eXTP Polarimetry

A New Science Window

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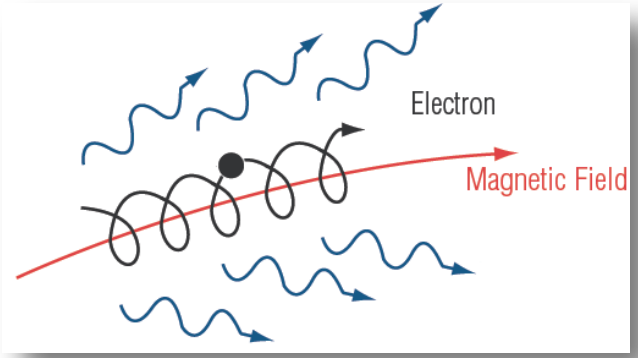
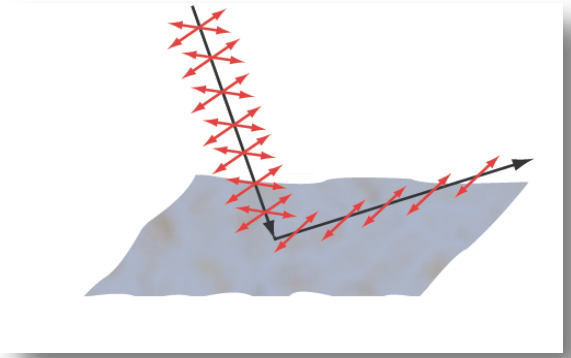
Outline

- Science with X-ray polarimetry
  - What are the unique science cases?
- A new window and beyond
  - History, today, and the future
- eXTP polarimetry
  - Instrument design
  - Optimization

What can we learn with X-ray polarimetry?

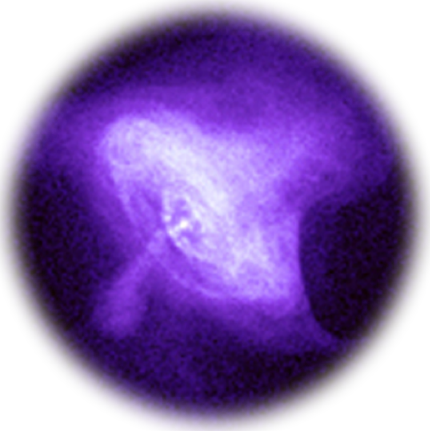
- **Information about the magnetic field**
  - Synchrotron radiation (PWNe, SNRs, Jets)
  - Plasma polarization (Magnetized plasma)
  - Vacuum polarization (Neutron Stars)
- **Information about the scattering medium**
  - Thomson/Compton/InverseCompton scattering
  - Geometric Symmetry (accretion flow, BH spin, Sgr B2, etc.)



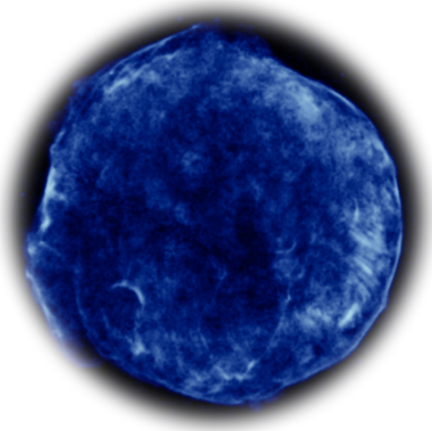


Unique science cases

- Particle acceleration
  - Probe the magnetic fields and place constraints on the acceleration mechanism
- Need angular resolution
  - 30" or better?



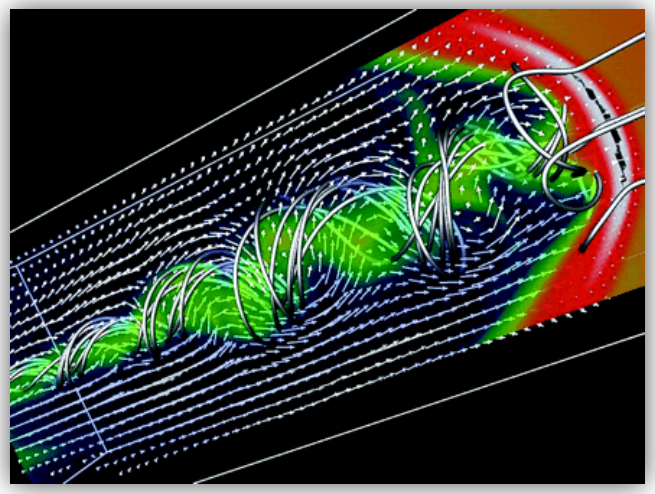
Pulsar wind nebulae



Supernova remnants

Unique science cases

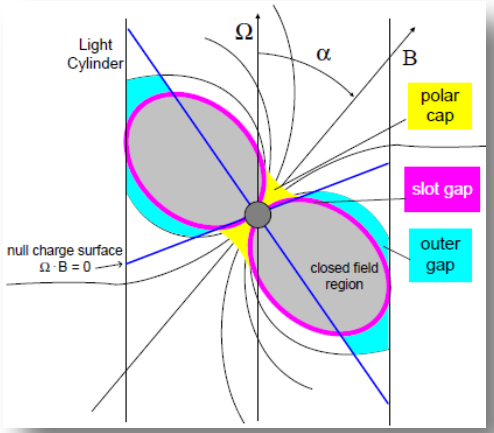
- Relativistic X-ray jets
  - Role of magnetic fields in jet formation (Marscher 2014)
  - Leptonic or hadronic? (Zhang & Bottcher 2013)
  - Emission mechanism for the blazar high energy peak
- Need monitoring (for blazars) and prompt re-pointing (for GRBs)

