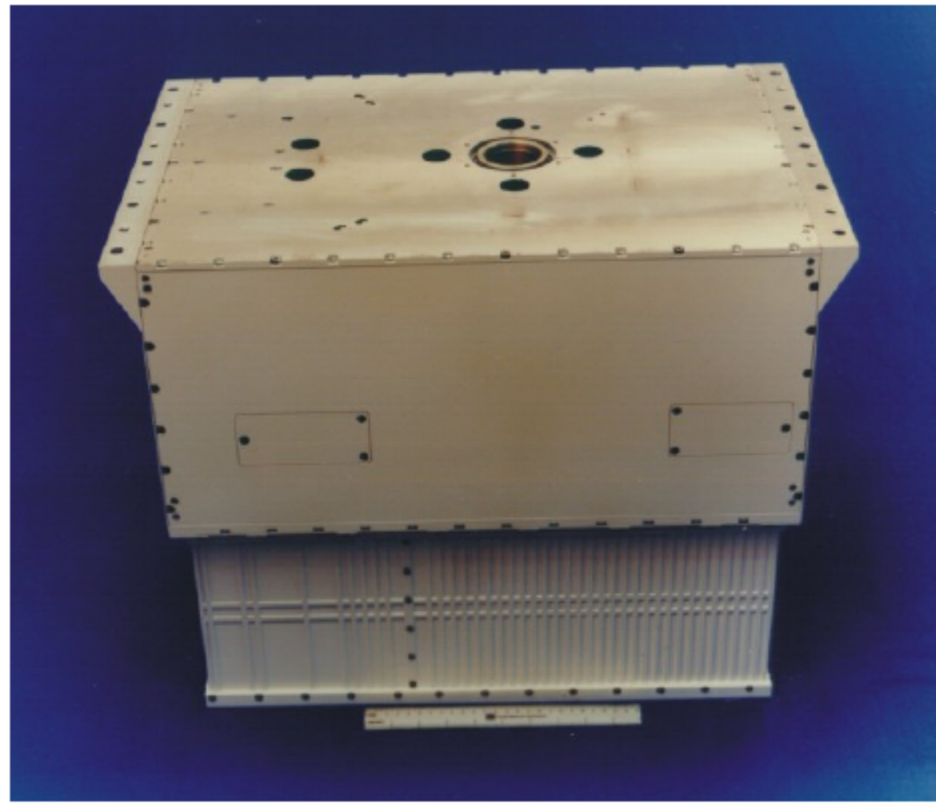






History: The Stellar X-Ray Polarimeter built but never flew (spectrum-X-gamma)



