Future Space Programs with X-ray Polarimetry in China

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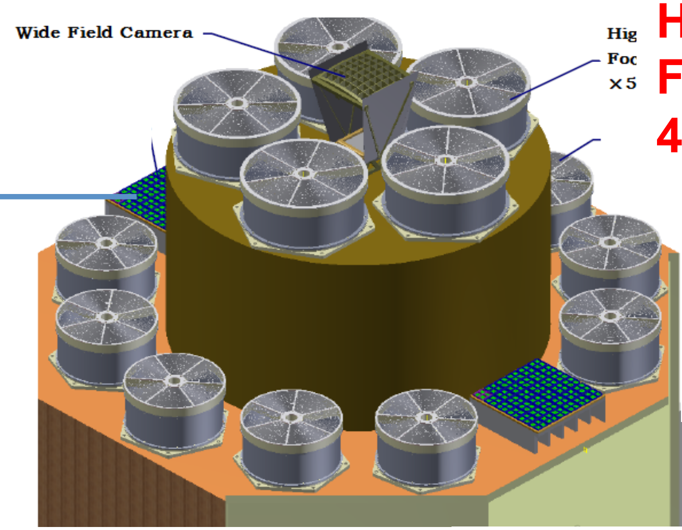
Outline

- Two mission concepts
  - X-ray Timing and Polarization (XTP)
  - Lightweight Asymmetry and Magnetism Probe (LAMP)
- Detector R&D
  - TPC polarimeter
  - GPD polarimeter

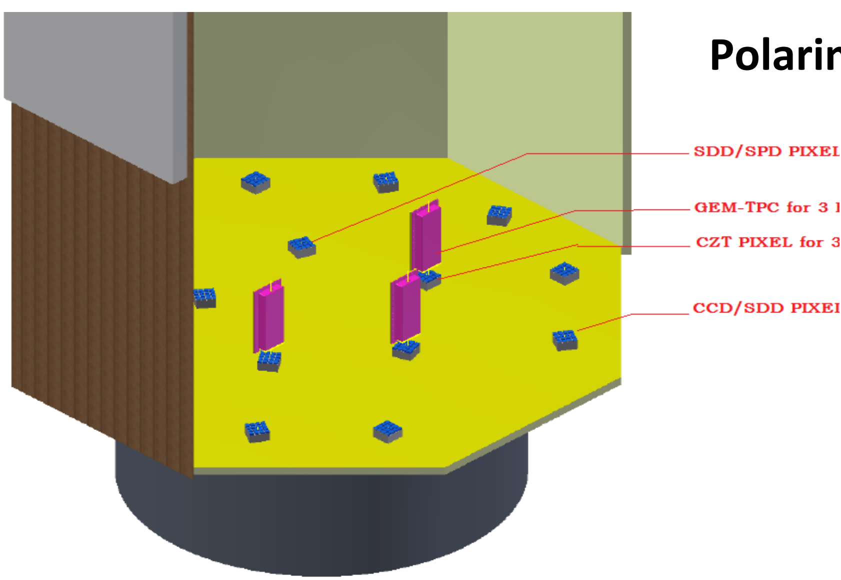
X-ray Timing & Polarization

High energy Collimating Array×2
1°×1°,8-100 keV

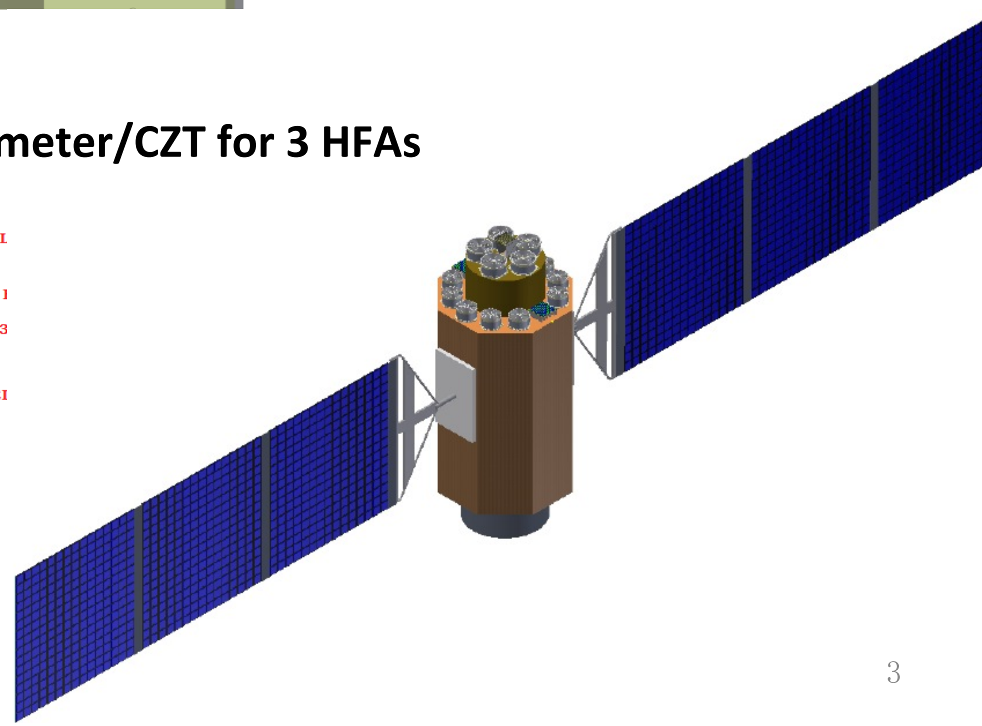


High Energy Focusing Array × 5
FL: 5.5m, FoV 16’,1~30keV
4000 cm^2 @ 2-6 keV

Low Energy Focusing Array×10
FL: 4.5m, FoV 16’, 0.5~10keV
5000 cm^2



Polarimeter/CZT for 3 HFAs

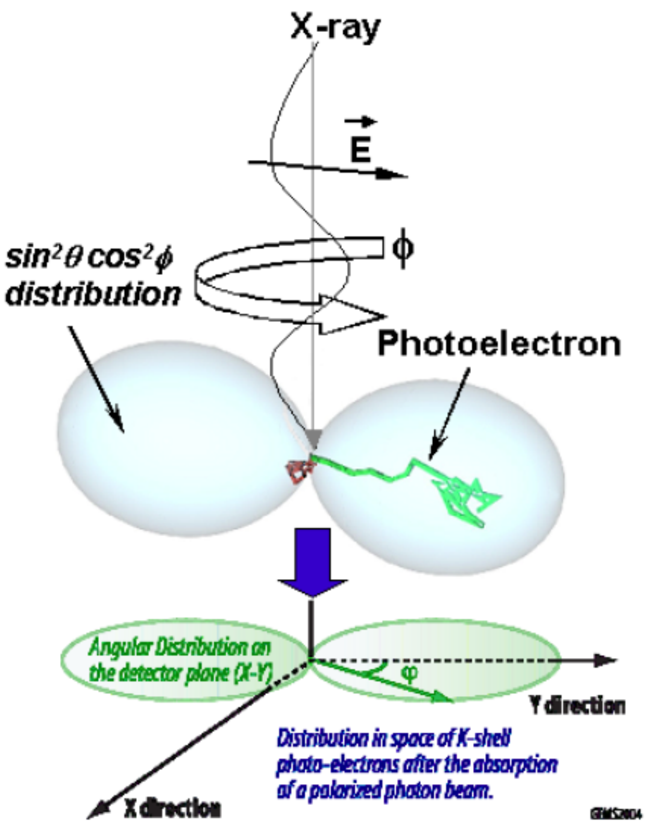


- Timing + Spectroscopy + Polarimetry
- LEO: 550 km & 28.5 deg, capability ~ 6 ton by LM 3-C.
- Mass: ~3200 kg (satellite); ~1200kg (payload)
- Power: 1300W (platform); 1600W (payload)
- Launch time: ~2020
- Lifetime: 5 years