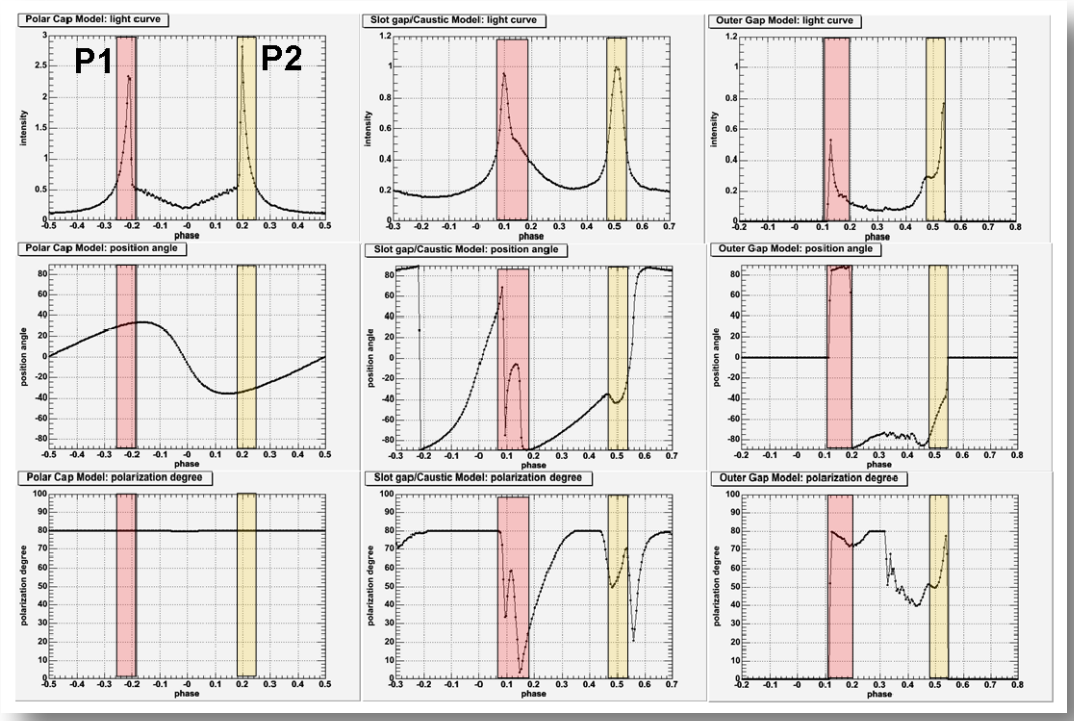


Blazars GRB afterglows Jetted TDEs

Unique science cases

- Pulsars
  - Rotation-powered
    - test the emission geometry

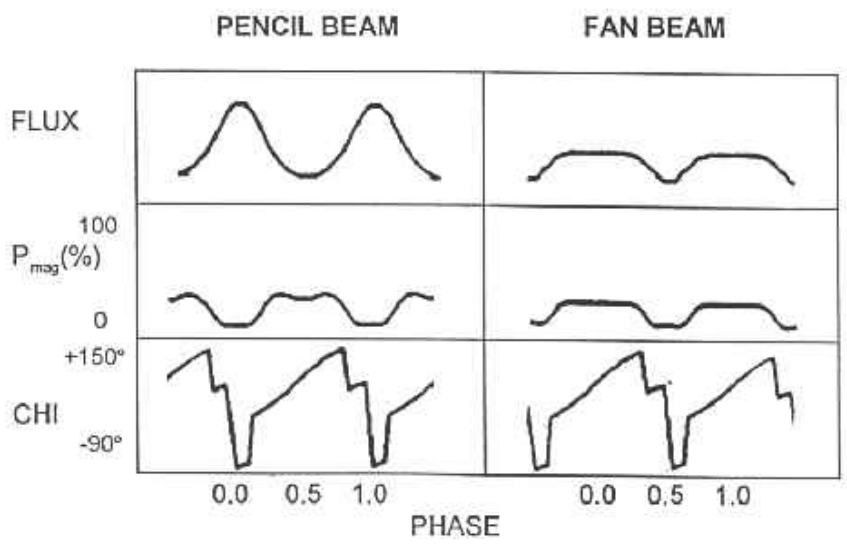




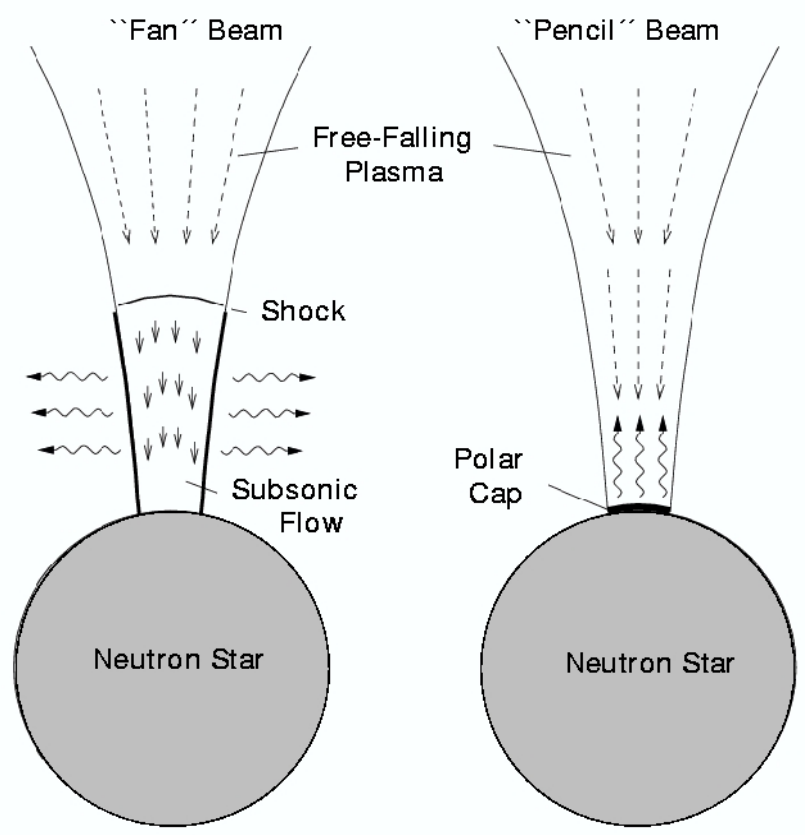
Polar cap (Daugherty & Harding 1996)
Slot gap (Muslimov & Harding 2004)
Outer gap (Romani 1996; Takana 2007)

Unique science cases

- Pulsars
  - Accretion-powered
    - fan beam vs. pencil beam

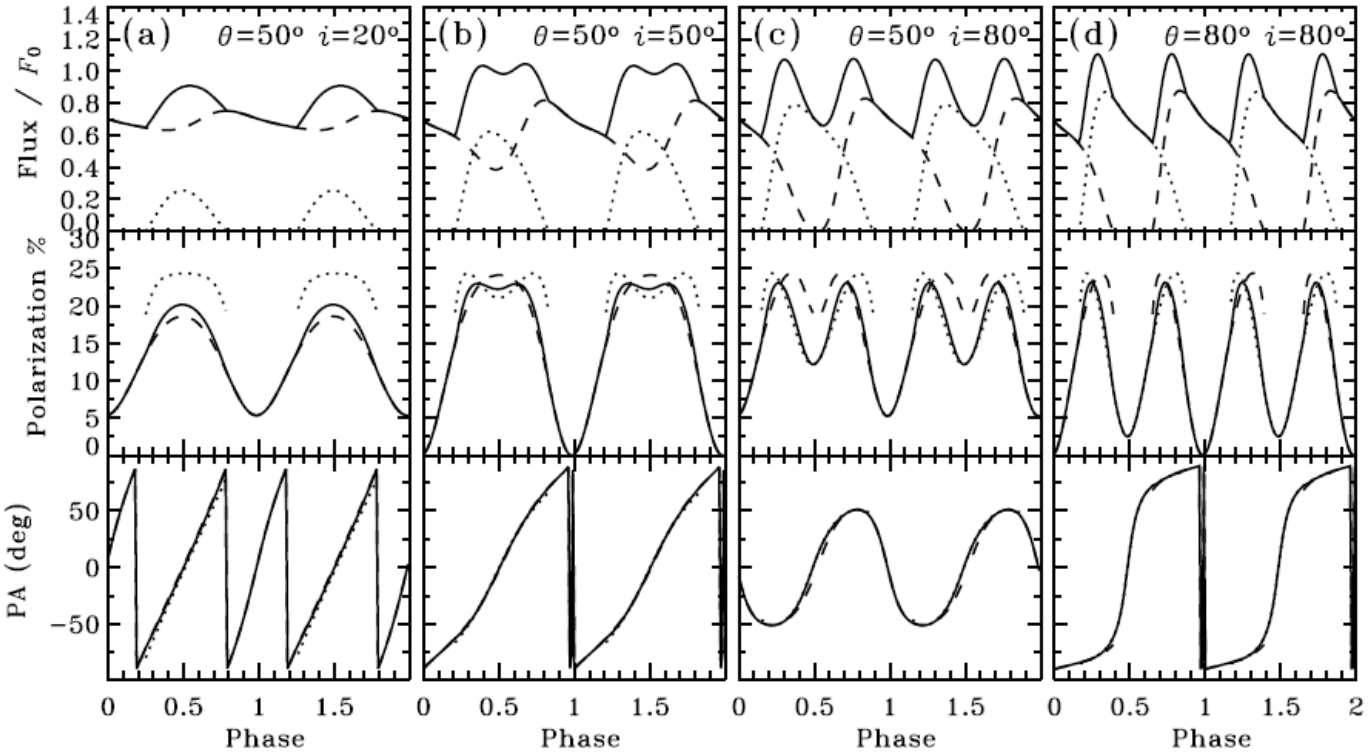


(Meszaros et al. 1988)



Unique science cases

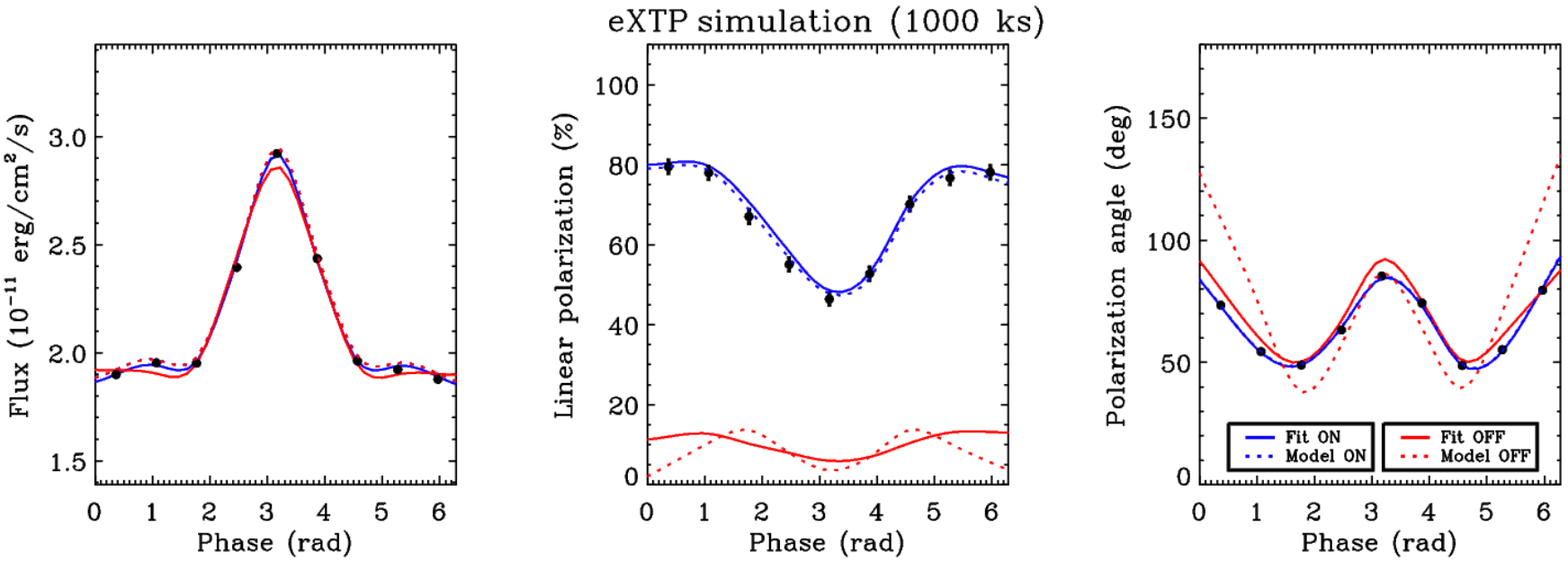
- Pulsars
  - Accreting millisecond pulsars
    - test the geometry; constraints on *M*/*R*
    - Polarimetry can help determine the geometry and orientation of the B fields



(Viironen & Poutanen 2004)

Unique science cases

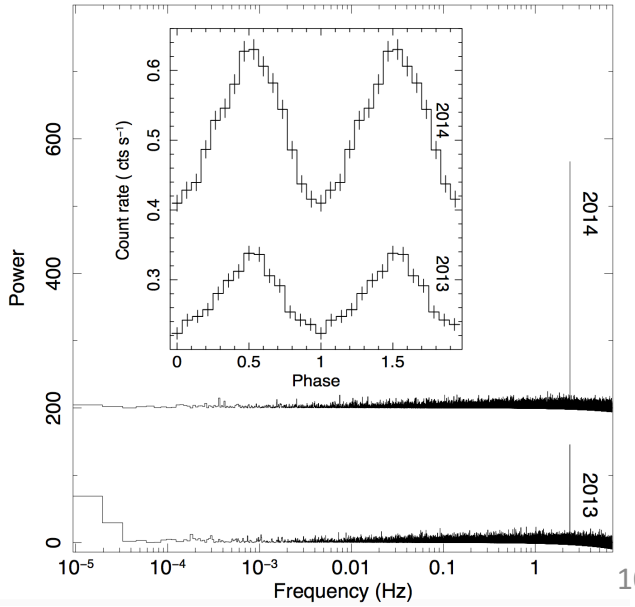
- Pulsars
  - Surface thermal emission
    - QED effects (vacuum birefringence) & B-field geometry
    - Tested in optical (RX J1856.5-3754; Mignani et al. 2017)
  - SGRs & AXPs