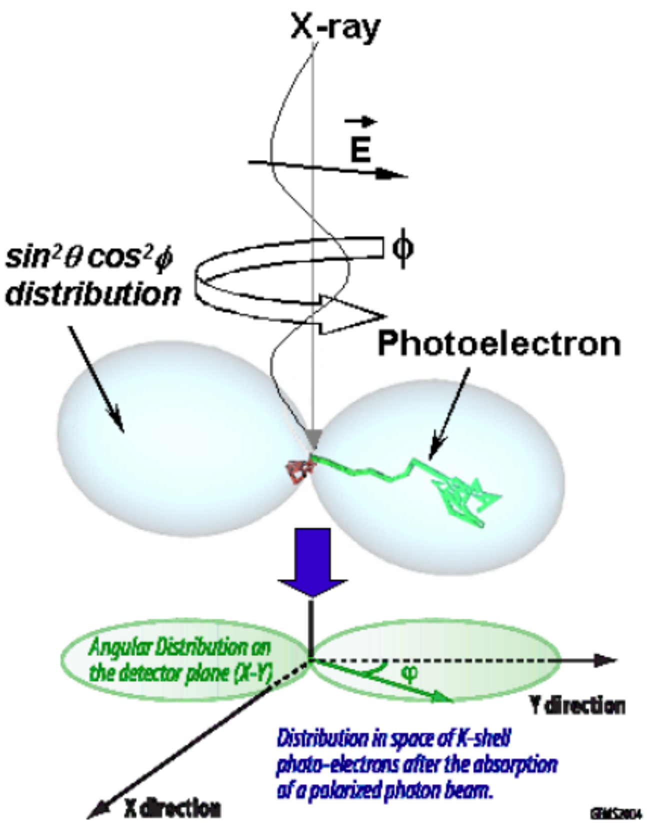


Flight model

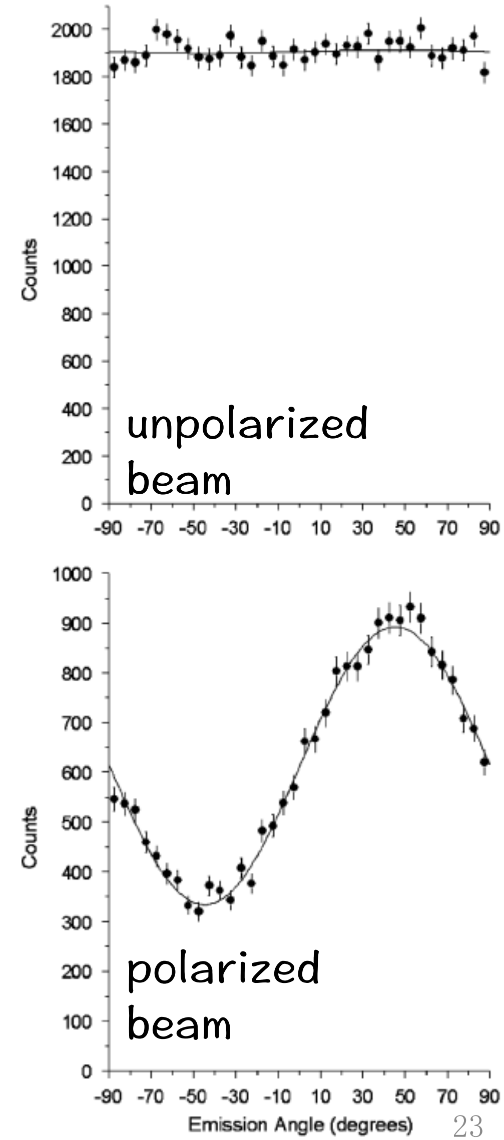
Photoelectric polarimeter

Cross-section of photoelectric effect

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

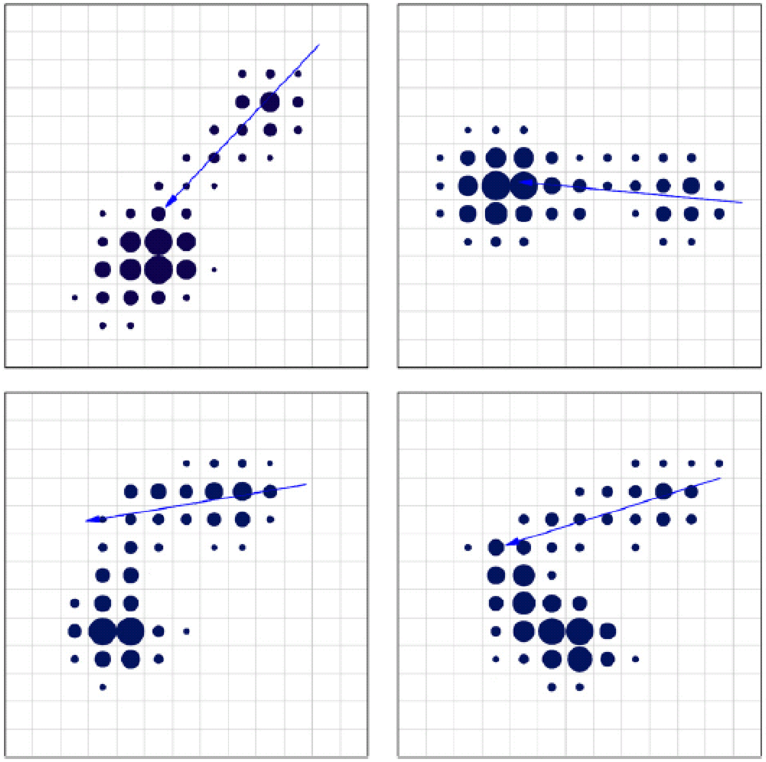


$$\frac{d\sigma}{d\Omega} \propto \cos^2\varphi$$



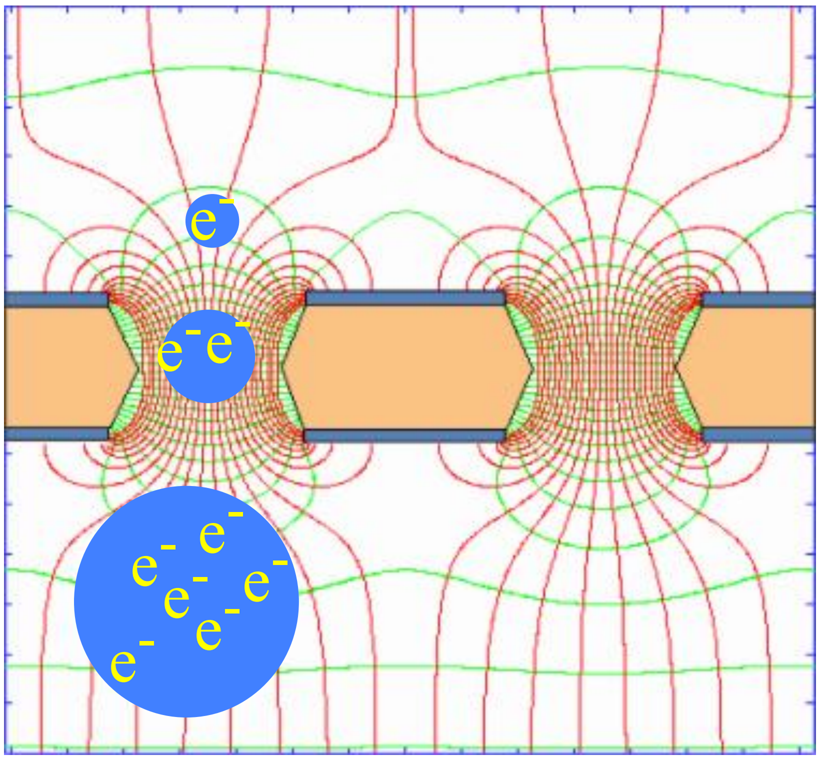
Technical difficulties

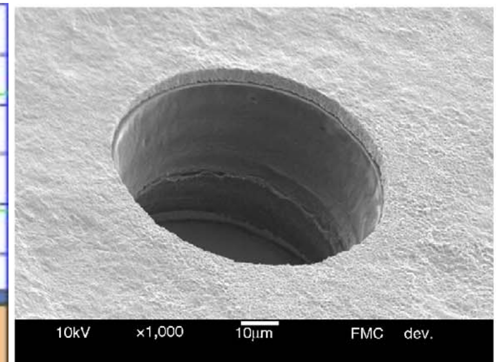
- Short range for electrons of a few keV
  - in silicon: ~μm
  - in gas: ~mm
  - Require 2D imaging device
- Electron tracks are not straight during ionization
- Challenge for nuclear detector

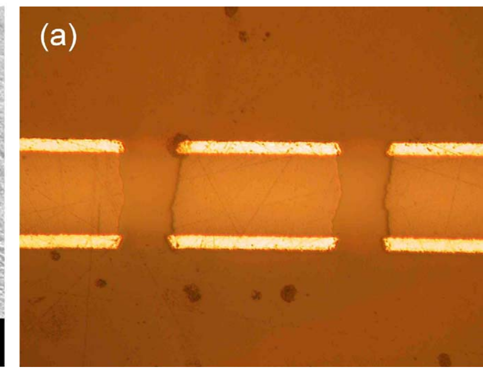


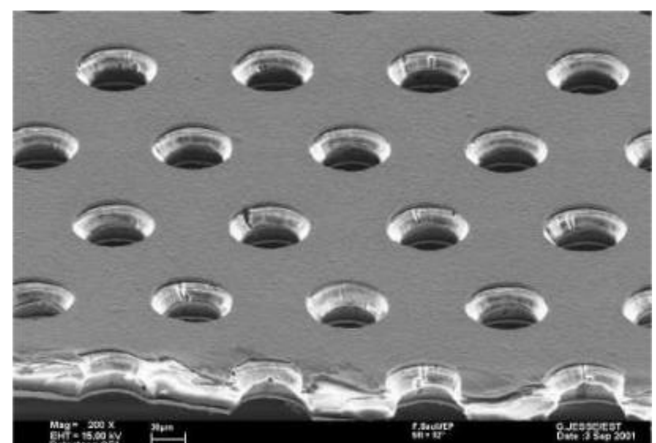
Micro-Pattern Gas Detector (MPGD)

- GEM (gas electron multiplier)
  - Electron multiplication in micro-holes
  - Spatial resolution ~100 μm