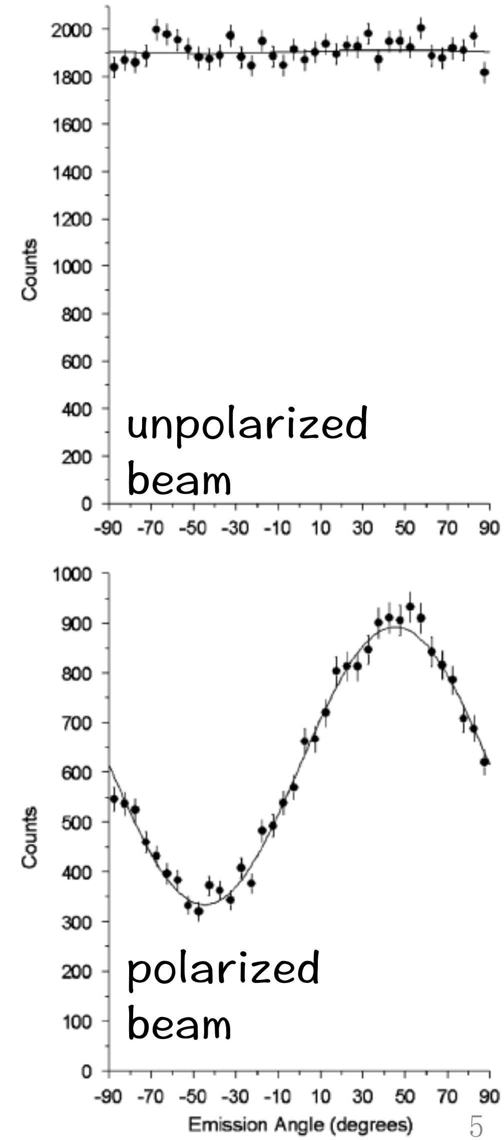
Photoelectric polarimeter

Cross-section of photoelectric effect

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

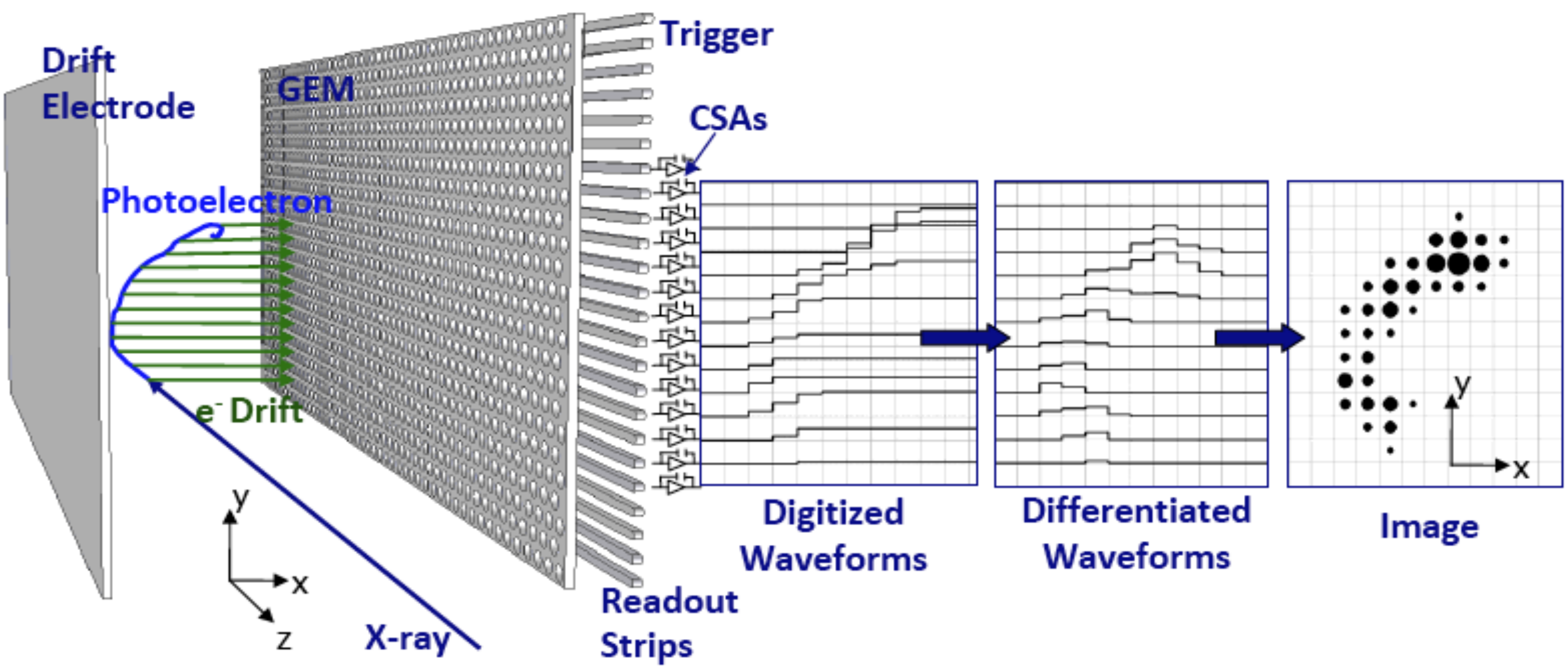


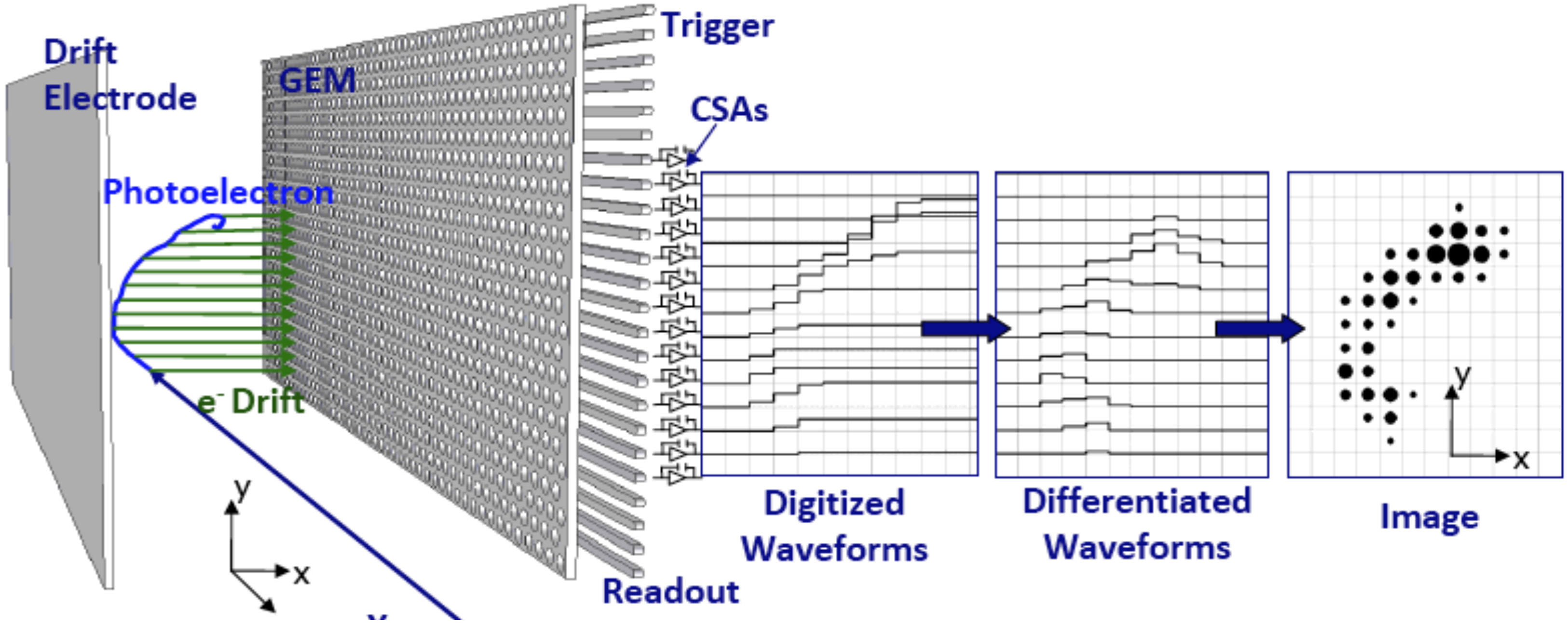
$$\frac{d\sigma}{d\Omega} \propto \cos^2\varphi$$

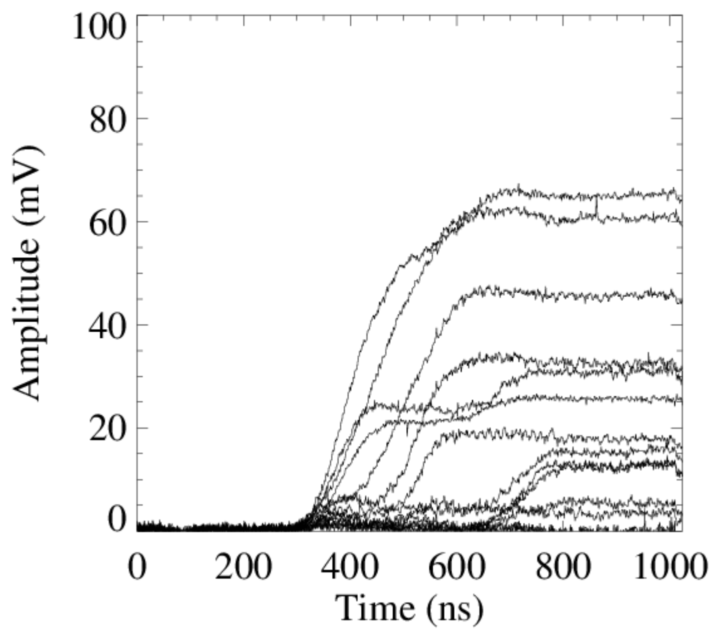


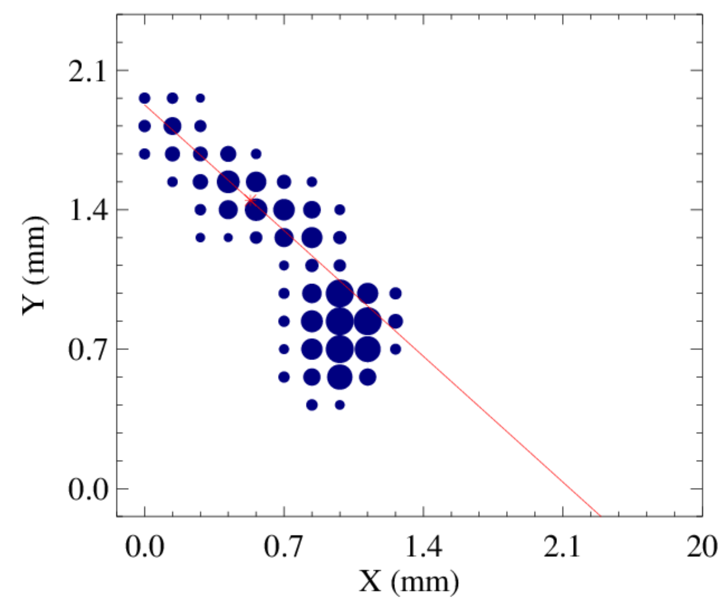
Time Projection Chamber (TPC)

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

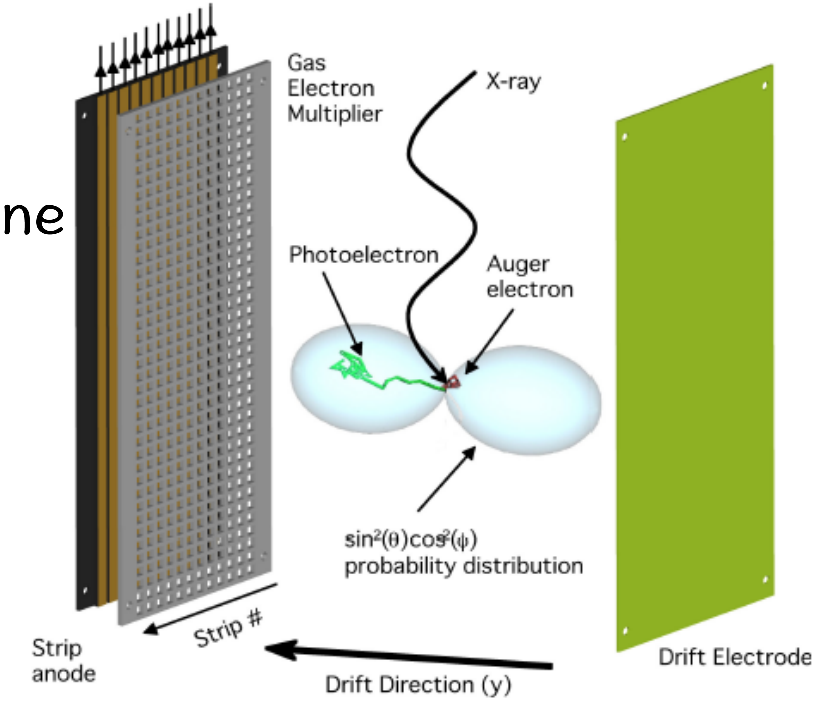


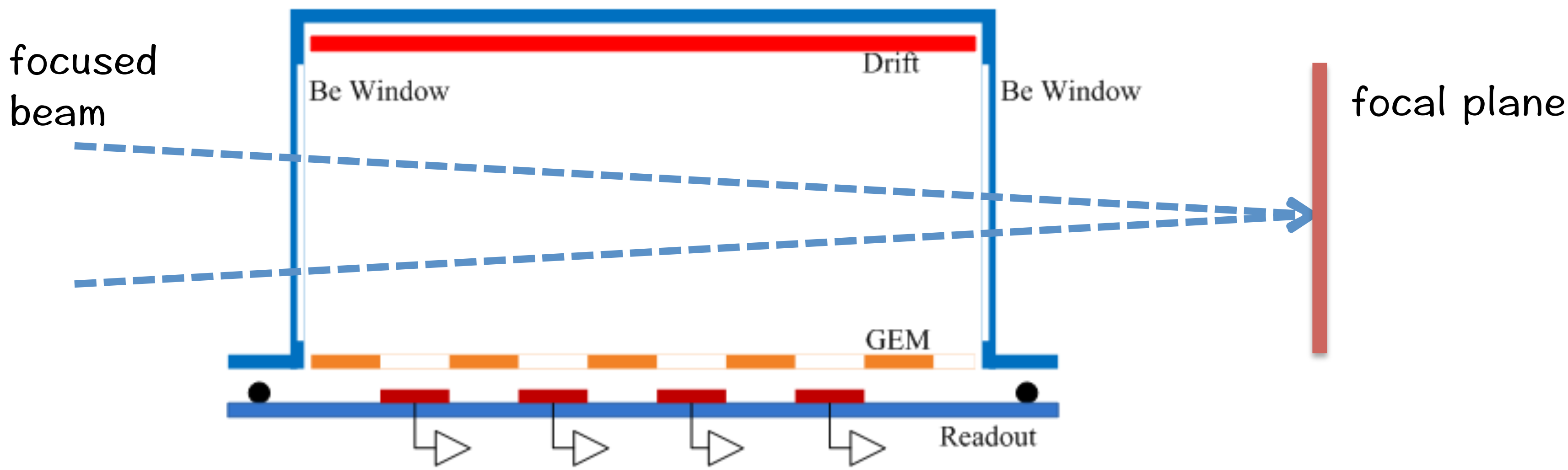

Drift
Electrode
GEM
Trigger
CSAs
Photoelectron
e- Drift
y
x
Readout
Digitized
Waveforms
Differentiated
Waveforms
Image
y
x