Simulations by R. Taverna and R. Turolla

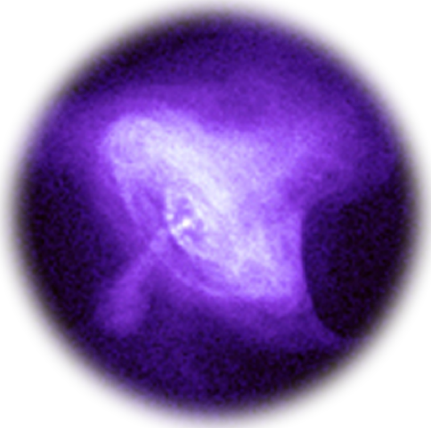
Unique science cases

- Pulsars
  - Ultraluminous X-ray pulsars
    - 3 known objects
      - M82 X-2 (Bachetti et al. 2014) – crowded region
      - NGC 7793 P13 (Israel et al. 2016; Furst et al. 2016)
      - NGC 5907 ULX-1 (10^{41} erg s^{-1}; Israel et al. 2016)
    - Why they can break the Eddington limit by a factor of ~500
    - Sinusoidal modulation – no strong beaming
    - Large variability and bimodal luminosity distribution – propeller effect
- highly magnetized neutron stars (e.g., Dall'Osso, Perna & Stella 2015; Eksi et al. 2015; Mushtukov et al. 2015; Tsygankov et al. 2016)
- low magnetic neutron stars (Kluzniak & Lasota 2015)

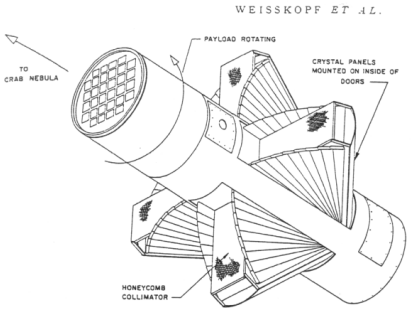


Exploration of the new window – since 1960s

First attempt: 1968
Scattering polarimeter
Aerobee 150



First precise measurement: 1975
Bragg polarimeter, OSO-8
P = 19.2% ± 1.0%
ψ = 156.4°± 1.4°
Weisskopf et al. 1976, 1978



First detection: 1971
Bragg polarimeter
Aerobee 350
Crab nebula P = 15.4% ± 5.2%

First satellite: 1974
Flat Bragg crystal
Ariel 5

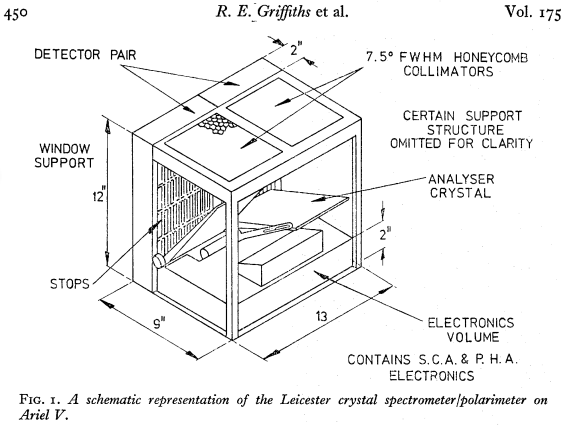
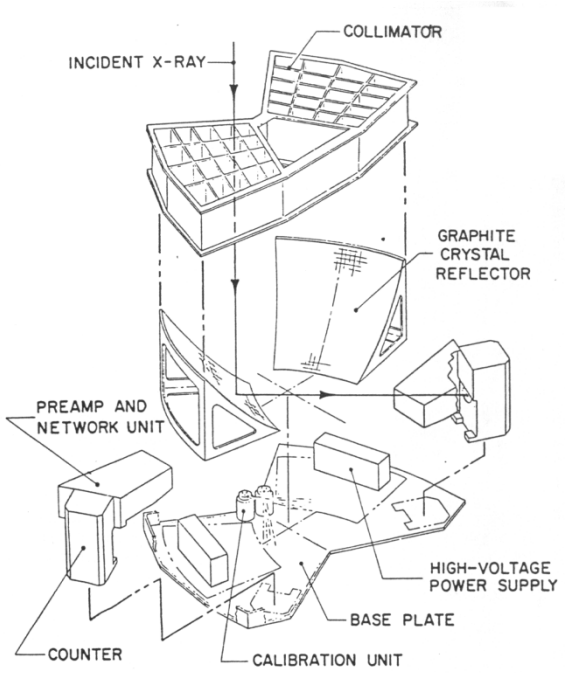
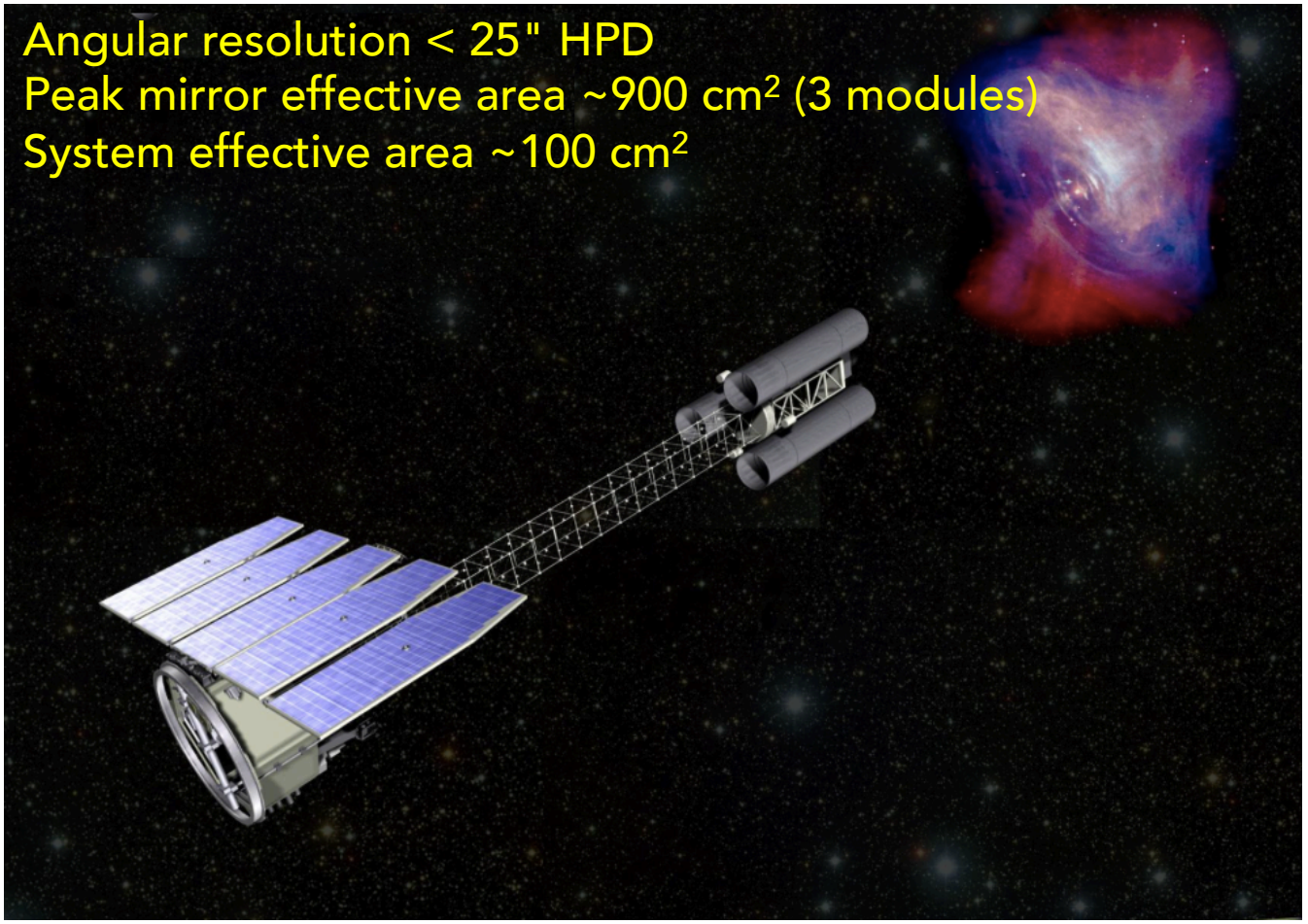


FIG. 1. *A schematic representation of the Leicester crystal spectrometer/polarimeter on Ariel V.*