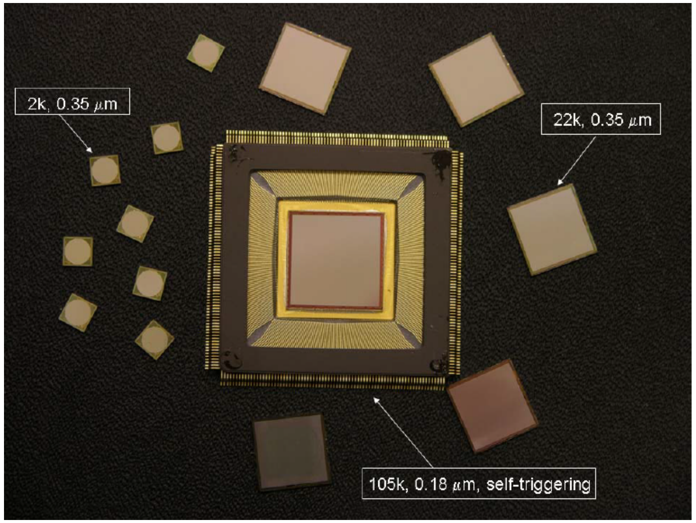


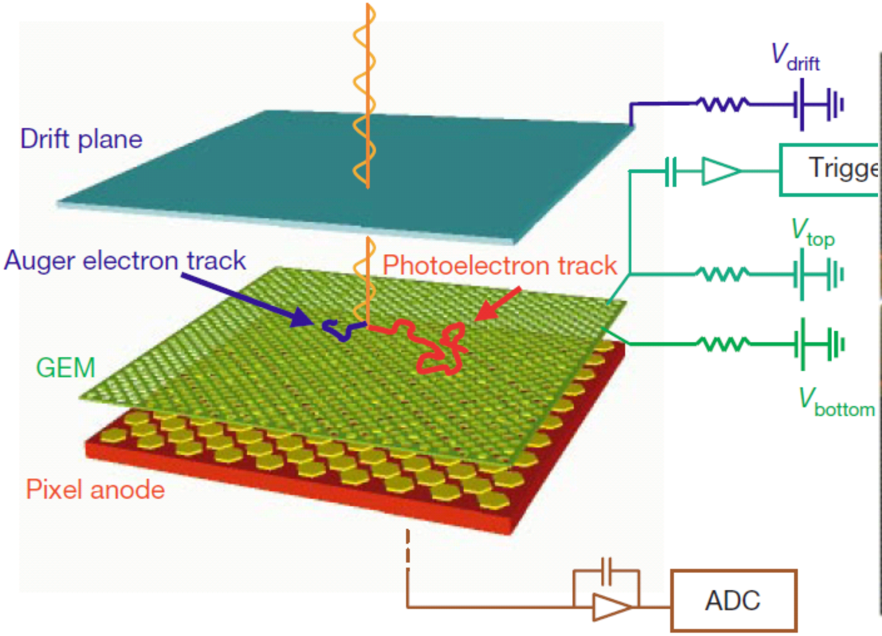


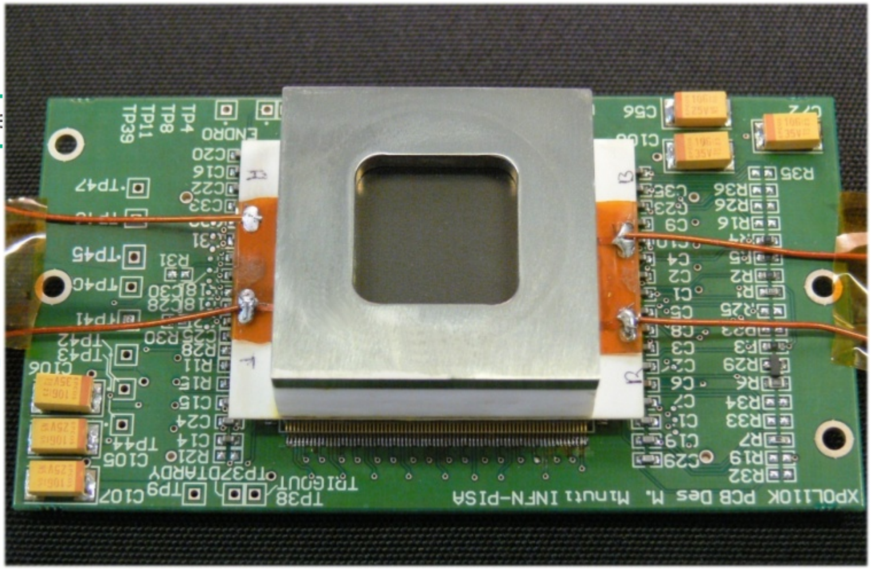


Gas Pixel Detector

- Direct 2D imaging
  - Pixel size 50µm
  - 110k pixels

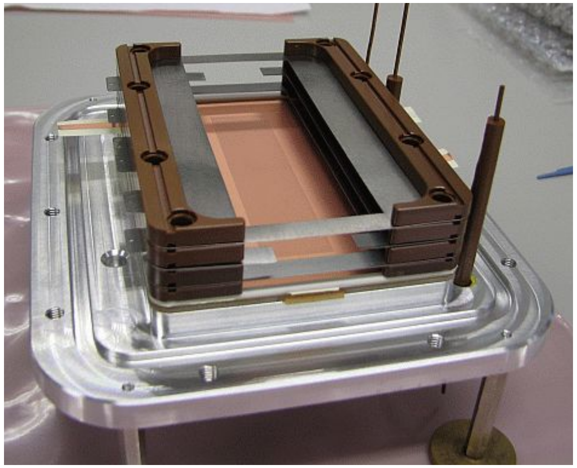


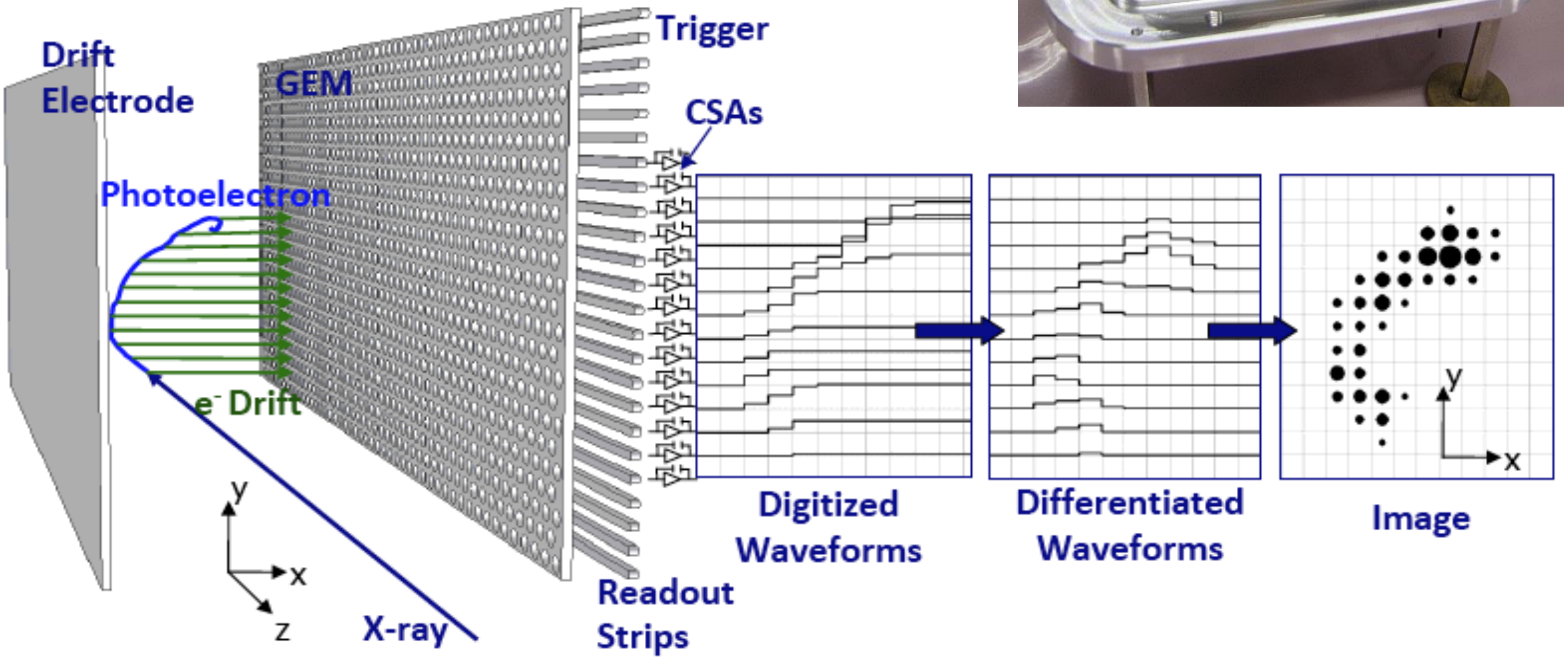




Time Projection Chamber

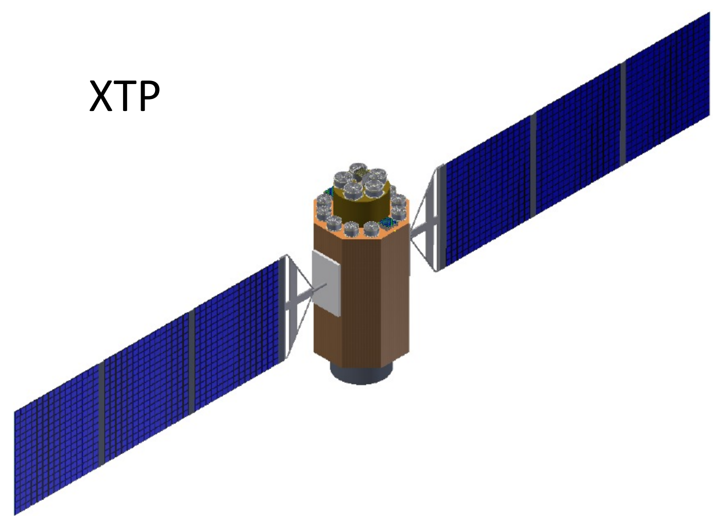
X: time difference × drift velocity
Y: strip position
Advantages: high efficiency, less readout channels



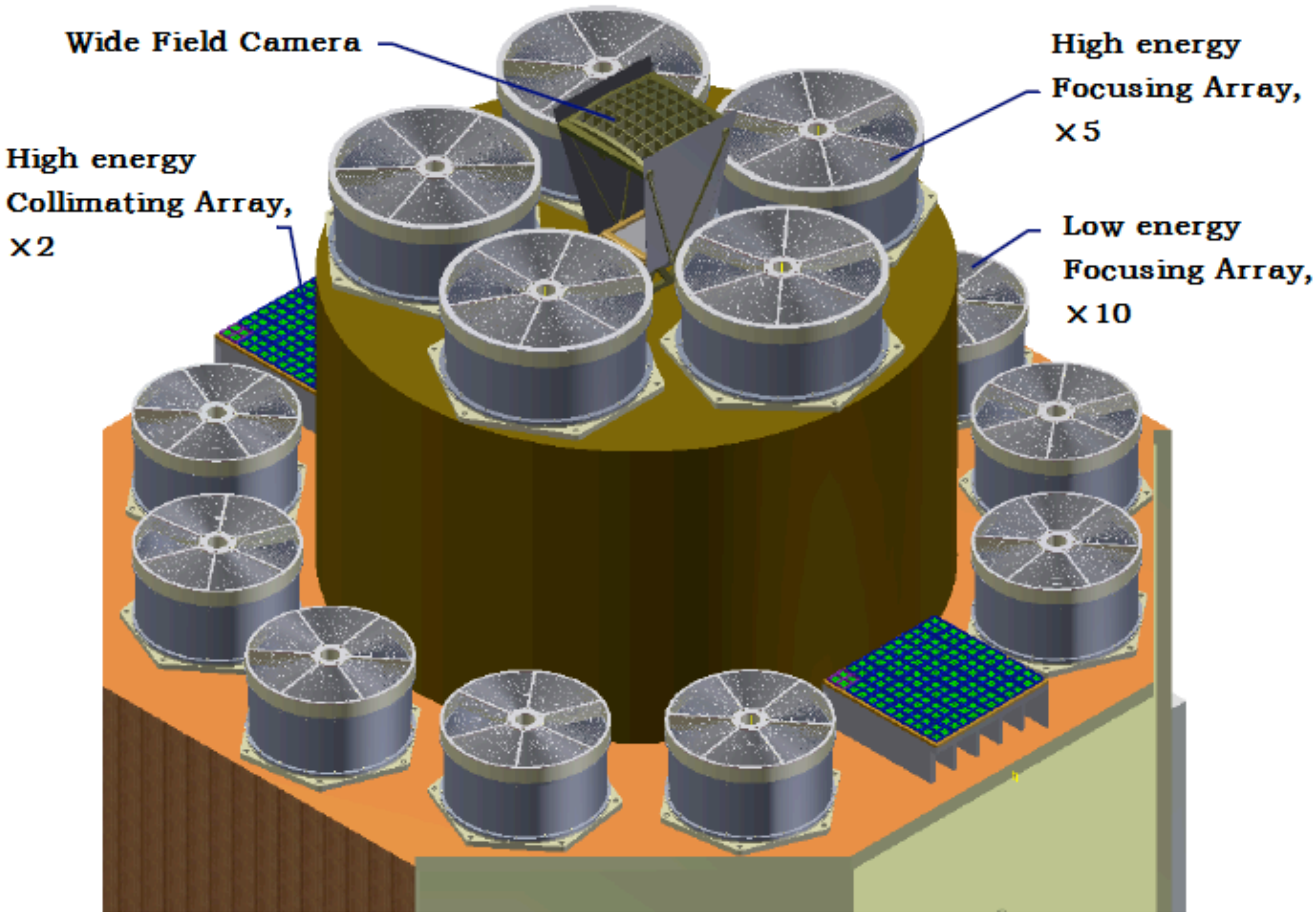


Future: photoelectric polarimeters

- GEMS, canceled in 2012
- XIPE, not selected by ESA
- XTP, selected for early phase study
- Orders of magnitudes improvements in sensitivity
- 2-10 keV or 10-30 keV