100
80
60
40
20
0
Amplitude (mV)
0
200
400
600
800
1000
Time (ns)


2.1
1.4
0.7
0.0
Y (mm)
0.0
0.7
1.4
2.1
20
X (mm)

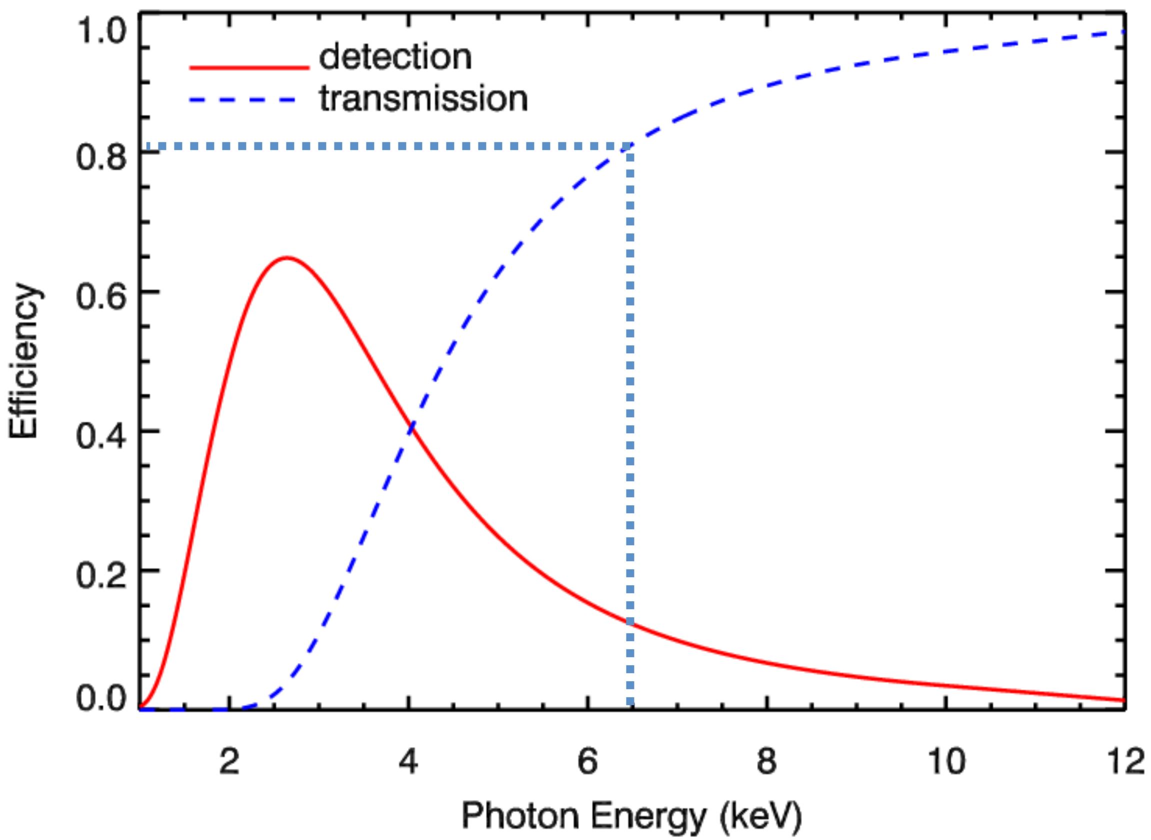
TPC polarimeter above the focal plane
Opaque to low energy photons
Transparent to high energy photons



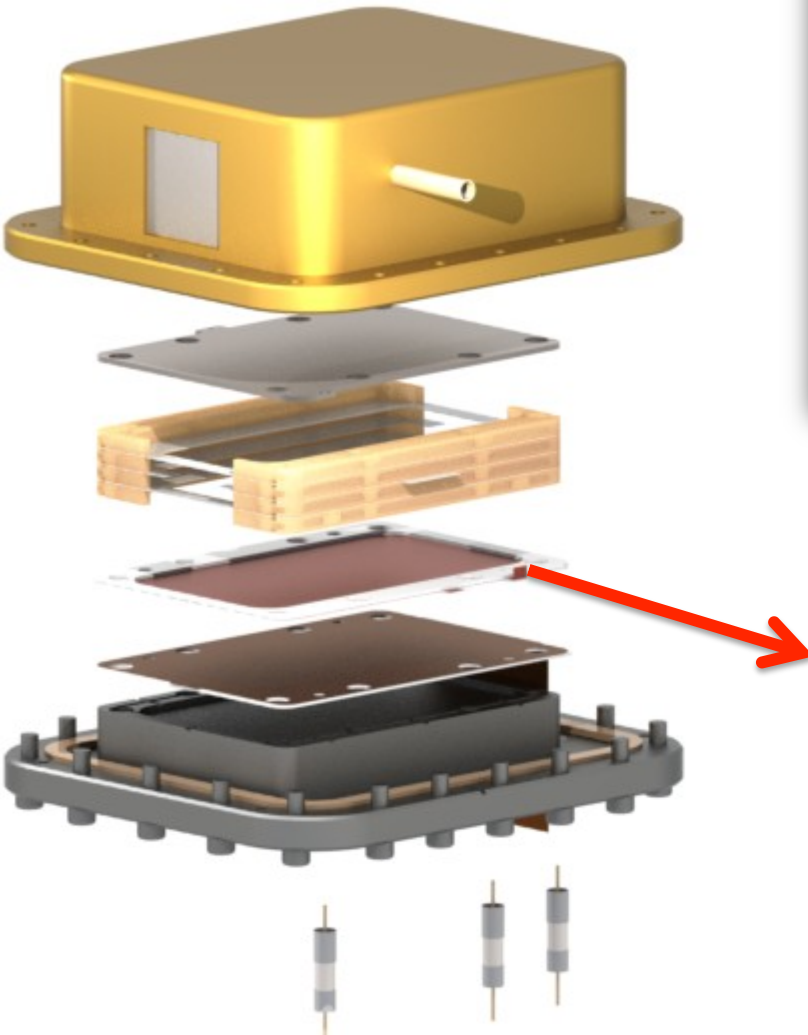


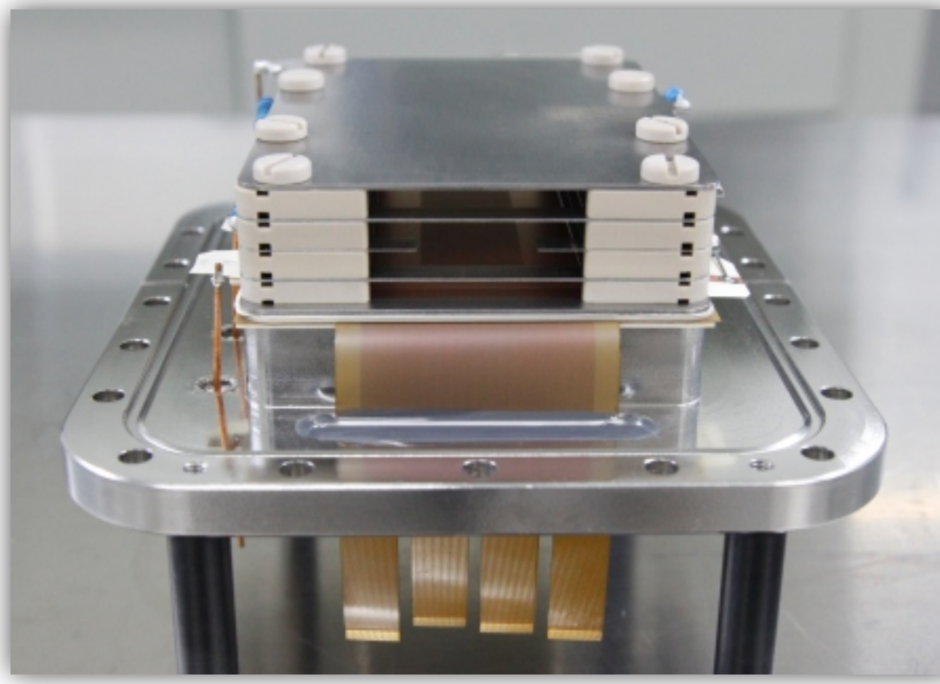
Quantum efficiency

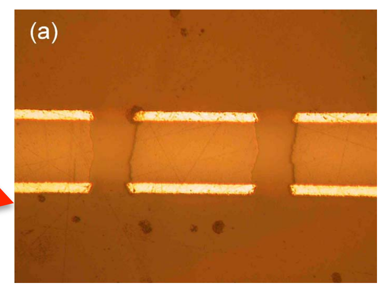
50μm Be (front window), 24/28 cm DME @ 190 Torr (gas) + 100 μm Be (rear window)