NASA SMEX - IXPE

- 100 times more sensitive than the polarimeter on OSO-8



Sensitivity of IXPE

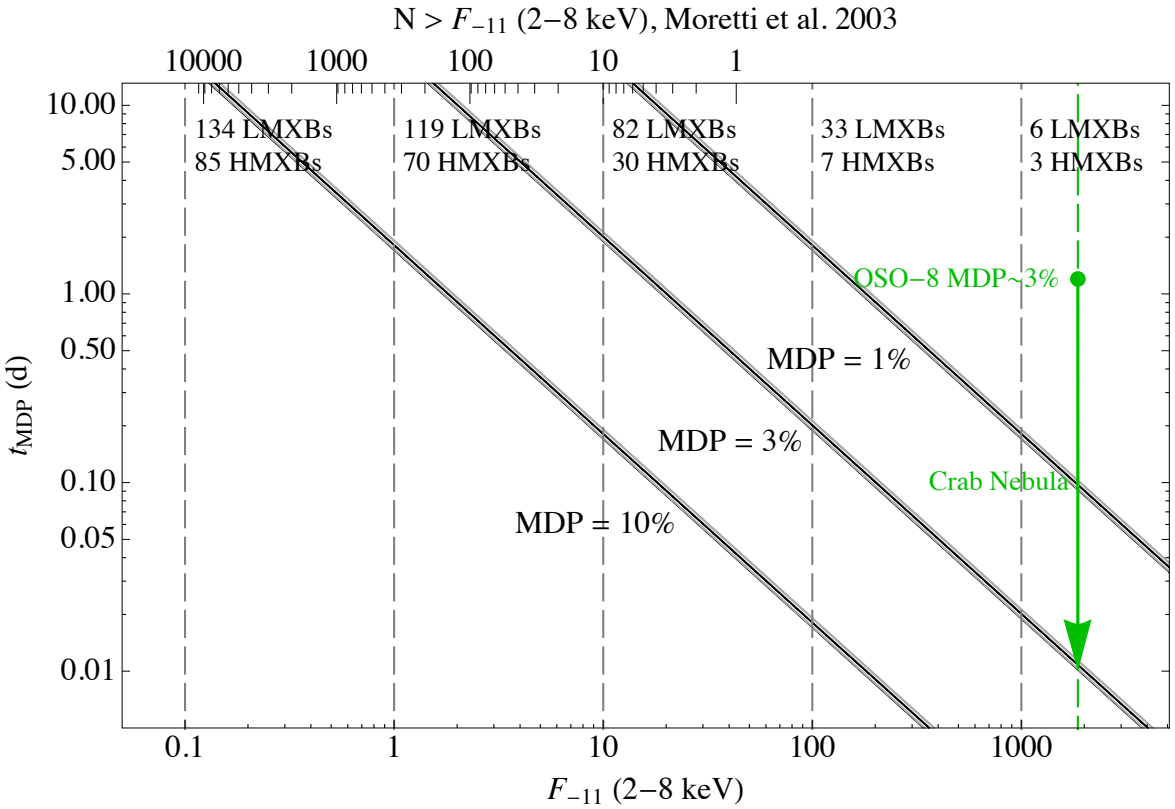


Figure 10—IXPE polarization sensitivity. The plot displays the integration time (in days) to reach a given $MDP_{99\%}$, as a function of 2–8-keV source flux (in 10^{-11} ergs cm^{-2} s^{-1}). See text for details.

40 targets within 6-month discovery phase:

4 PWNe, 4 other pulsars, 12 LMXBs, 6 HMXBs, 8 blazars, and 6 other AGNs.

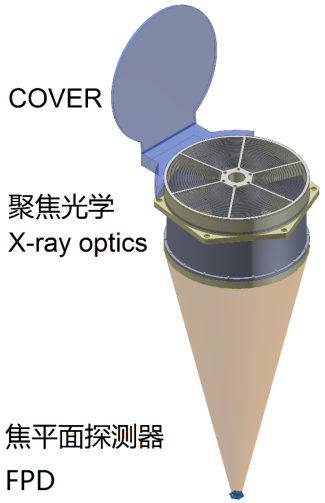
(Weisskopf et al. 2008)

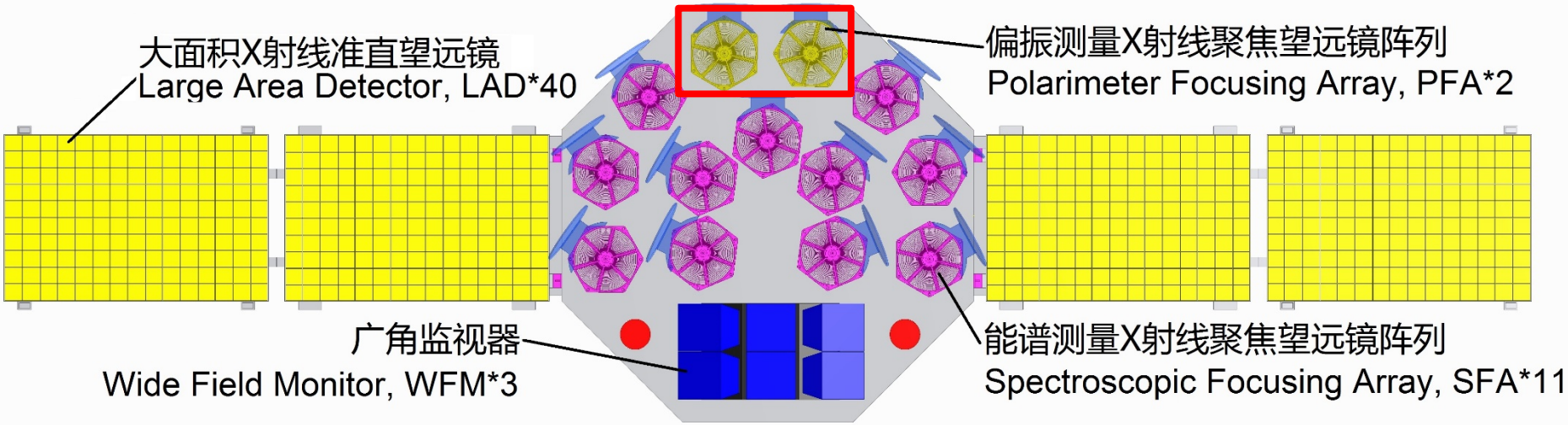
Why do we need polarimetry for eXTP?

- X-ray polarimetry is NOT a one-time science experiment.
- Imaging
  - Einstein → Chandra
- Timing
  - Ginga → XTE → LOFT & eXTP
- Gravitational wave
  - First detection → GW astronomy
- BeppoSAX
  - A smart design and successful operation
- eXTP must be more powerful than IXPE or properly designed

eXTP polarimetry – the current design

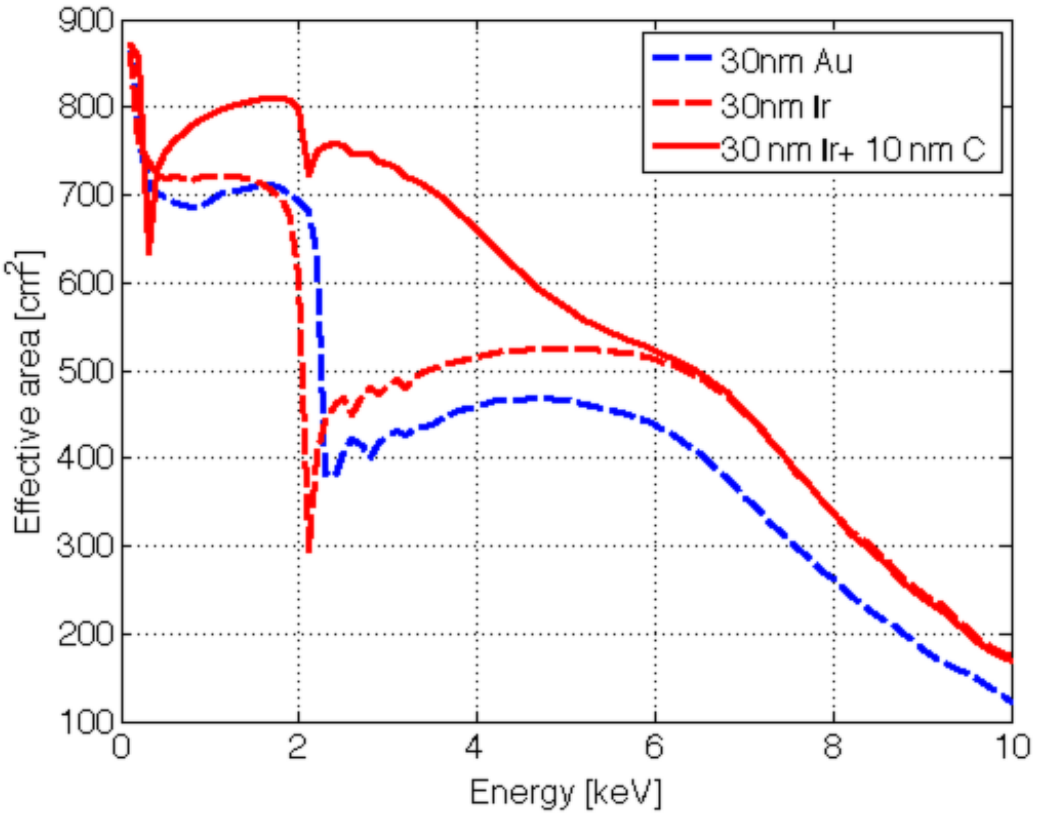
Payload	Configuration
Spectroscopic Focusing Array	11 sets/SGO/SDD element
Polarimeteric Focusing Array	2 sets/Nickel based optics/GPD
Large Area Detector	40 modules/Pb glass/SDD
Wide Field Monitor	3 units/1.5D coded mask/SDD