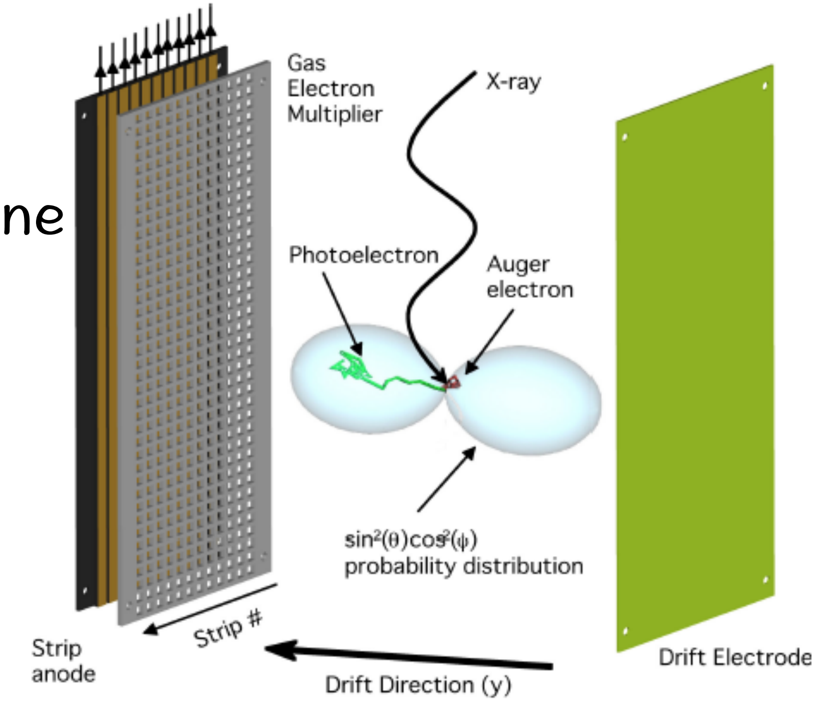


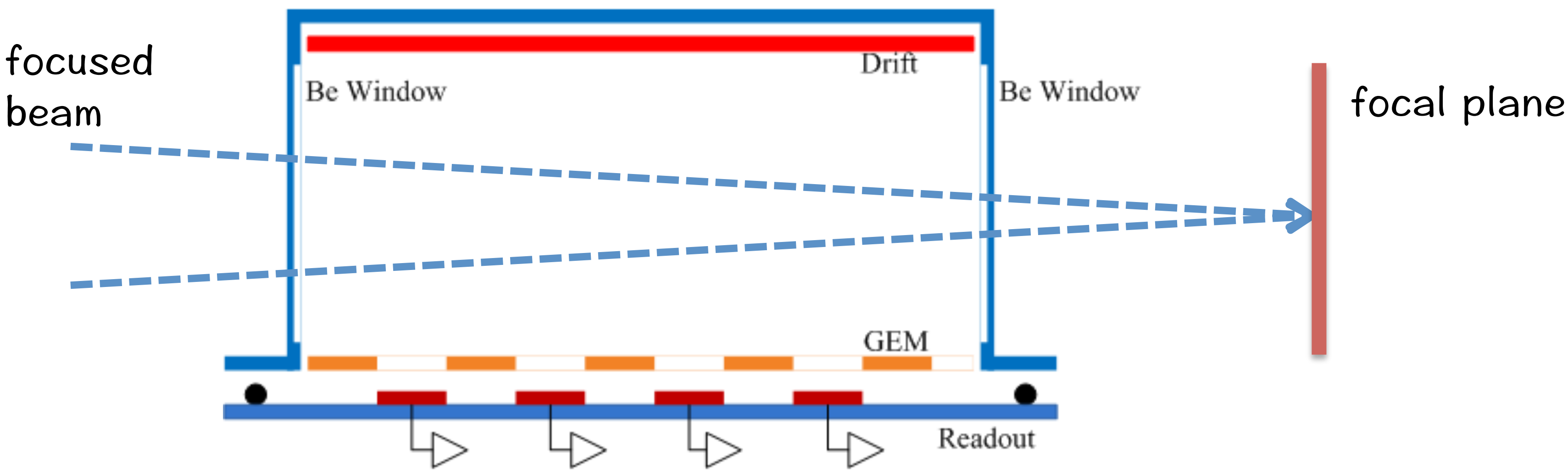
XTP payload



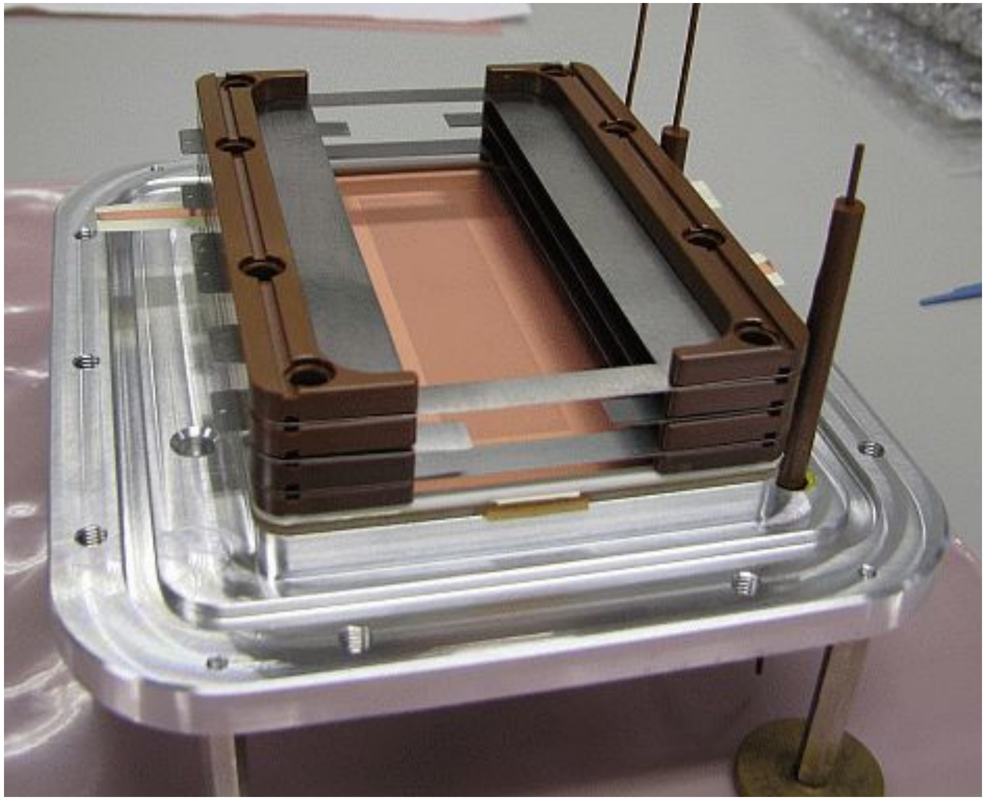
Wide Field Camera
High energy Focusing Array, ×5
High energy Collimating Array, ×2
Low energy Focusing Array, ×10

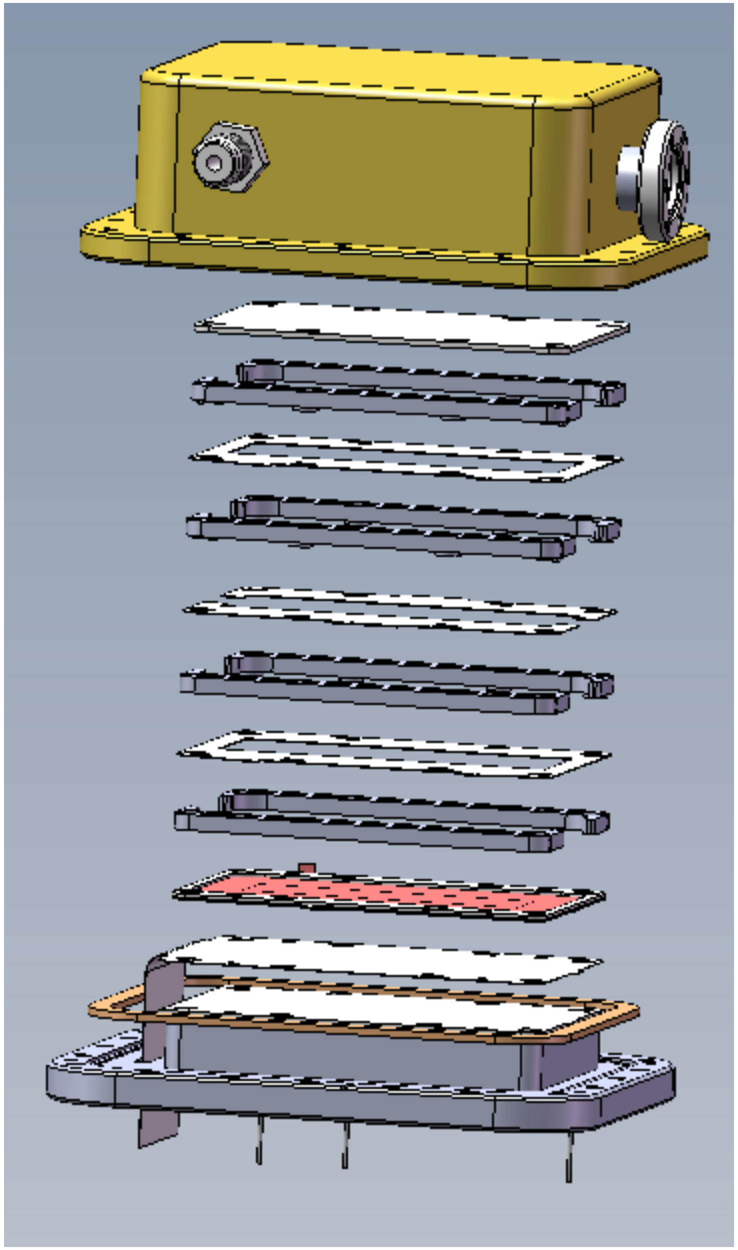
TPC polarimeter above the focal plane
Opaque to low energy photons
Transparent to high energy photons