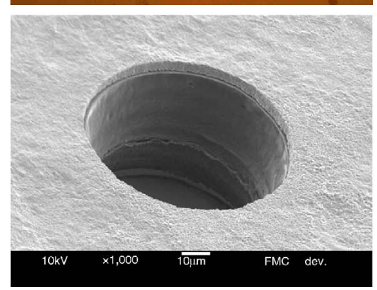


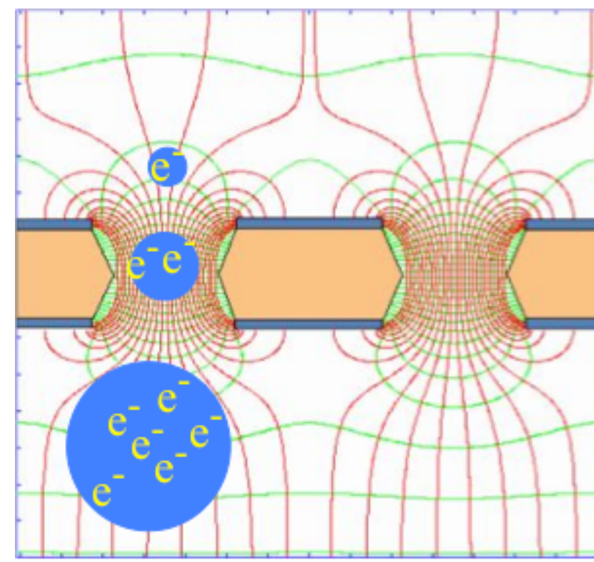
Test Prototype





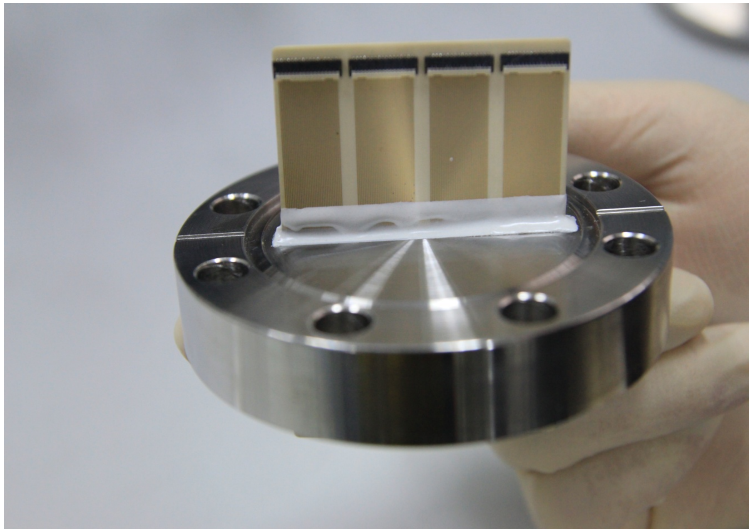




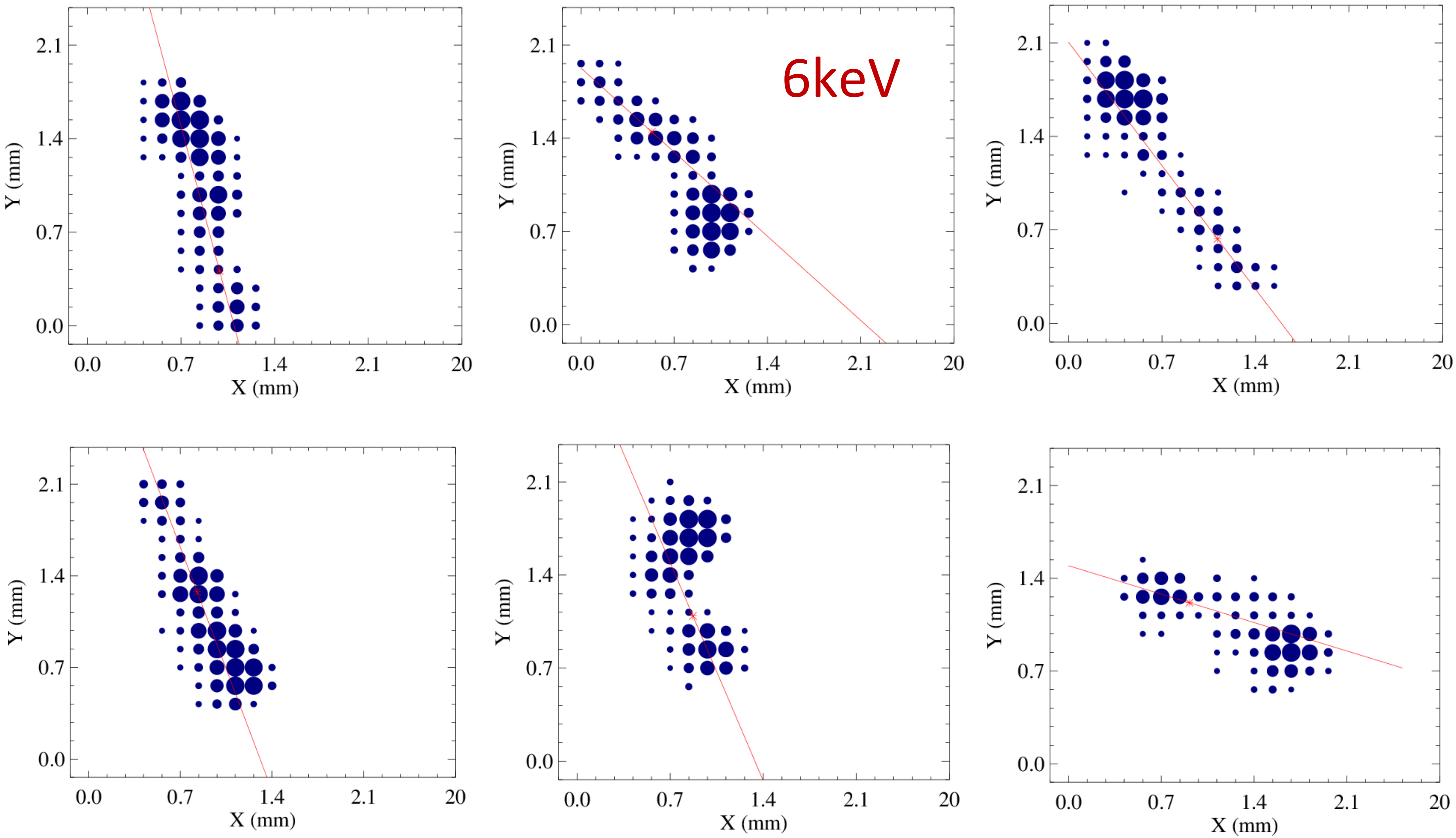


128-channel PCB feedthrough

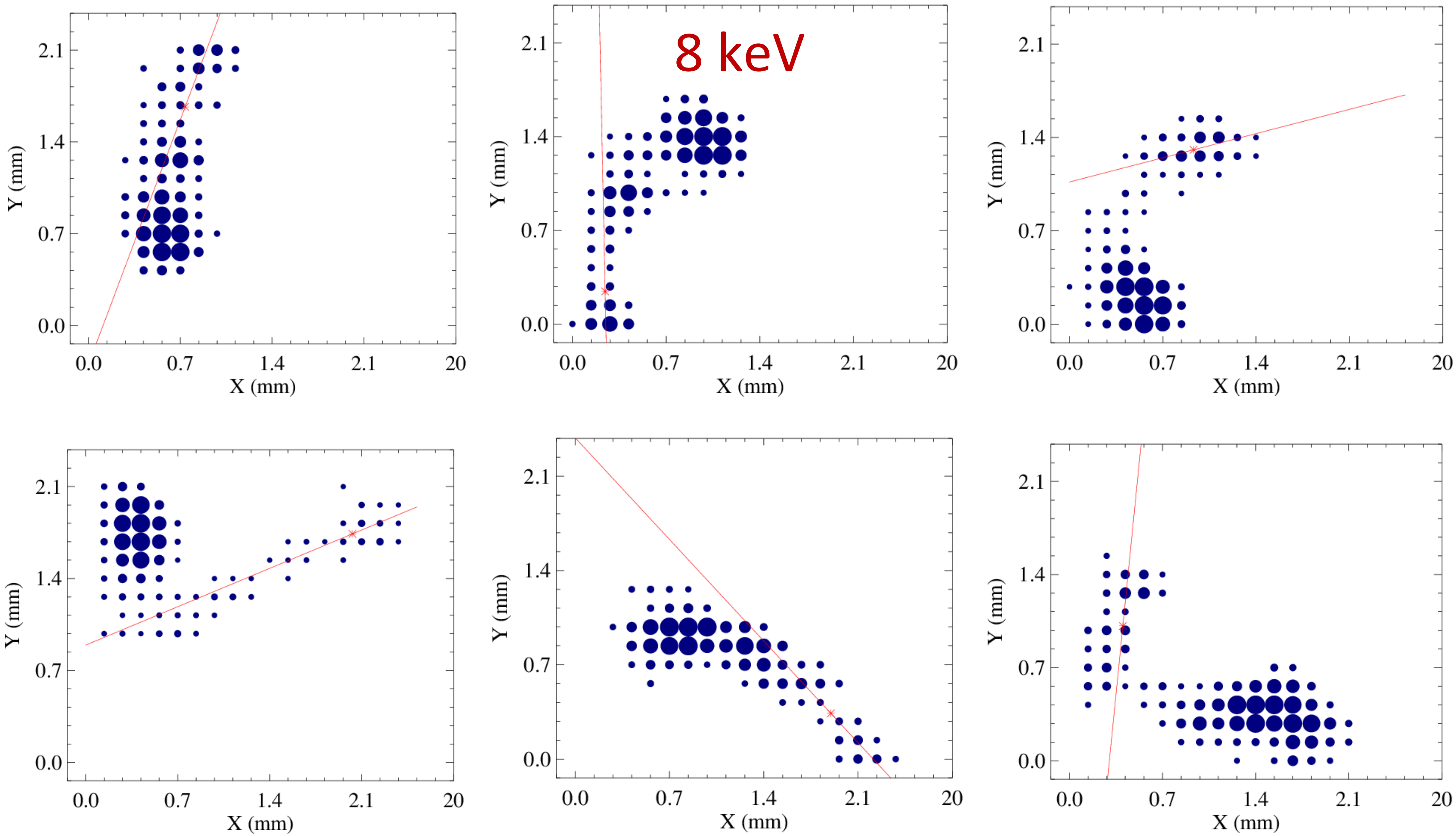
- Flexible or solid PCB
- NASA low outgassing specifications
- Works from -30 °C to 120 °C