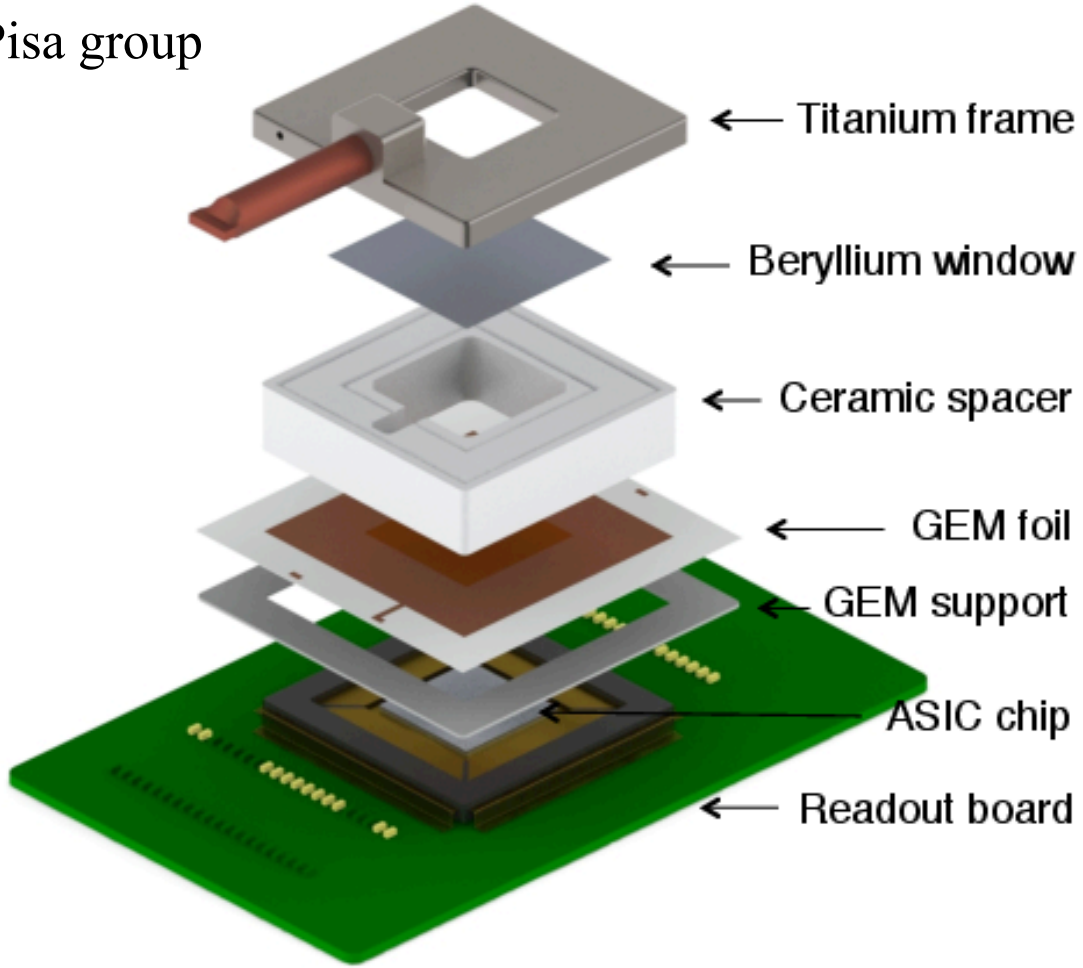
PFA optics

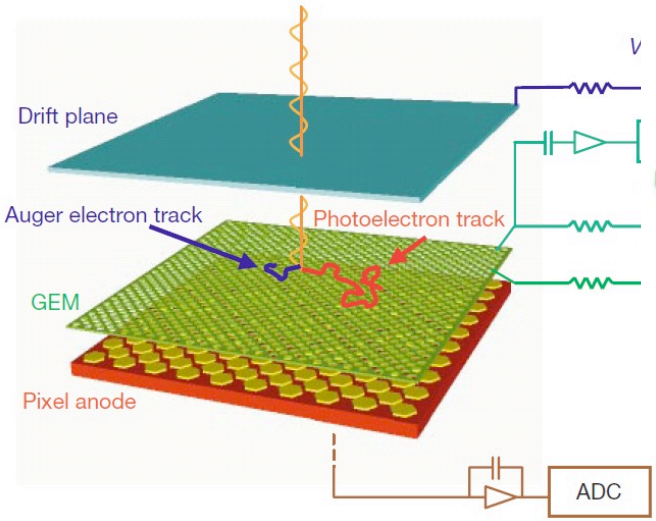
Focal length	4.5 m
Effective area	>800 cm^2 @2 keV (collecting area)
Field of View	12 arcmin
Angular res	<30” (goal 15”) HPD



PFA detector: gas pixel detector (GPD)

- Designed by the INFN-Pisa group (Bellazzini et al.)



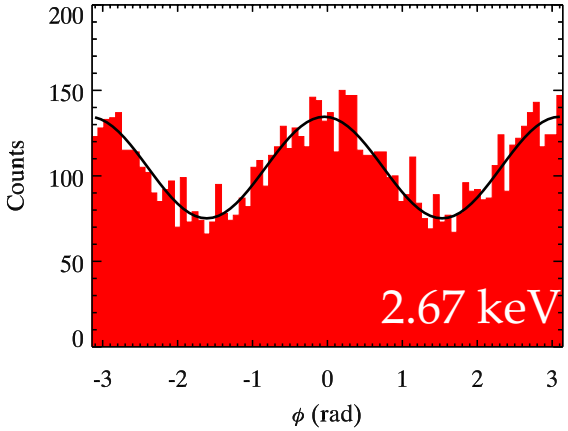


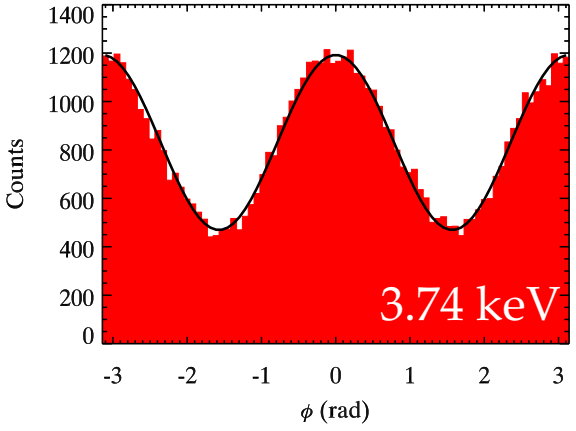
Gases with low Auger energy and diffusion coefficient

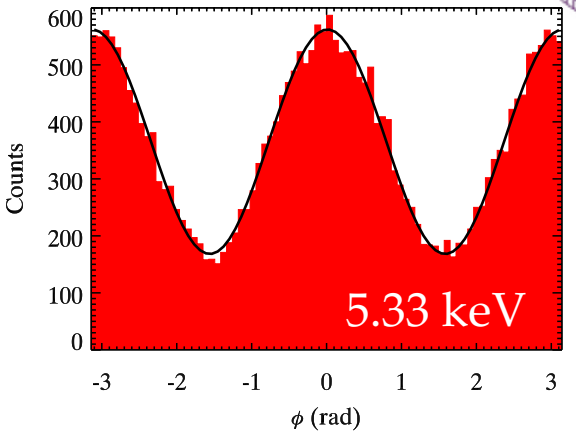
Gas	Density ($g\ cm^{-3}$)	Average ionization energy (eV)	Auger electron energy (eV)	Transversal diffusion coefficient ($\mu m\ cm^{-0.5}$)
He	0.178	41	-	520
Ne	0.900	36.3	849	600
CO_2	1.963	33	277/525	75
DME(C_2H_6O)	2.055	23.9	277/525	65
CH_4	0.716	28	277	220

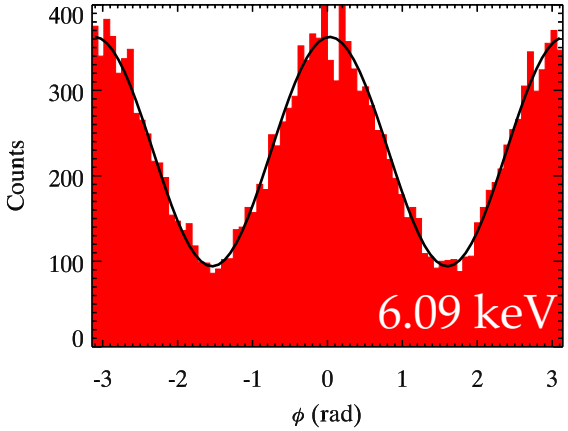
The gain with CO_2 is one order of magnitude smaller than with DME

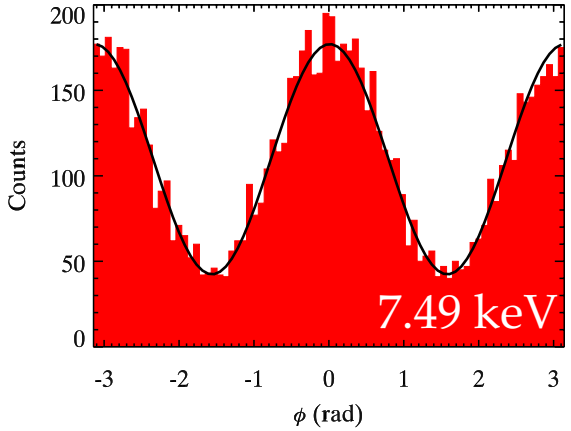
Modulation

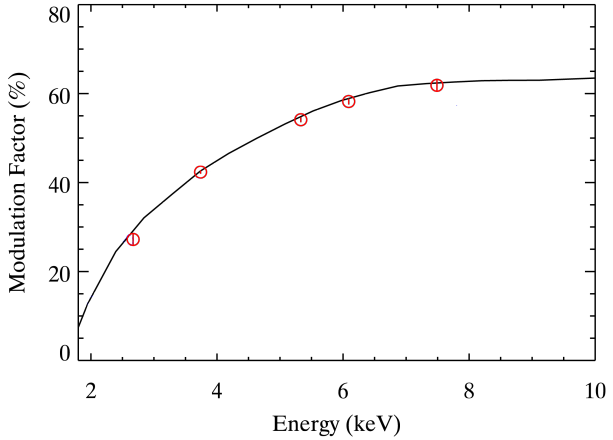

Counts
2.67 keV
ϕ (rad)