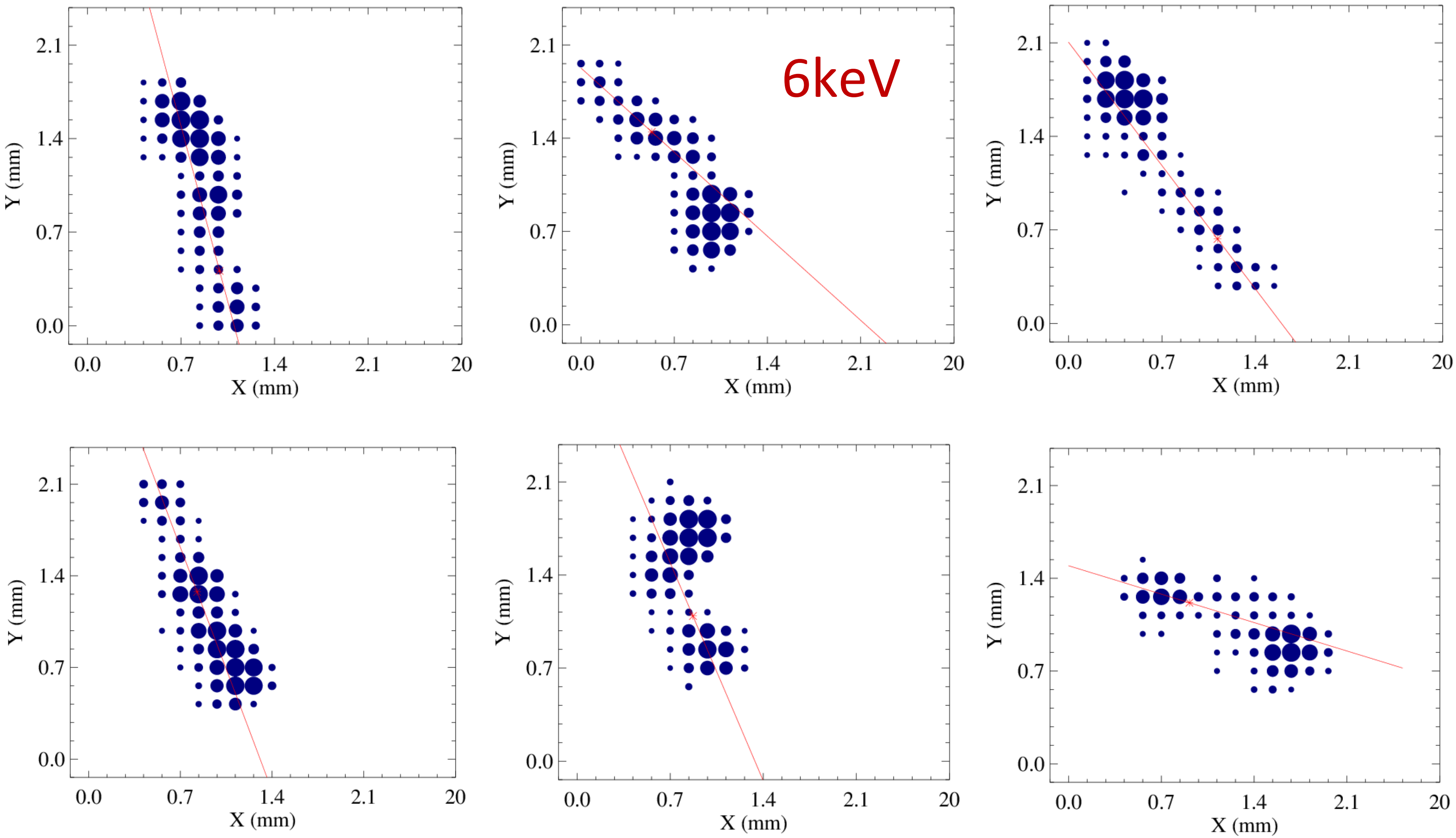


Prototype





➢ Measured photoelectron tracks



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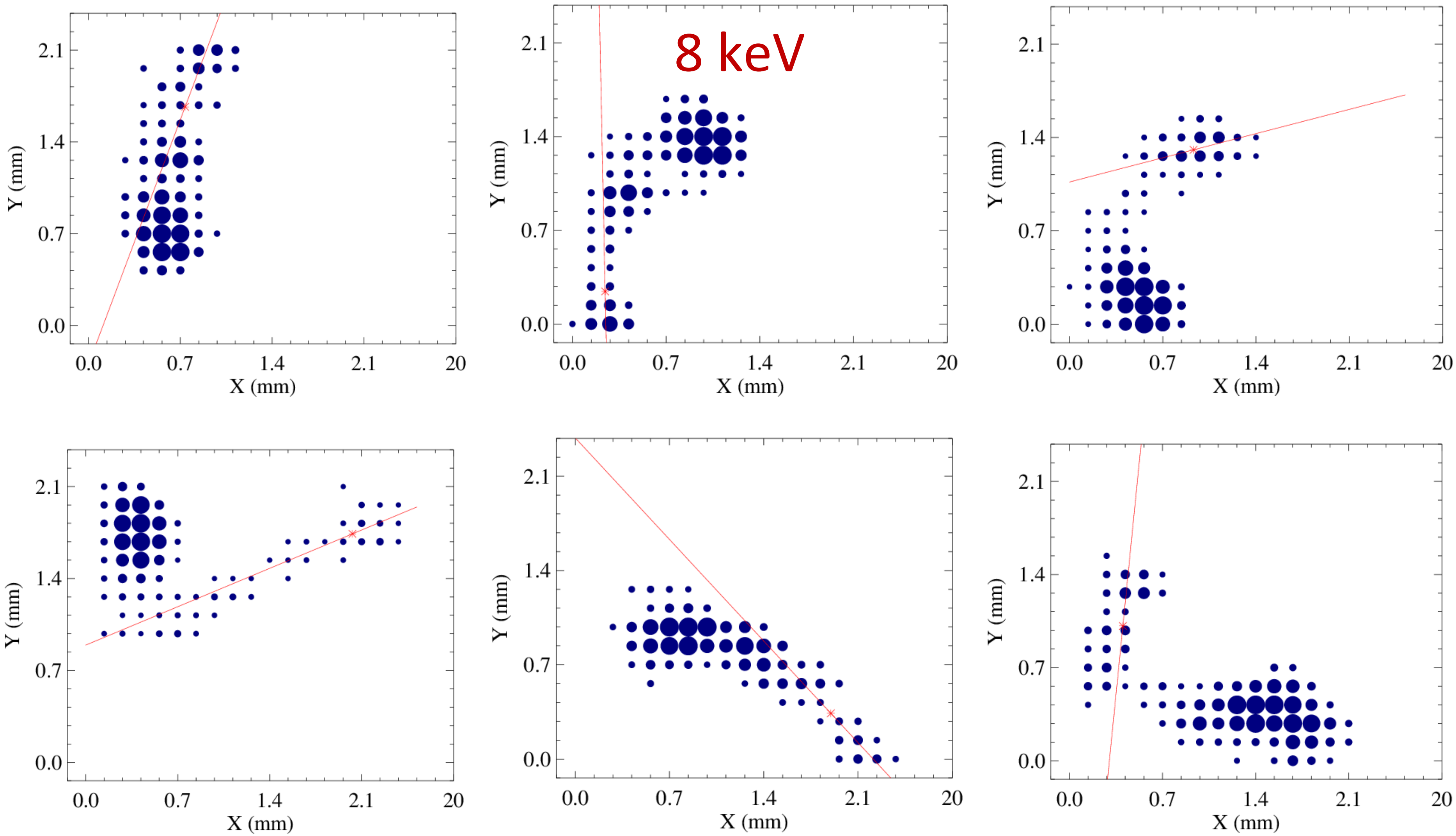
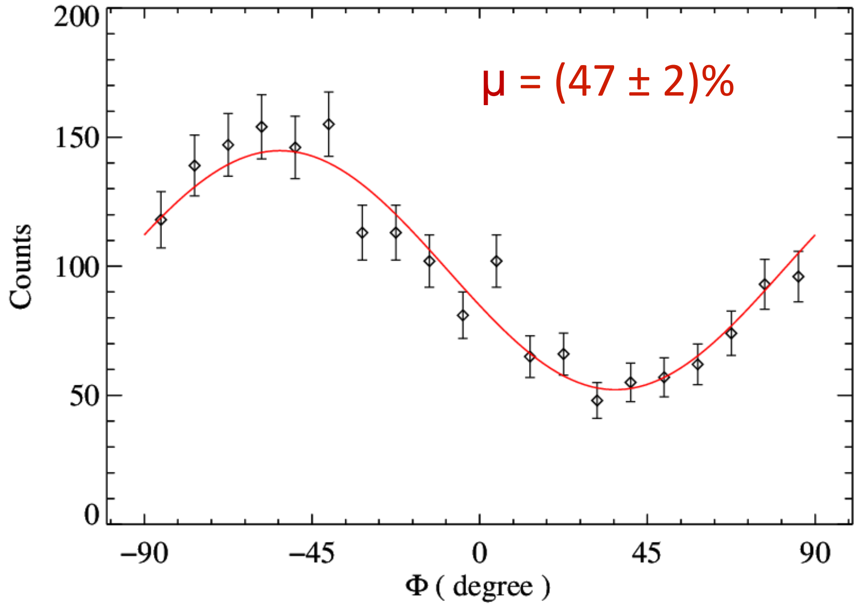
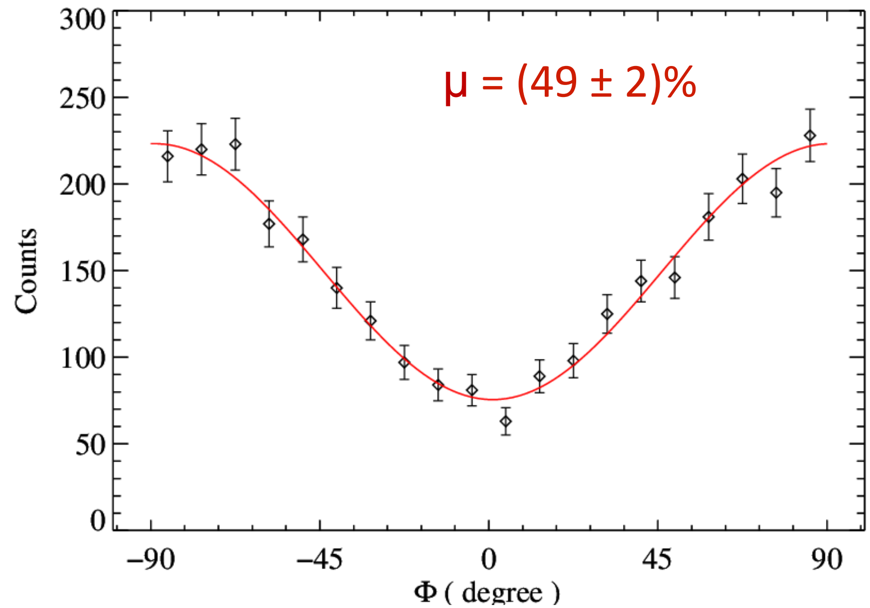
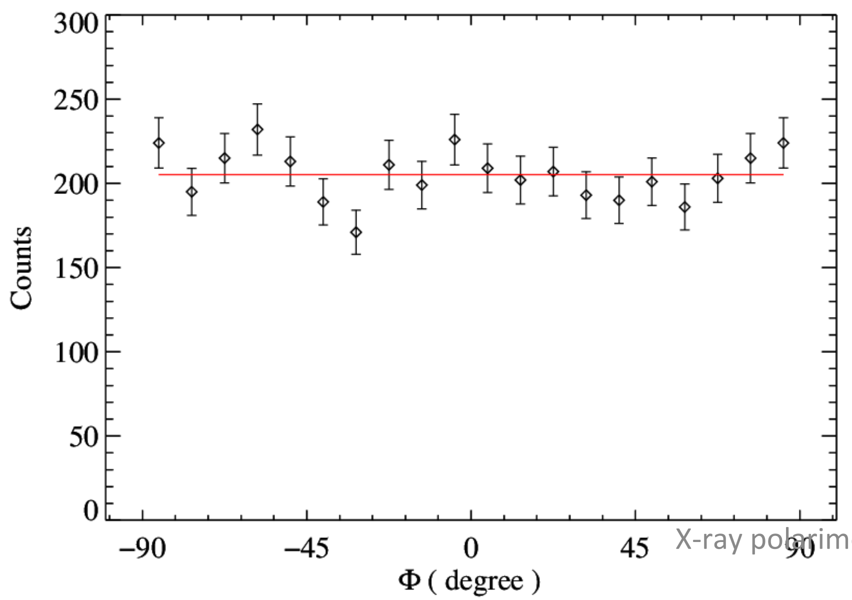


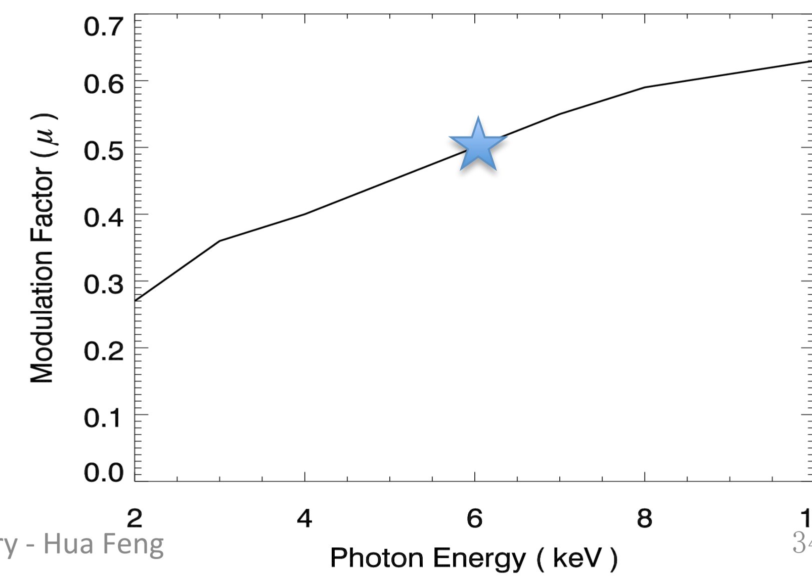
➢ Modulation curves

50% at 6 keV









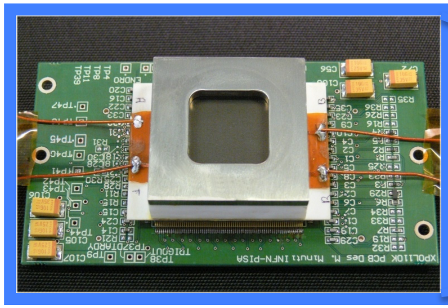
Technical difficulty: detector sealing

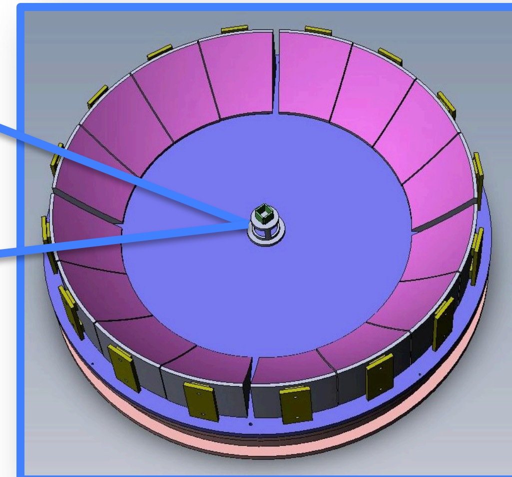
- Long lifetime sealed proportional counter
  - NASA/Goddard Space Flight Center
  - Oxford Instrument Analytical Oy
- Outgassing of materials decreases electron transportation rate
  - High vacuum technology + nuclear detector technology
  - Our detectors are now approaching a lifetime of 5-10 years

- No X-ray polarimeter planned before 2020
- Photoelectric polarimeters
  - On the focal plane of X-ray mirrors
  - Long focal length
    - Large envelope or deployable bench
  - At least ~100 kg and relatively high cost
- What to do in the near future?
  - In the framework of a micro-satellite?