➢ Measured photoelectron tracks

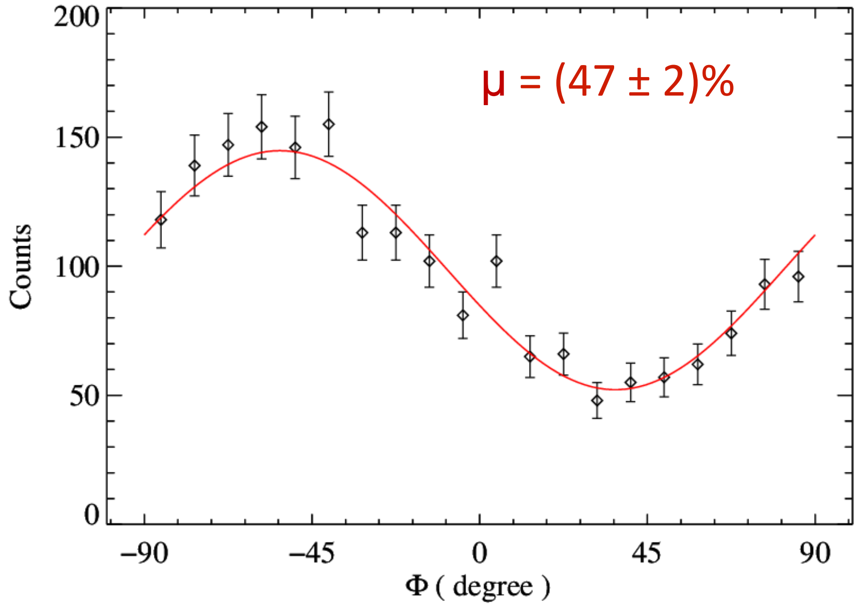


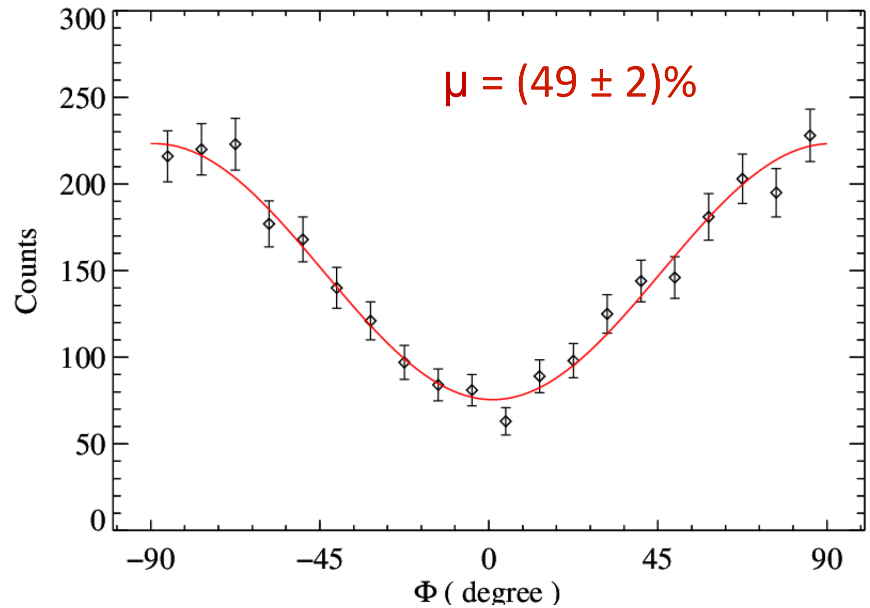
➢ Measured photoelectron tracks

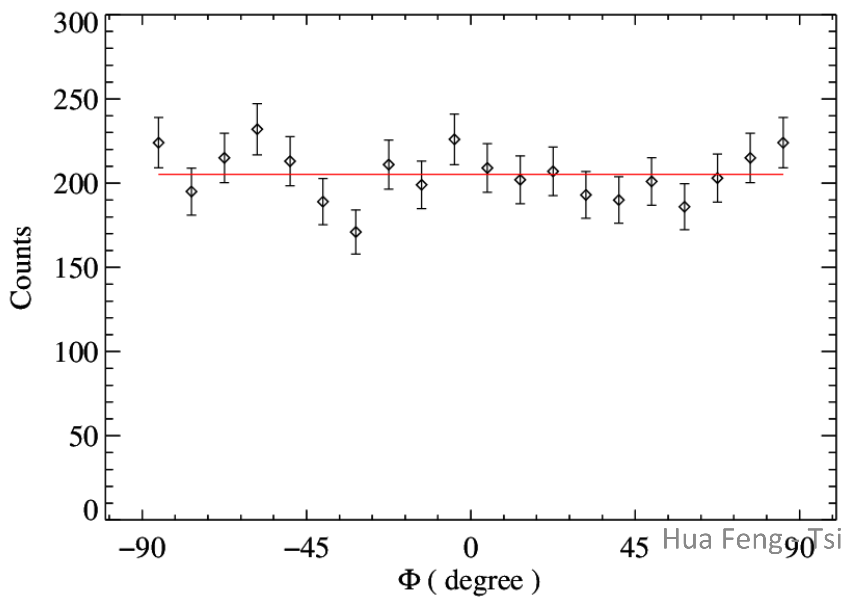


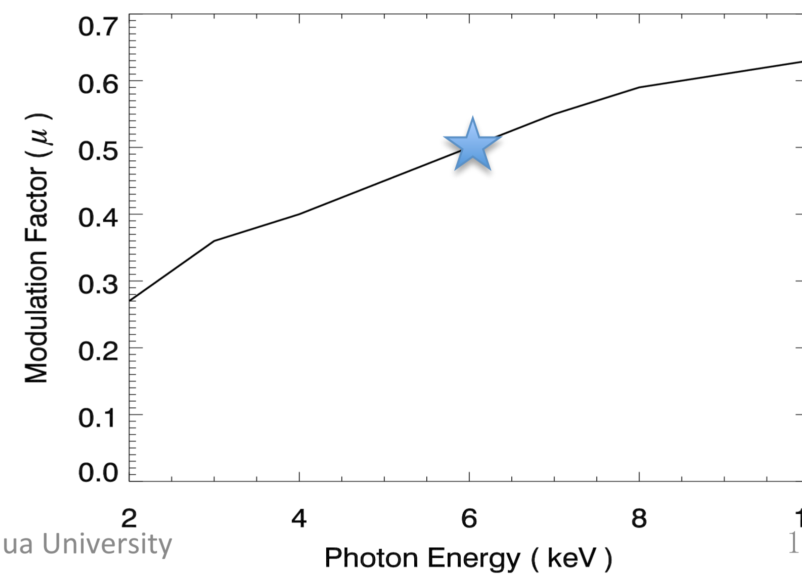
➢ Modulation curves

50% at 6 keV









Science with X-ray polarimetry for XTP

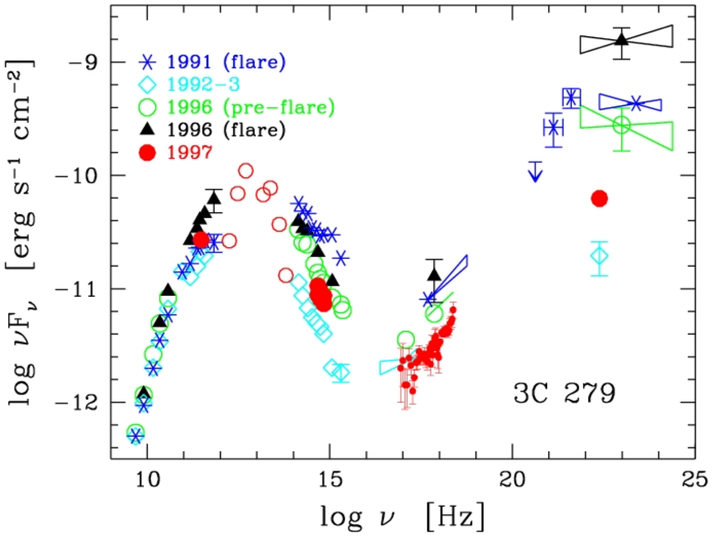
- Neutron Stars
  - Rotation-powered pulsars: emission mechanism (polar cap/slot gap/outer gap)
  - Accretion-powered pulsars: pencil beam vs. fan beam
  - Millisecond pulsars: geometry
- Black Holes
  - Black hole spin measurement
  - AGN: disk inclination & scattering geometry
  - Corona geometry
  - 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 afterglow
  - emission mechanism & B-fields

Expected number of sources brighter than 0.1 mCrab with positive detection

	total	P>1%		P>3%	
		10^5 s	10^6 s	10^5 s	10^6 s
SNR	19	19	19	19	19
Blazar	314	278	294	277	285
AGN	990	528	823	522	674
Pulsar	10	9	10	9	9
AMXP	14	14	14	13	13
LMXB	139	124	126	102	103
HMXB	102	84	89	72	73

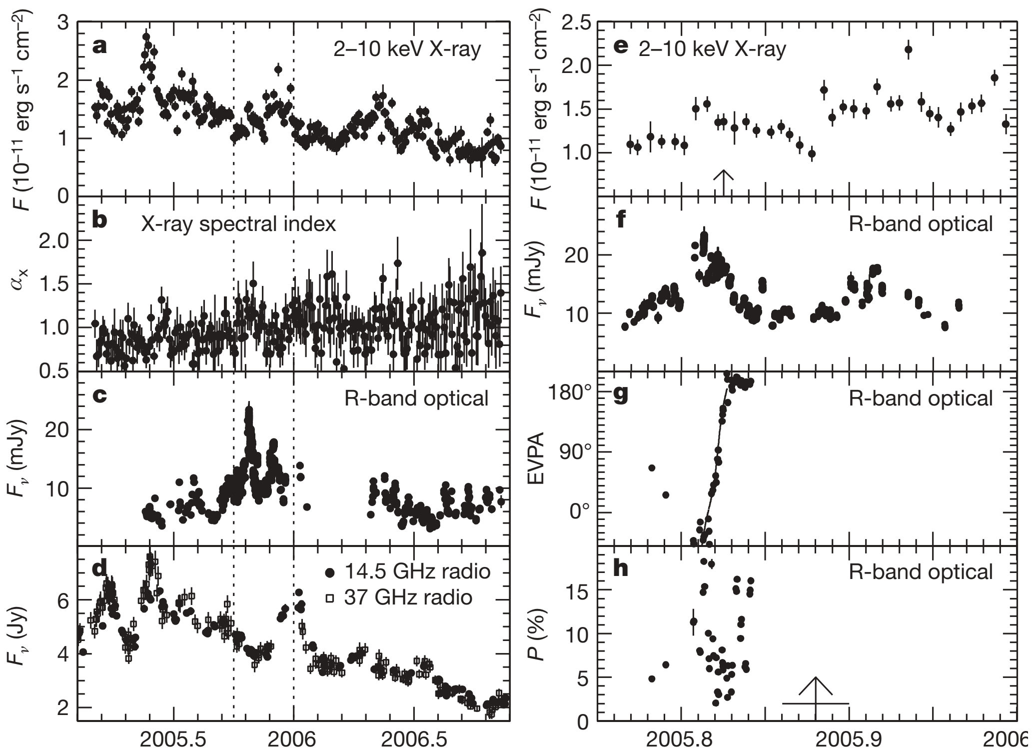
Structure of the magnetic fields in jets

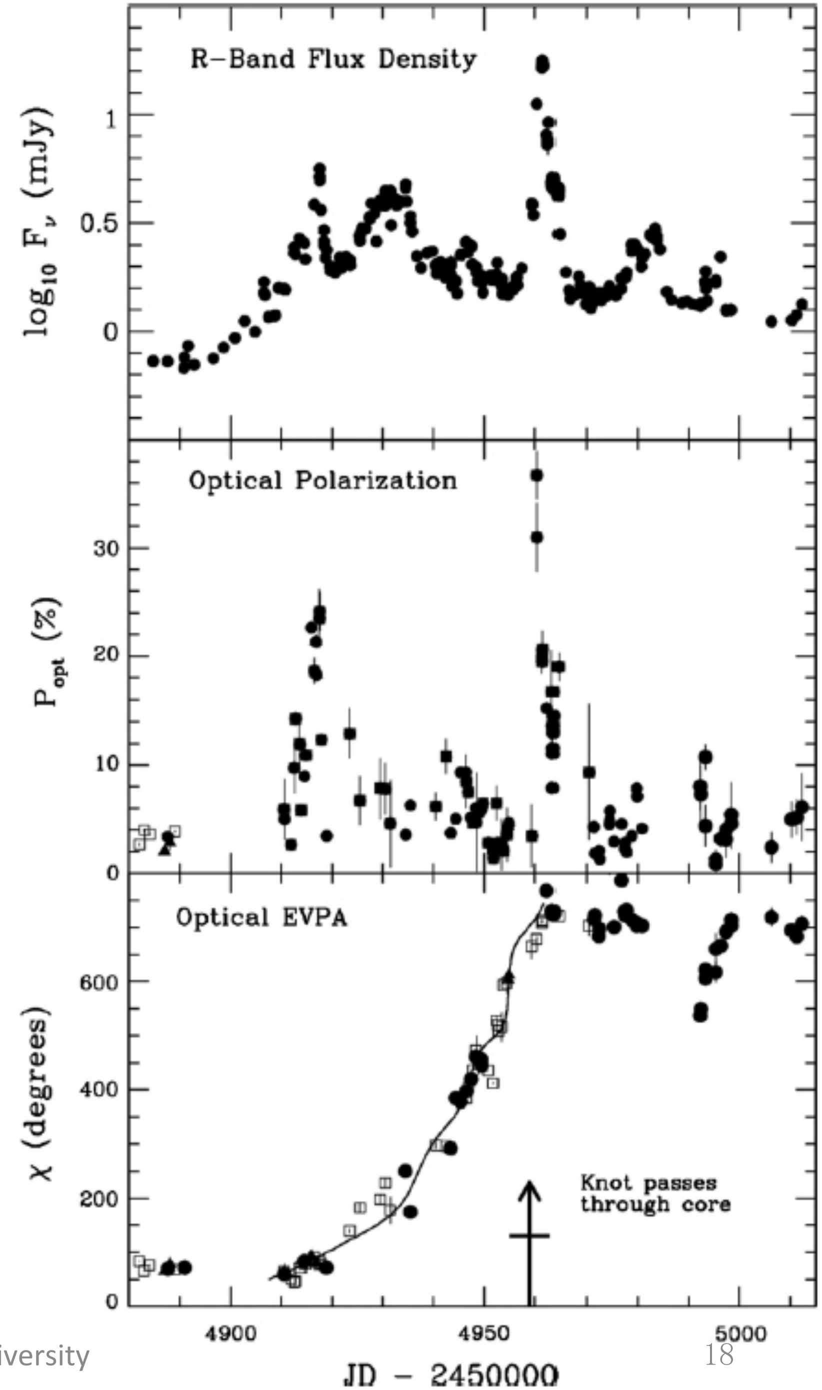
- How are the jets launched?
- Role of magnetic fields in jets collimation and acceleration
- The local B-filed orientation can be measured by synchrotron emission in the jets
- Objects: High Synchrotron Peaked Blazars whose Synchrotron emission peaks in the X-ray band