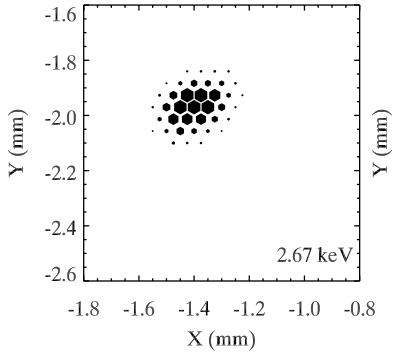

Counts
3.74 keV
ϕ (rad)

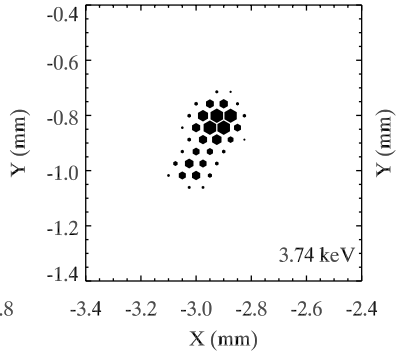

Counts
5.33 keV
ϕ (rad)

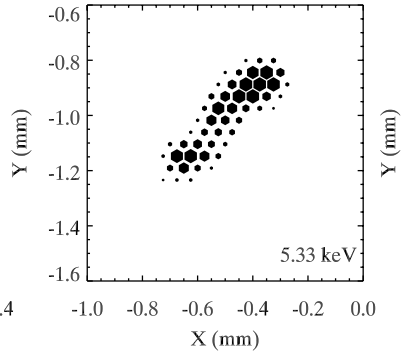

Counts
6.09 keV
ϕ (rad)

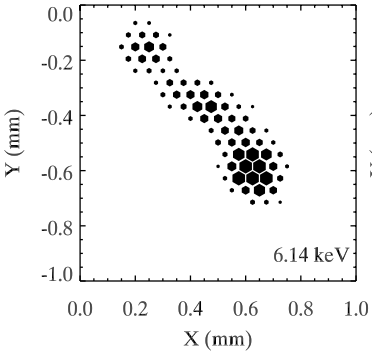

Counts
7.49 keV
ϕ (rad)

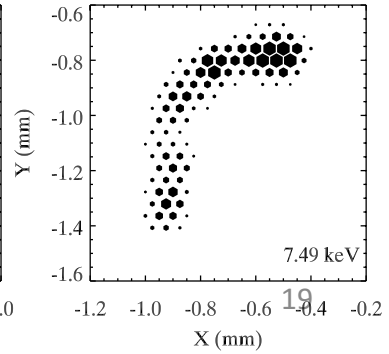

Modulation Factor (%)
Energy (keV)


Y (mm)
2.67 keV
X (mm)


Y (mm)
3.74 keV
X (mm)

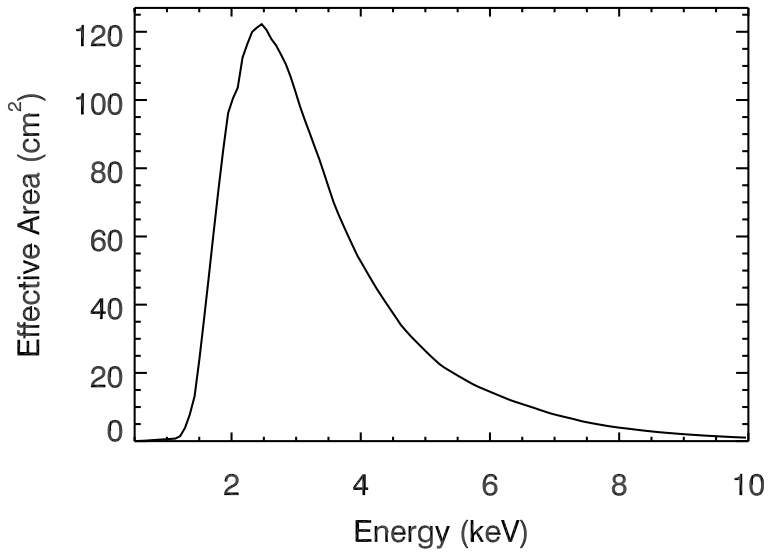

Y (mm)
5.33 keV
X (mm)

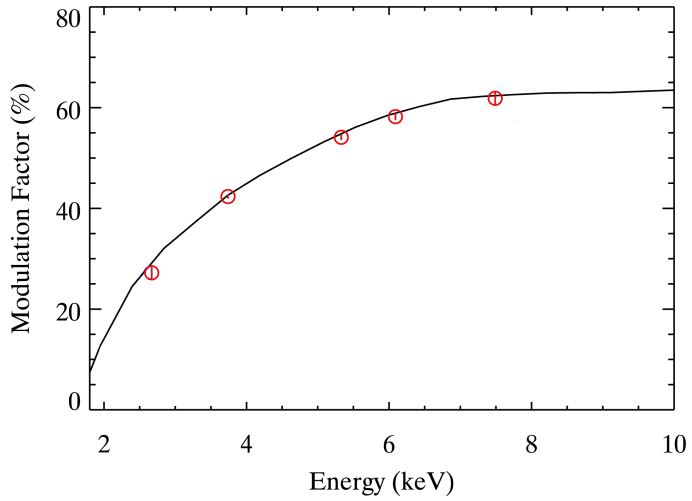

Y (mm)
6.14 keV
X (mm)


Y (mm)
7.49 keV
X (mm)

Effective area and quality factor

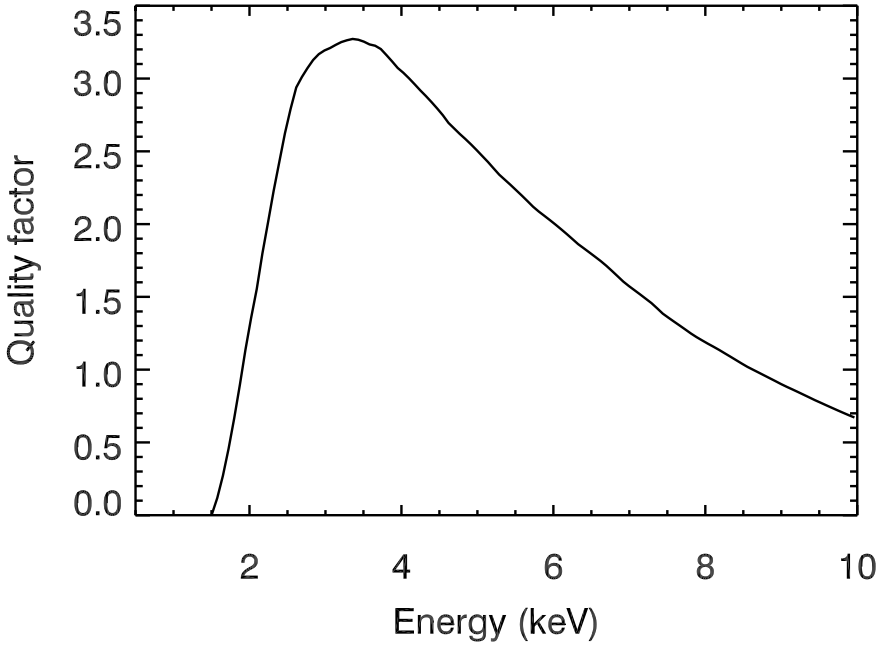
Single Unit (optics + GPD)





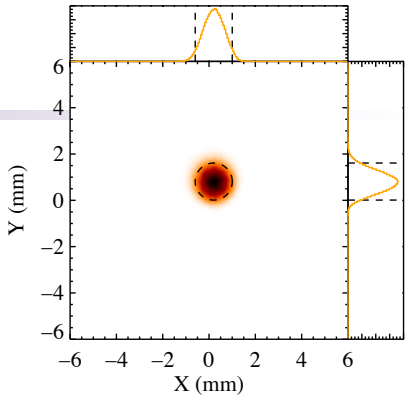
$$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N}} = \frac{4.29}{\mu\sqrt{SA_{\mathrm{eff}}T}}$$