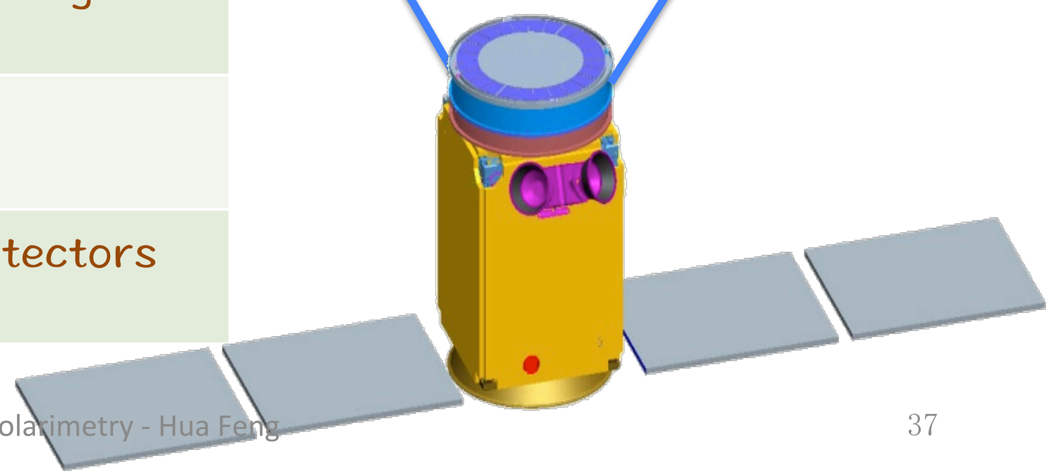
LAMP

Lightweight Asymmetry and Magnetism Probe

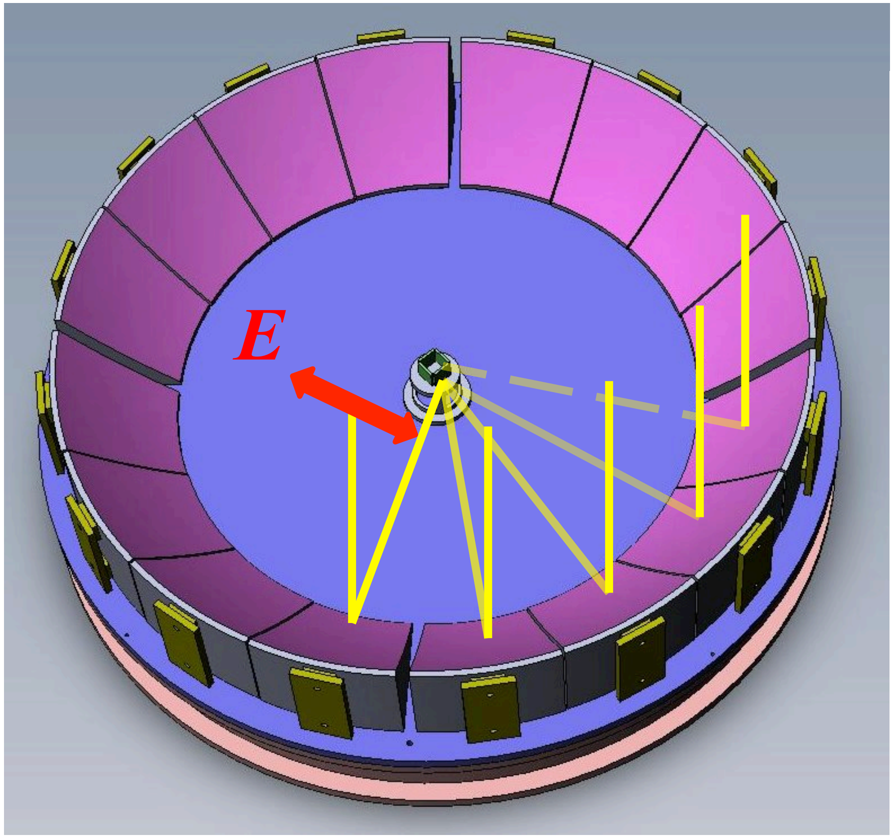




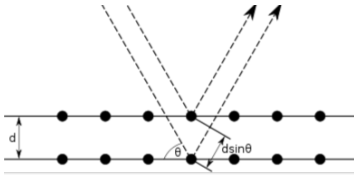
Optics	16 segments of paraboloidal multilayer-coated mirrors
Energy	250 eV; bandwith 2.6 eV
Weight	< 35 kg for payload; ~100 kg in total
Collecting area	1300 cm^2
Focal plane detector	Position sensitive gas detectors with ultrathin window