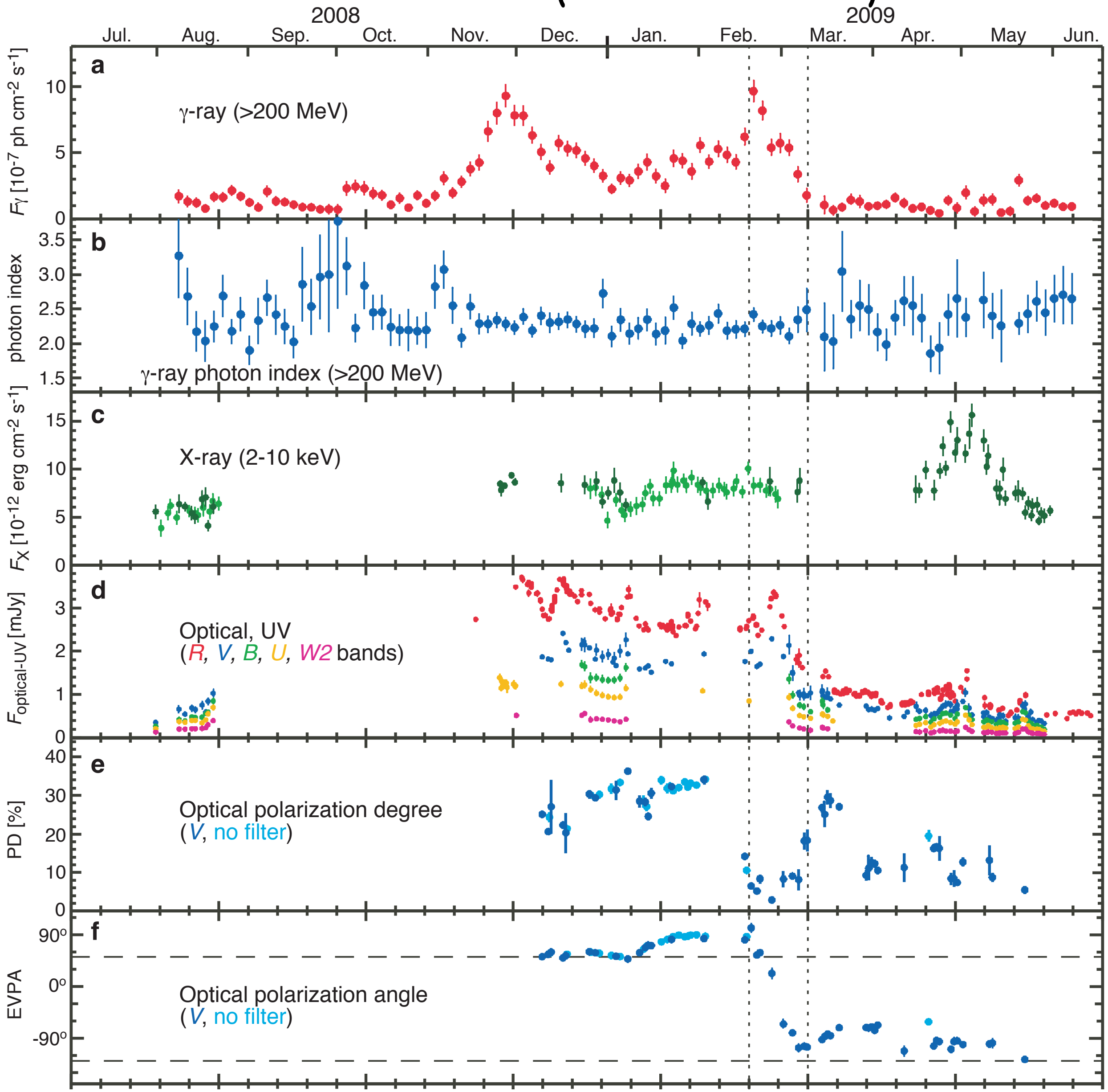
Polarization position angle changed during flares

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



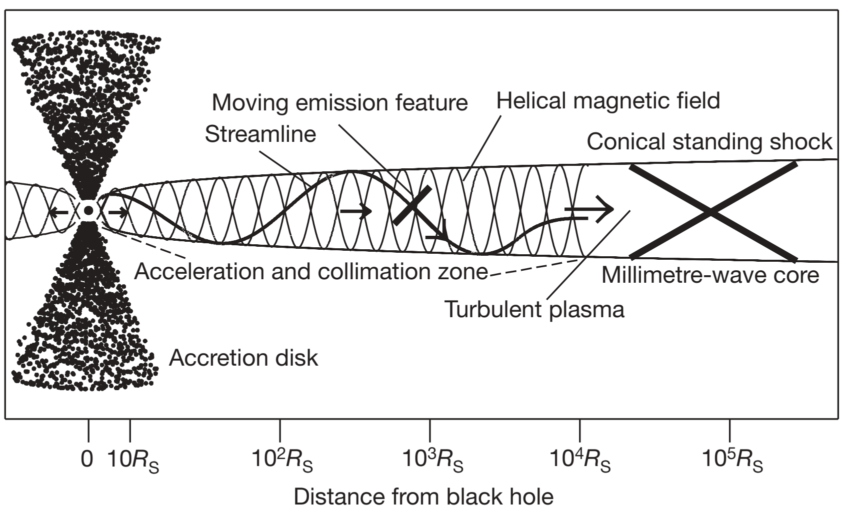


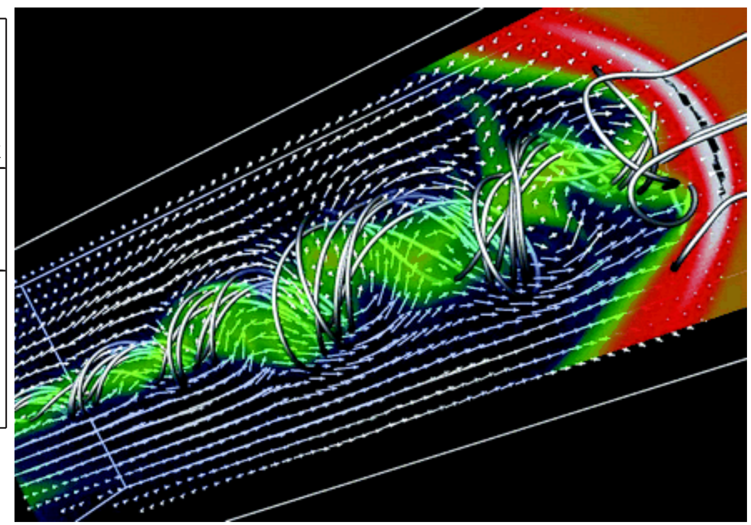
3C 279 (Abdo+2010)



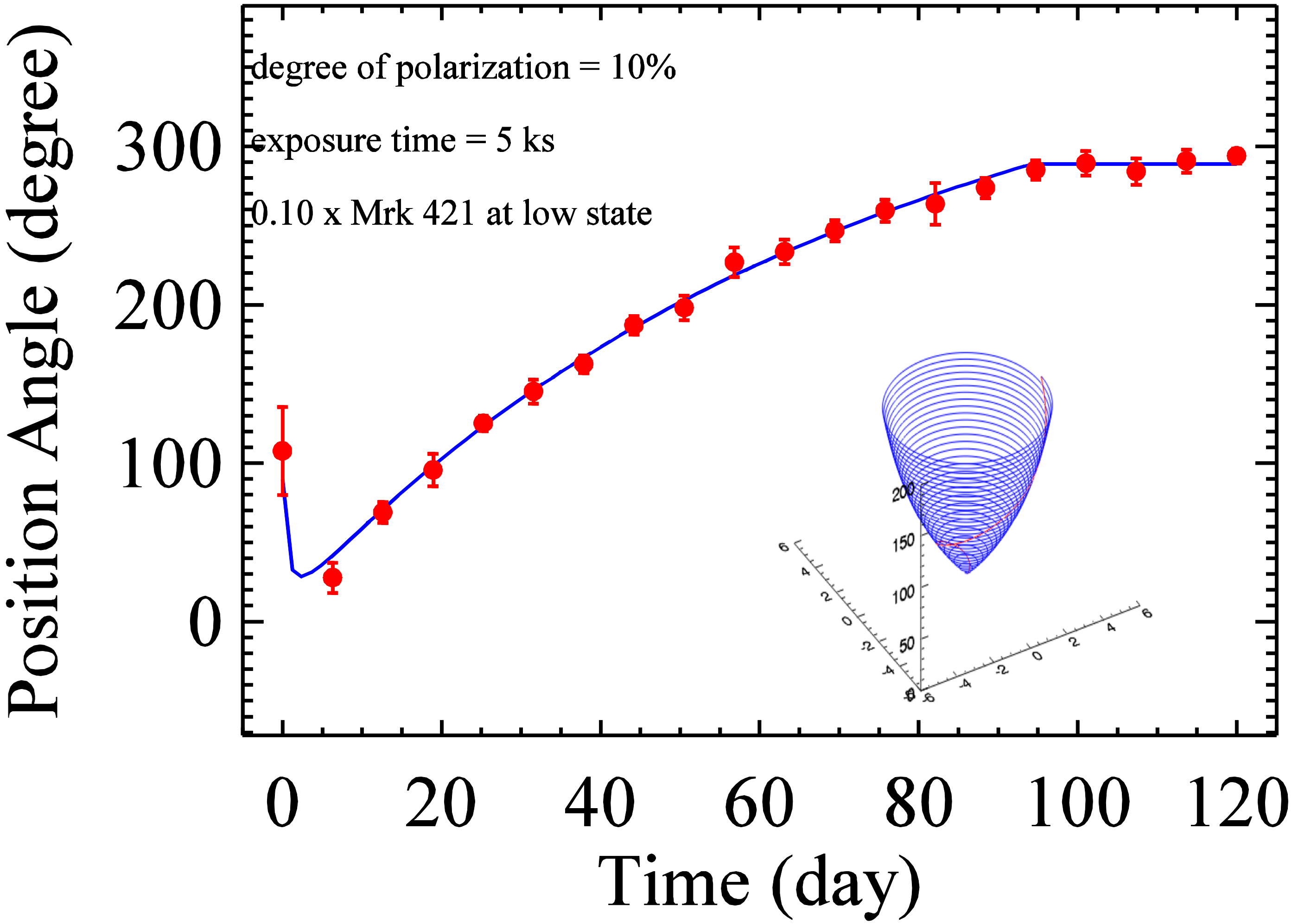
Structure of the magnetic fields in jets