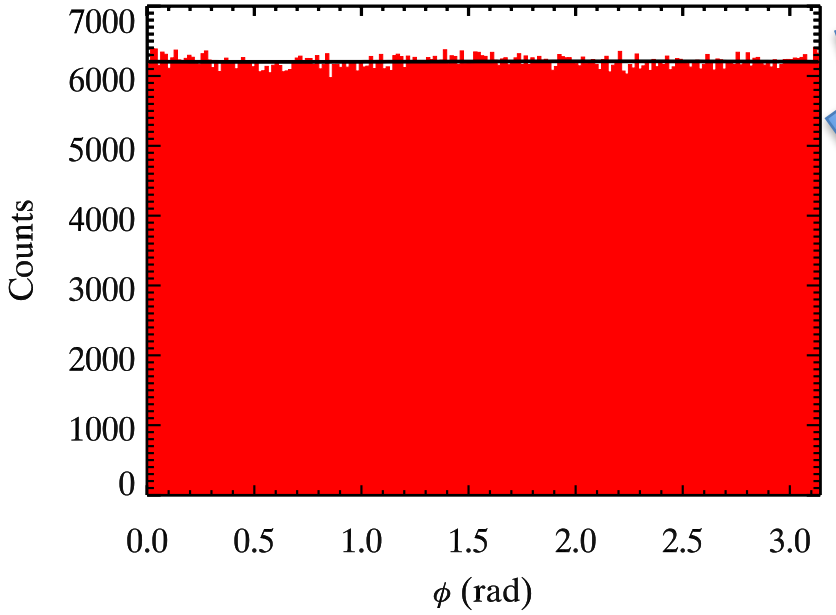
$$Q = \mu\sqrt{A_{\mathrm{eff}}}$$

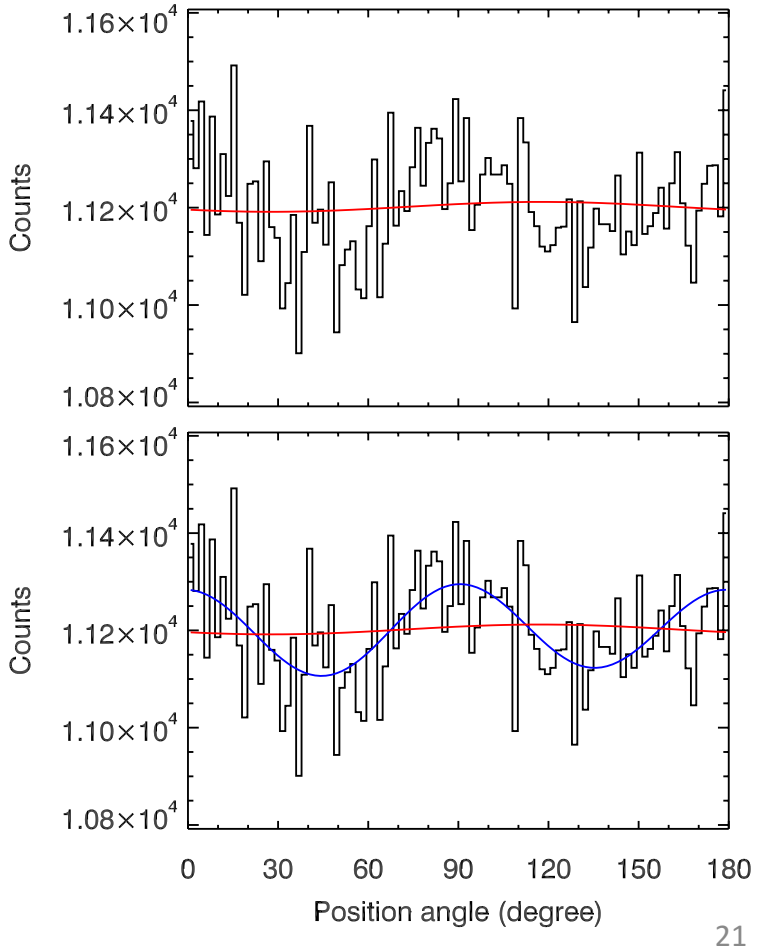


The sensitivity limit (systematics)

- residual modulation
- 1.24 M counts collected
- 800μm in radius

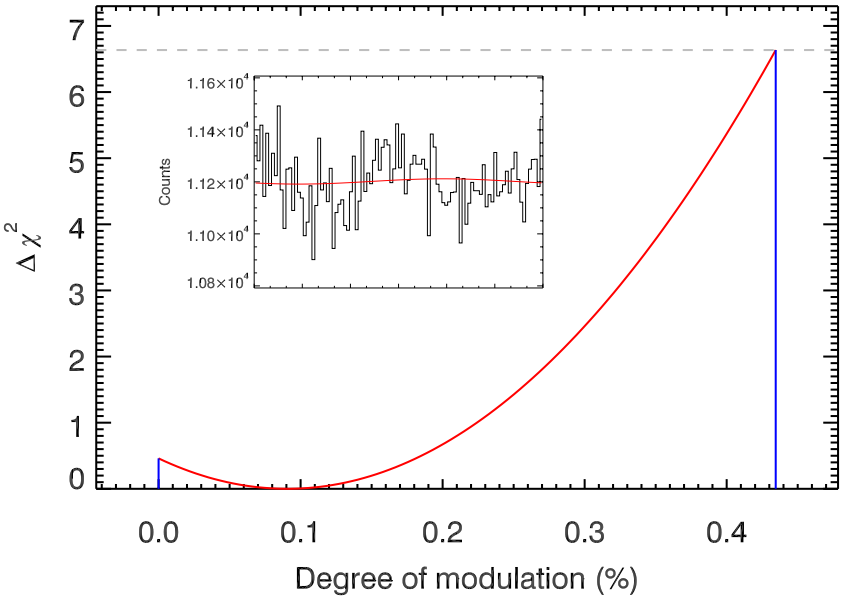


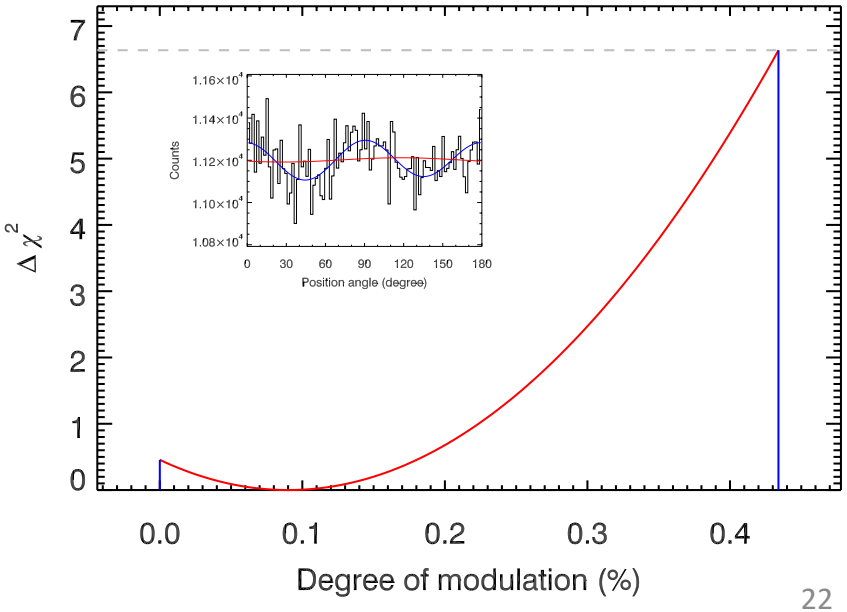




Upper limit 0.8% (99% C.L.) or 0.6% (90% C.L.)

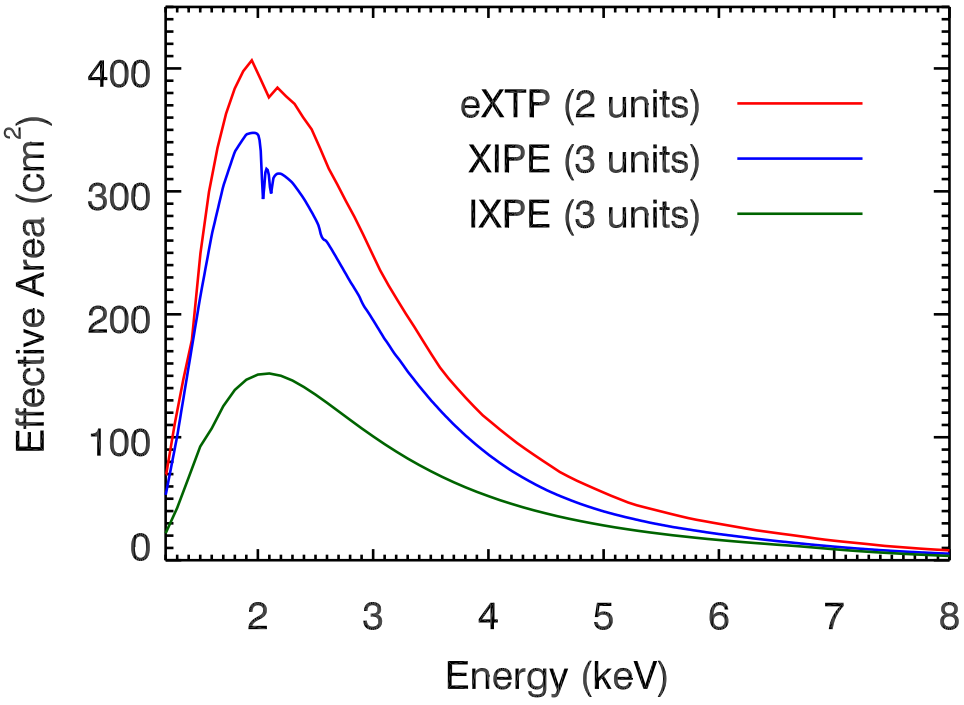
Without a P = π/2 component	With a P = π/2 component
χ2/dof = 118.93/97	χ2/dof = 85.0/95
DoM = 0.091%	DoM = 0.090%
99% DoM upper limit = 0.43%	99% DoM upper limit = 0.43%
μ = 0.54	μ = 0.54
99% DoP upper limit = 0.80%	99% DoP upper limit = 0.80%





eXTP vs. XIPE vs. IXPE

- 5x larger than IXPE in effective area – it is possible! by increasing the PFA unit numbers or focal lengths