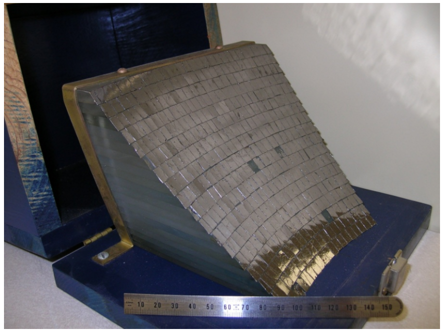


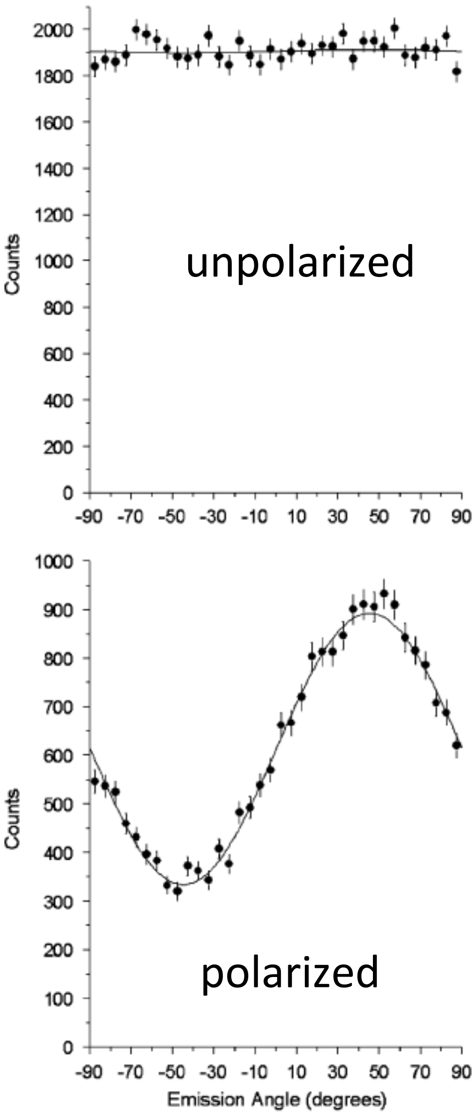
Improved Bragg polarimeter



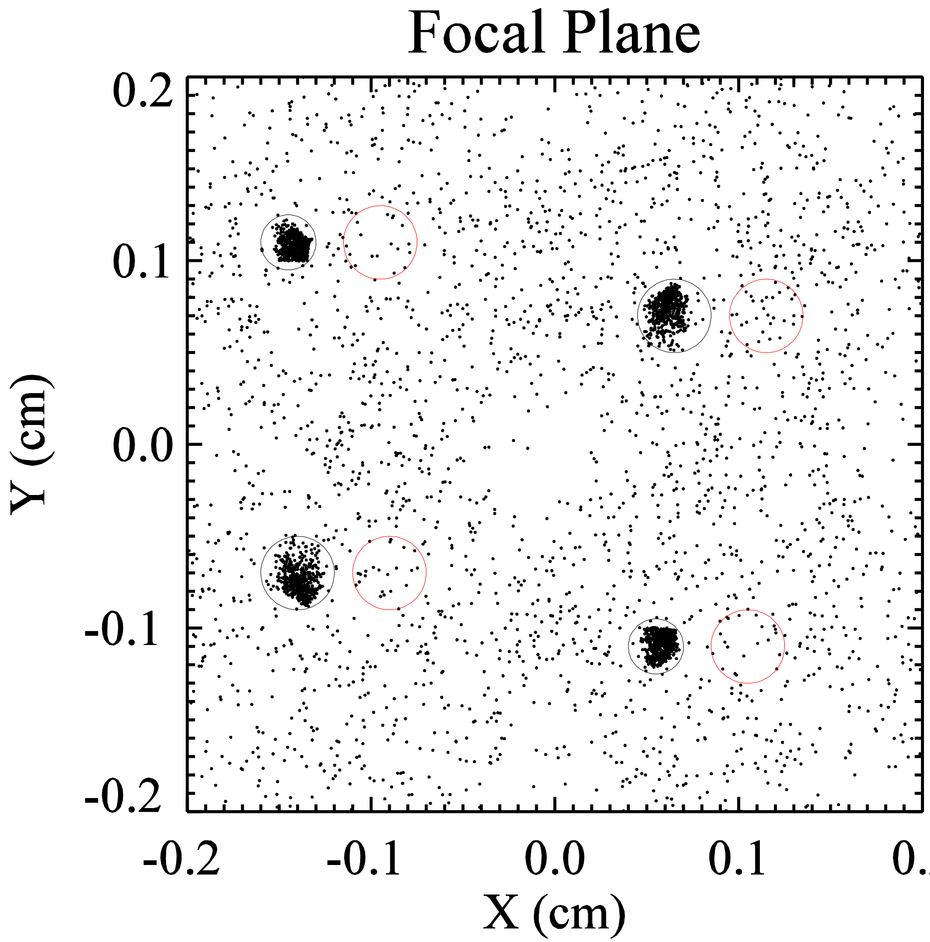
$$2d\sin\theta = m\lambda$$

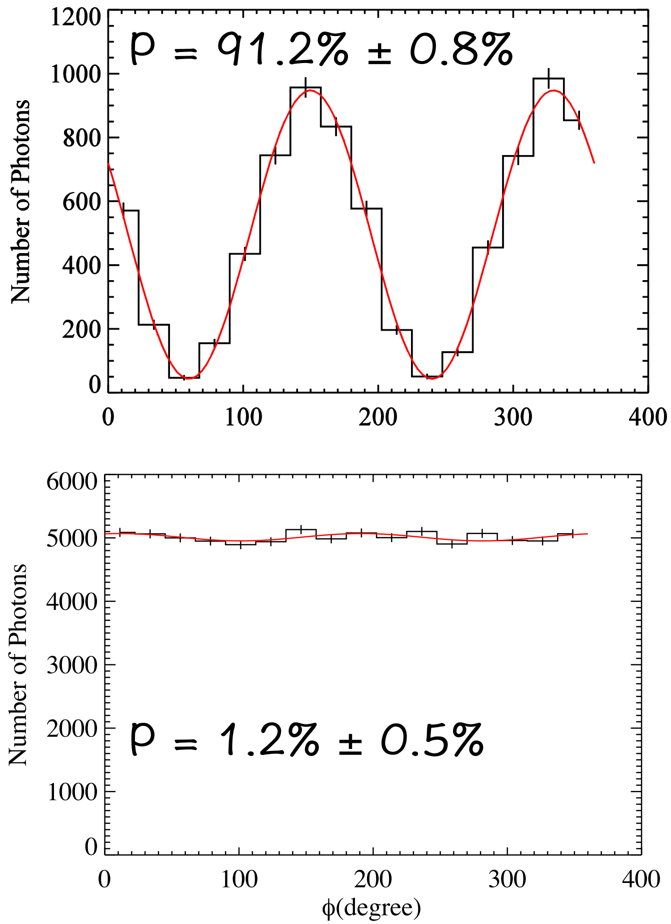






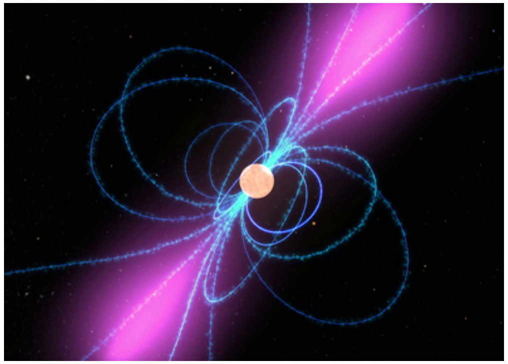
Simulation with raytracing

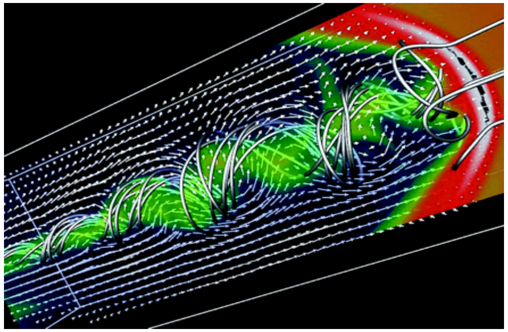


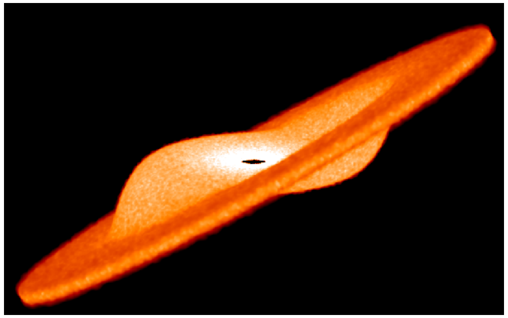


Science with LAMP

- ✧ Measuring the magnetic field structure of pulsars and testing the vacuum birefringence predicted by QED
- ✧ Capable of finding bare quark stars if they exist
- ✧ Probing the magnetic fields in relativistic jets: their role in jet formation, collimation, and acceleration
- ✧ Measuring the inner disk inclination: spin measurement and AGN geometry







Sensitivity

Minimum detectable polarization

$$MDP = \frac{4.29}{\mu S}\sqrt{\frac{(S+B)}{T}}$$

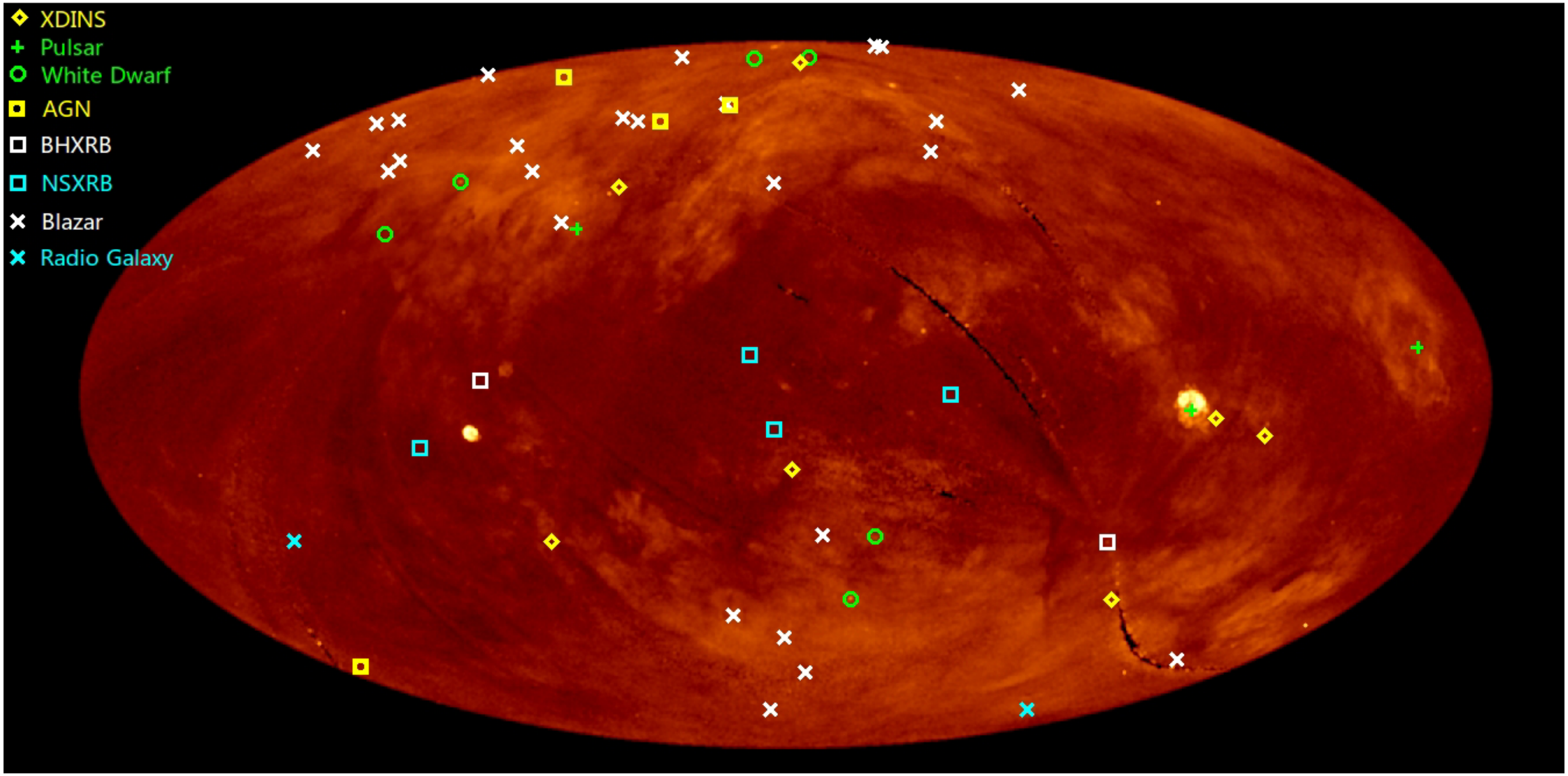
MDP ~ 1% for brightest objects

$T = 10^6$ s, 99% c.l.

Type	Number (MDP < 0.1)	Number (MDP < 0.2)
XDINS	3	5
Pulsars	3	3
Persistent XRBs	17	28
Blazars+QSO	42	171
AGN	100	408

Core program

- 1.5-2 years: the brightest of each class



Summary

- Astronomical X-ray polarimetry
  - High technical readiness level
    - Photoelectric polarimeter based on gas detectors
    - Bragg polarimeter based on multilayer mirrors
    - Long lifetime proportional counters: technical ready in China
- Opportunities for China
  - XTP: <4500 kg, under early phase study
  - LAMP: <100 kg, 3 years for technical demonstration, 5-6 years to launch
  - A pathfinder: <10 kg?
- Welcome to join the science team of LAMP!