- 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

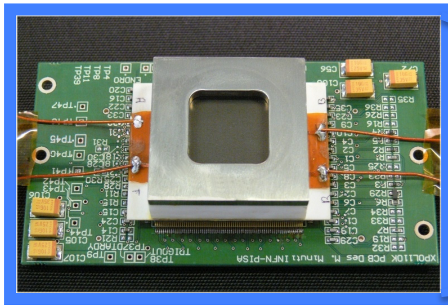


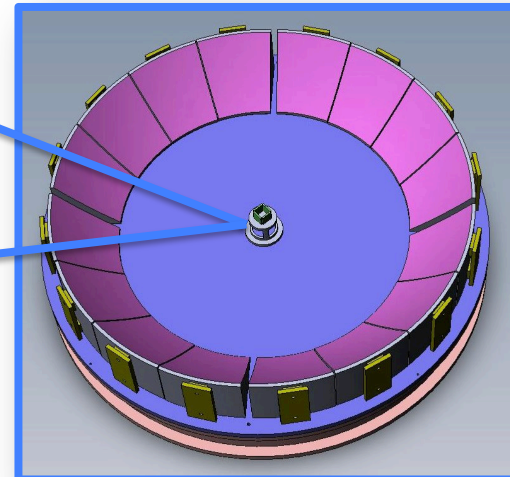


Simulations – 0.1 x Mrk 421 low state

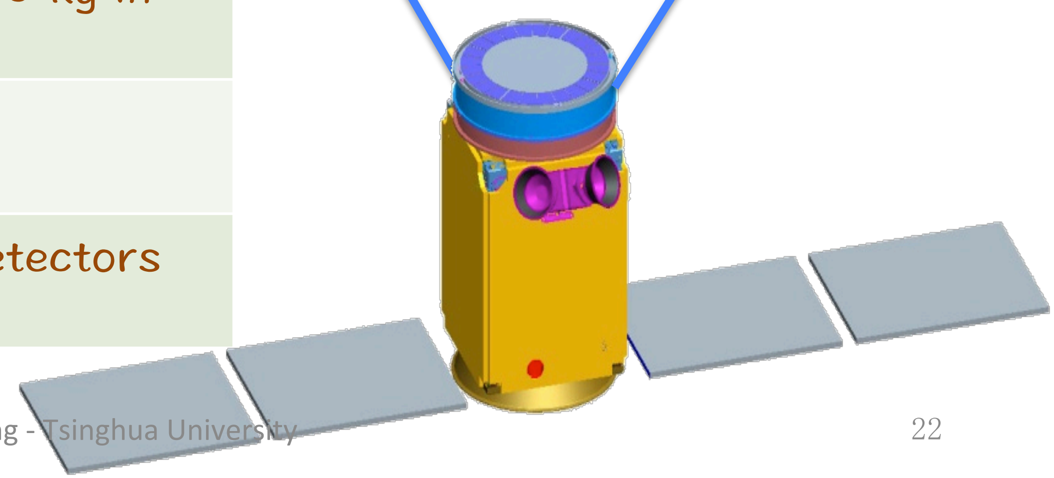


LAMP
Lightweight Asymmetry and Magnetism Probe



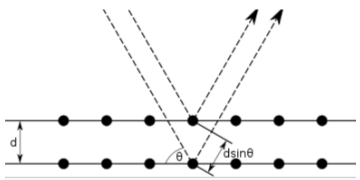


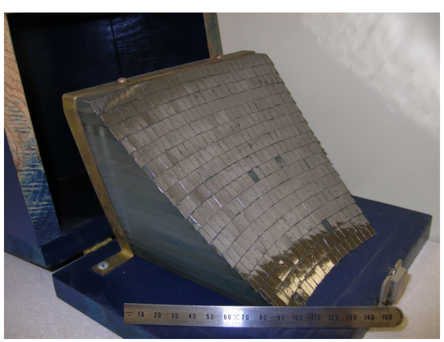
Optics	16 segments of paraboloidal multilayer-coated mirrors
Energy	250 eV; bandwith 2.6 eV
Weight	< 35 kg for payload; ~100 kg in total
Collecting area	1300 cm^2
Focal plane detector	Position sensitive gas detectors with ultrathin window

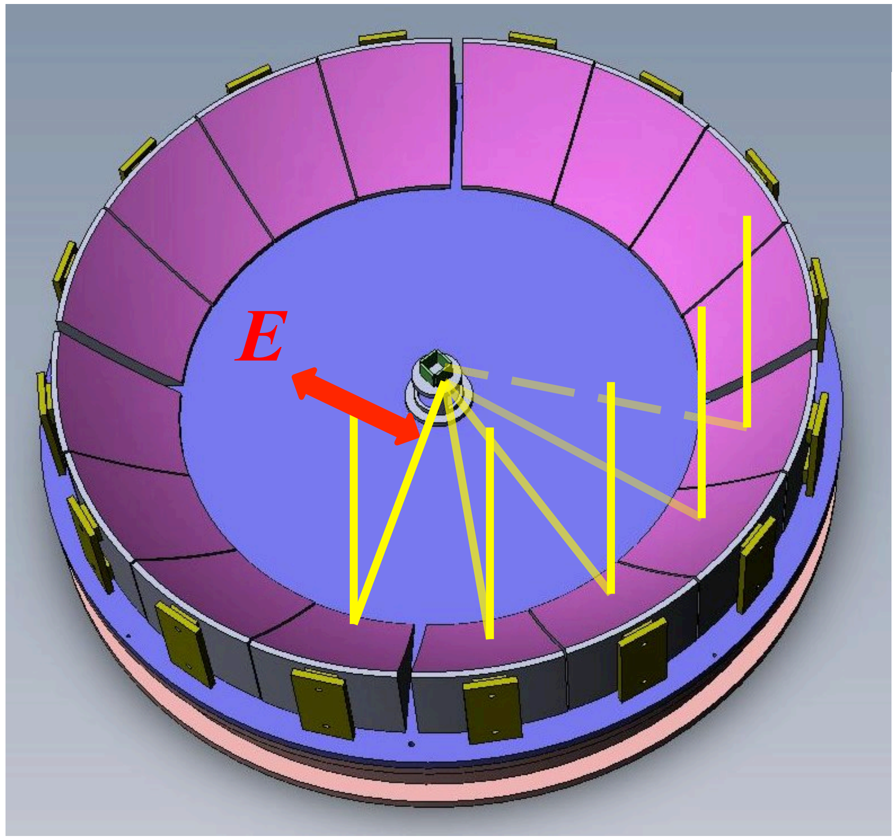


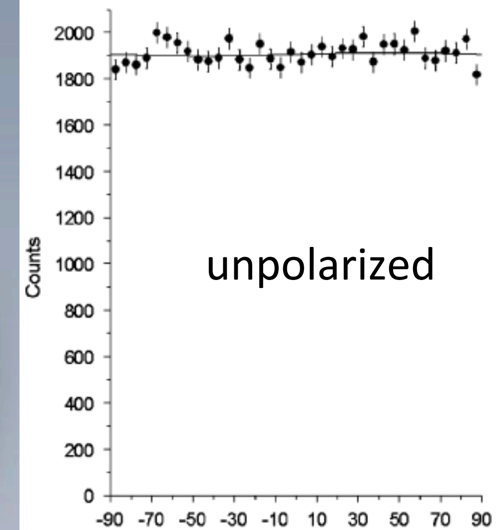
Improved Bragg polarimeter

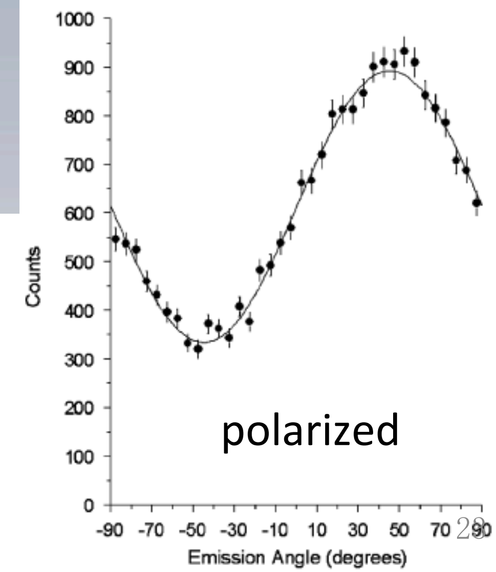
$$2d \sin\theta = m\lambda$$





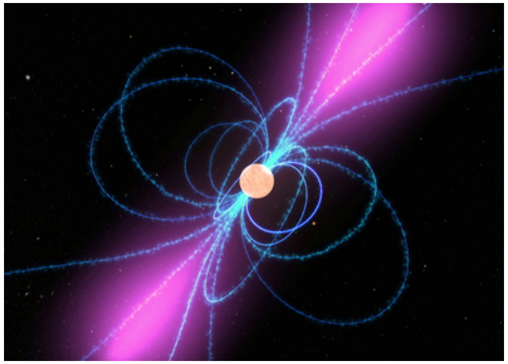


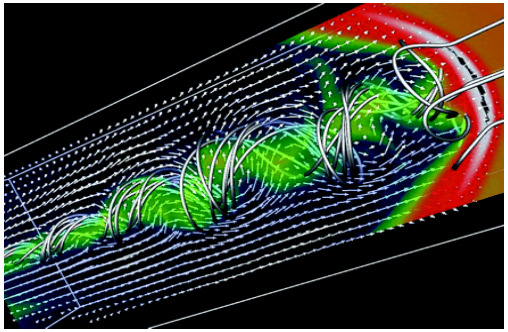


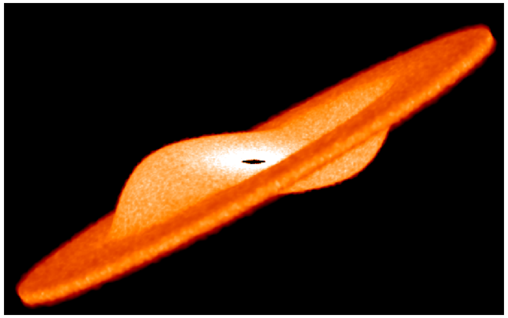


Science with LAMP

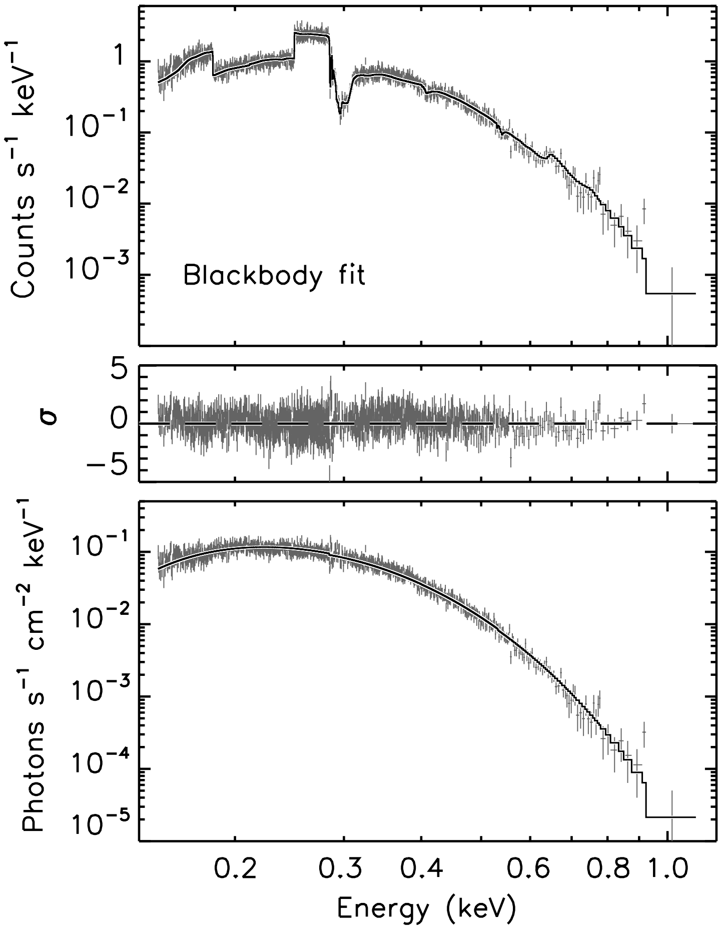
- ✧ Measuring the magnetic field structure of pulsars and testing the vacuum birefringence predicted by QED
- ✧ Capable of finding bare quark stars if they exist
- ✧ Probing the magnetic fields in relativistic jets: their role in jet formation, collimation, and acceleration
- ✧ Measuring the inner disk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