Area (cm^2)	eXTP	XIPE	IXPE
3 keV	248	195	101
4 keV	114	86	52

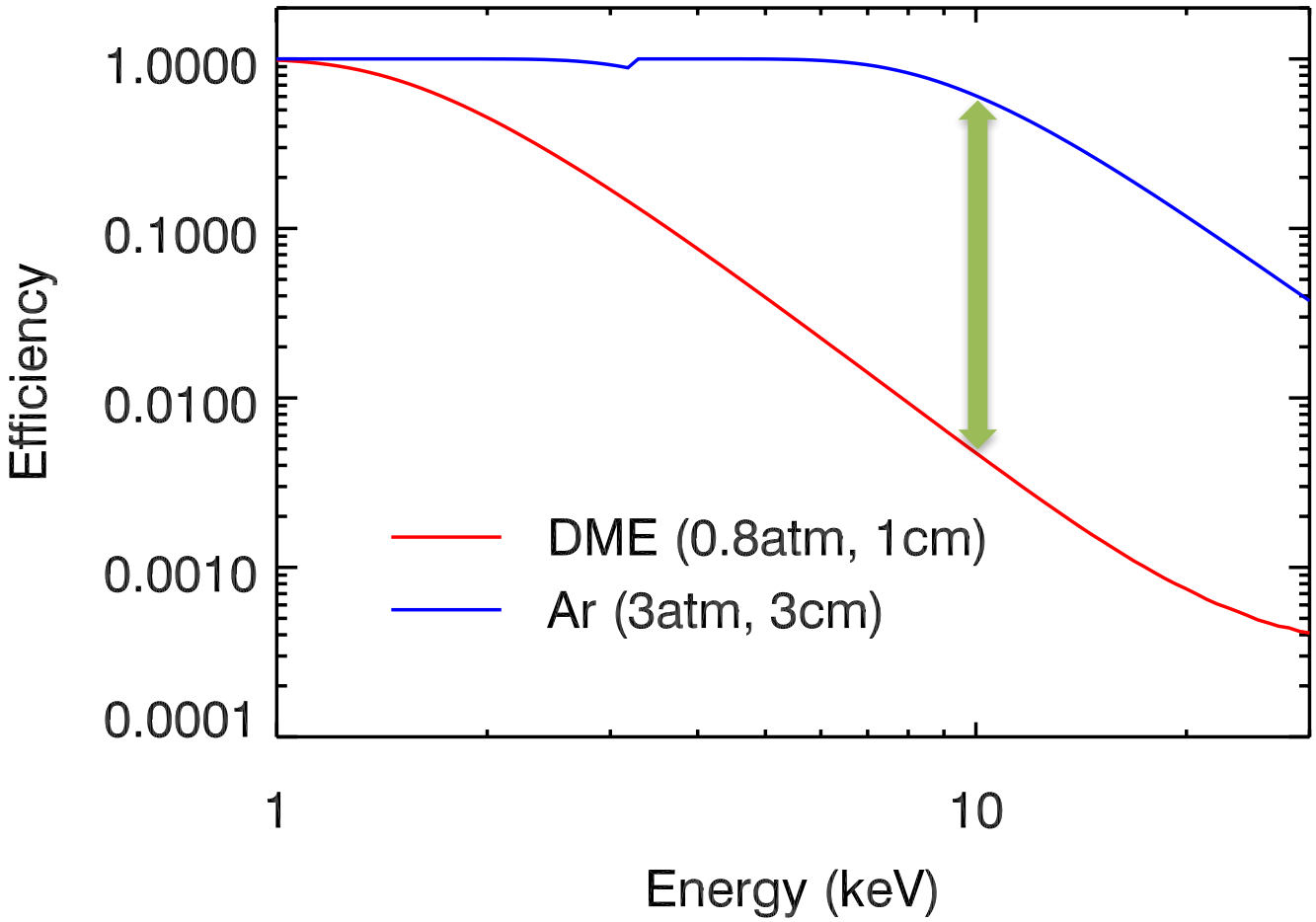
eXTP is not a dedicated polarimeter

- What are the primary targets for eXTP?
- How polarization can help constrain their physical nature?

Other possible channels for exploration

- Current detector
  - GPD filled with 0.8 atm DME
  - Sensitive in 2-8 keV, peaked at 3-4 keV
- Possible extensions
  - Hard X-ray polarimetry
    - Filled with Ar (E_{Auger} ~ 3.0 keV), sensitive in 10-20 keV
  - Soft X-ray polarimetry
    - Multilayer Bragg reflection polarimeter
    - Sensitive around 0.25 keV

Hard X-ray polarimetry

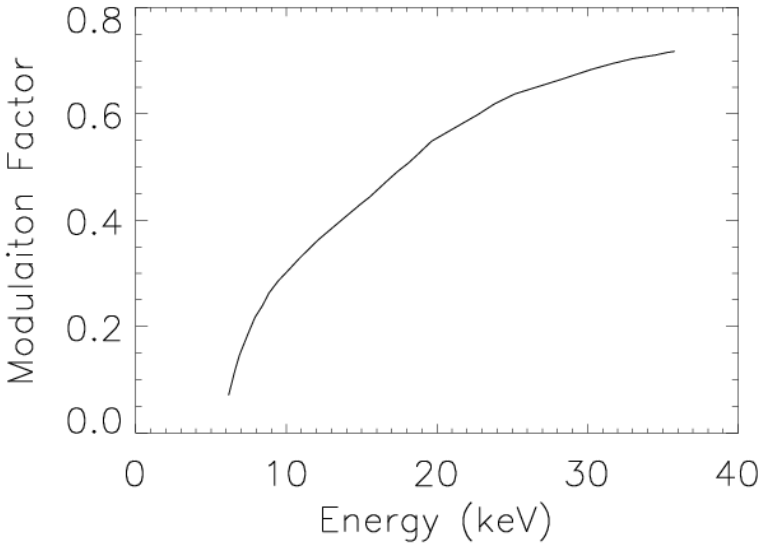


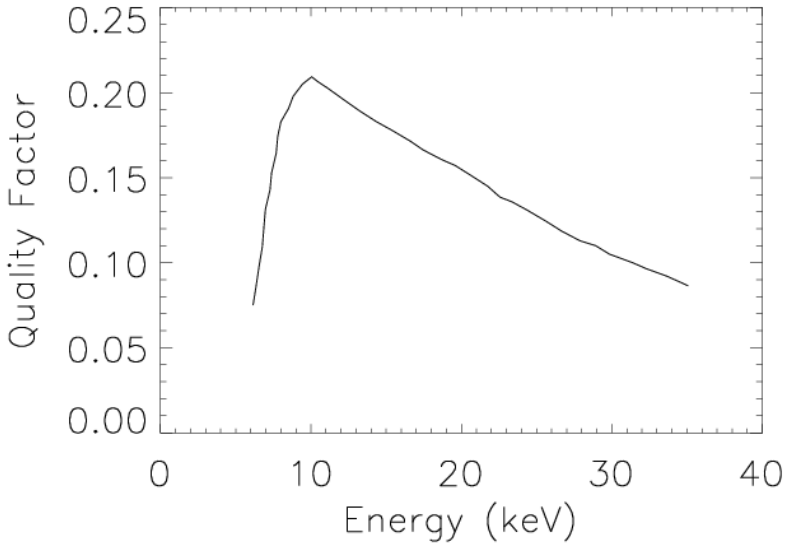
Ar

Efficiency
0.61 @ 10 keV
0.12 @ 20 keV

DME

Preliminary simulations & tests



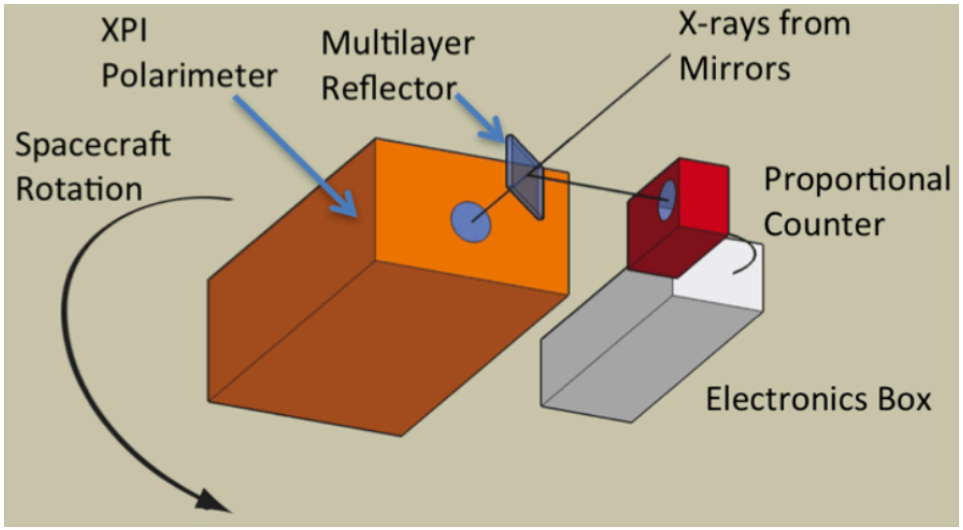


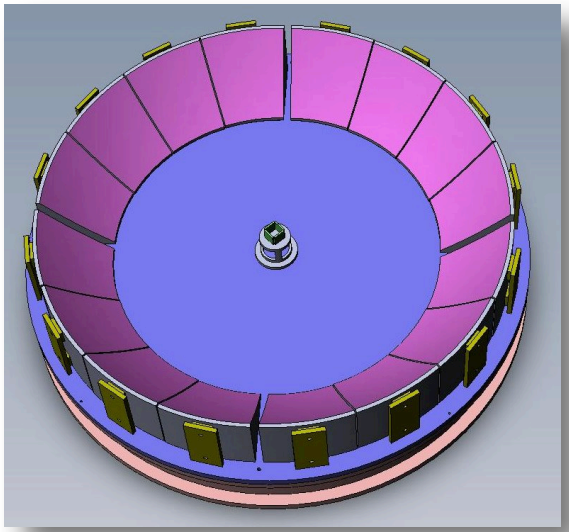
- ✓ **Gas mixture: Ar(60%) + DME(40%)**
- ✓ **Pressure: 3 bar**
- ✓ **Depth: 3 cm**

Muleri et al. (2006), Fabiani et al. (2012)

Soft X-ray polarimetry

- Reflecting Multilayer Bragg polarimeters
  - A student project for GEMS
    - a beam splitter above the focal plane
  - Grating + energy dependent (Marshall's talk)
  - Difficult if thermal film is used
  - OSO-8 like focusing polarimeter at 250 eV
    - LAMP concept, compact but with a total collecting area of 1300 cm^2





Summary

- We need to define the science requirement for PFA
  - Current discussions of the science cases are mostly about the *discovery sciences*; we need to discuss sciences that requires deeper polarimetric observations
  - Sciences with PFA should be in line with that with SFA
- A significant step beyond IXPE is expected!

Thank You!