Thermal emission from the surface of NSs

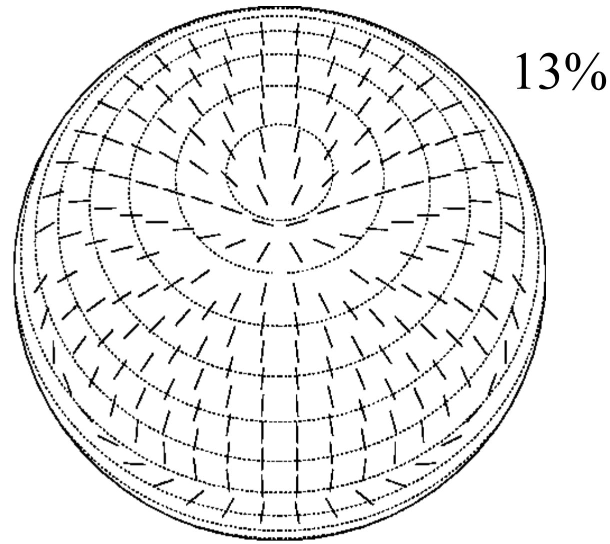


RX J1856.5-3754 (Burwitz et al. 2003)

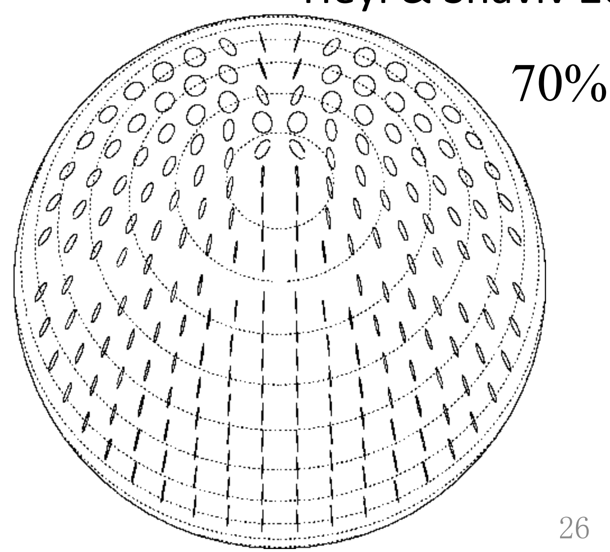
- Low temperature blackbody component
- X-ray dim isolated neutron stars (XDINS)
  - Pure, featureless blackbody spectrum
- Better probe to NS interior
  - Close to the NS body
  - Well known radiation mechanism

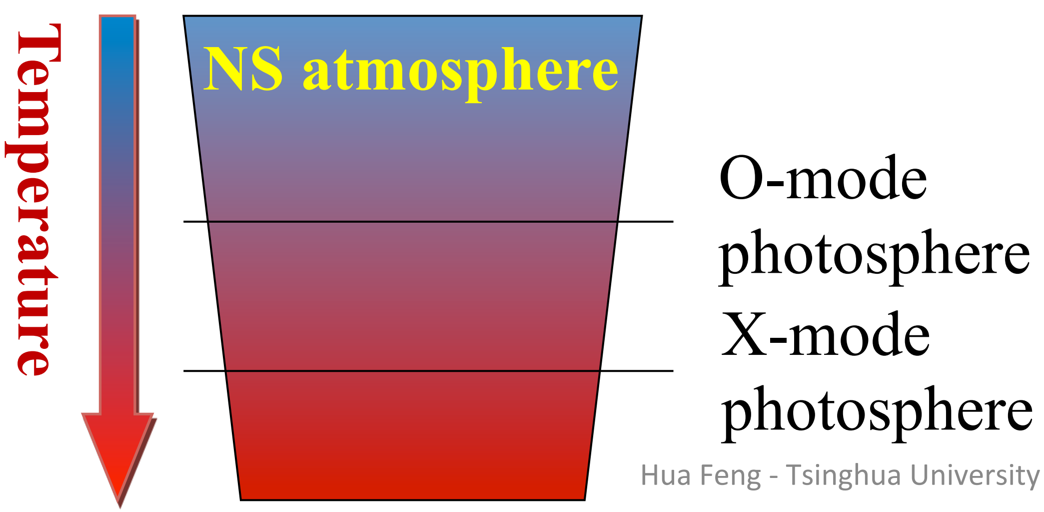
Thermal emission from the surface of NSs

- 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

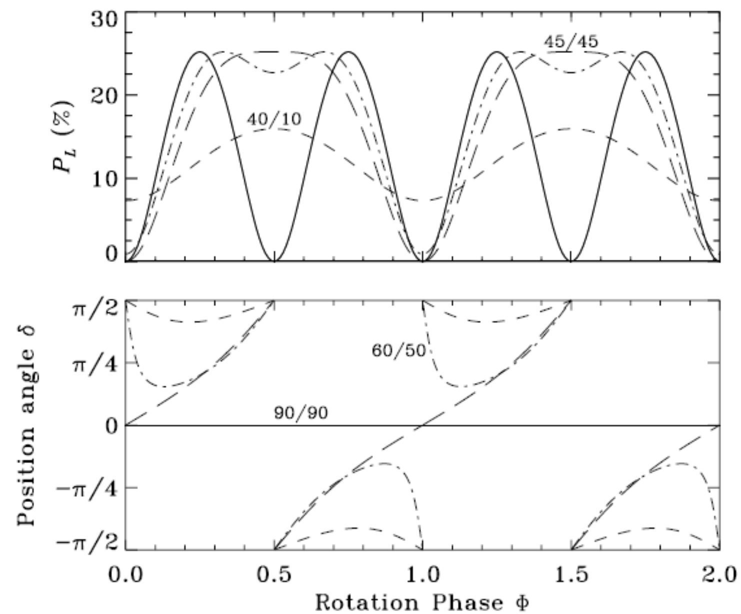


Heyl & Shaviv 2000



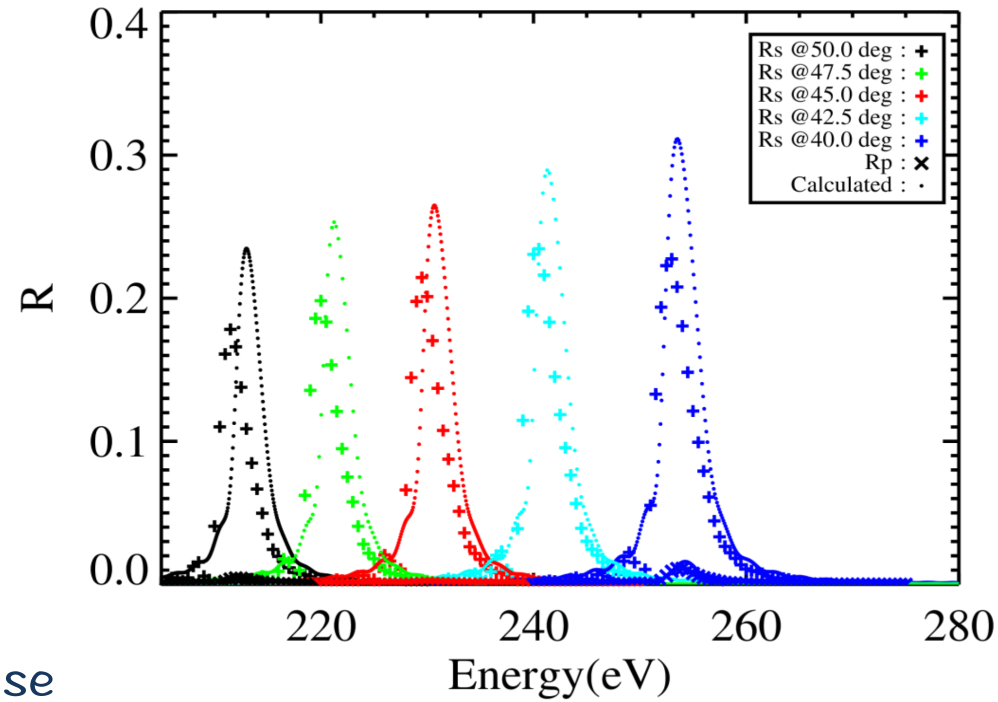


- Phase resolved polarimetry
  - B-field (dipole component) strength & orientation
- Neutron Stars
  - High polarization
- Bare Quark Stars
  - self-bound, no atmosphere (bare)
  - Low temperature gradient
  - $T_{\text{O-mode}} = T_{\text{X-mode}}$
  - Zero polarization (Lu, Xu & Feng 2013)



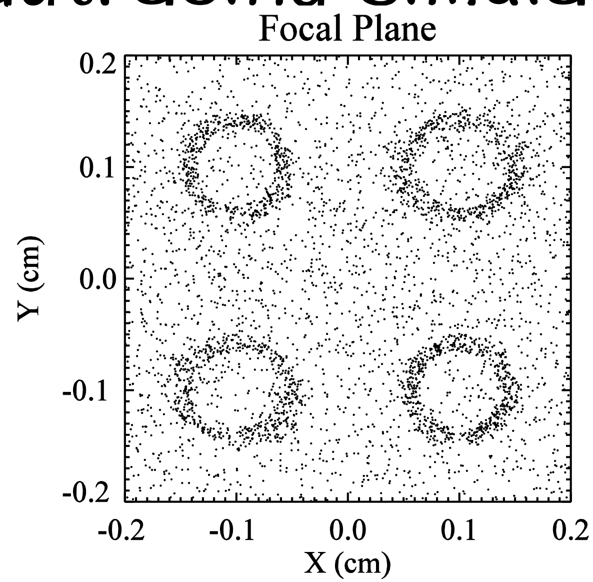
- Pavlov & Zavlin 2000, ApJ, 529, 1011
- Heyl & Shaviv 2000, MNRAS, 311, 555
- Ho & Lai 2001, MNRAS, 327, 1081
- Heyl & Shaviv 2002, Phys. Rev. D, 66, 3002
- Heyl, Shaviv, Lloyd 2003, MNRAS, 342, 134
- Lai & Ho 2003, PRL, 91, 1101
- van Adelsberg & Lai 2006, MNRAS, 373, 1495
- Wang & Lai 2009, MNRAS, 398, 515
- Fernandez & Davis 2011, ApJ, 730, 131

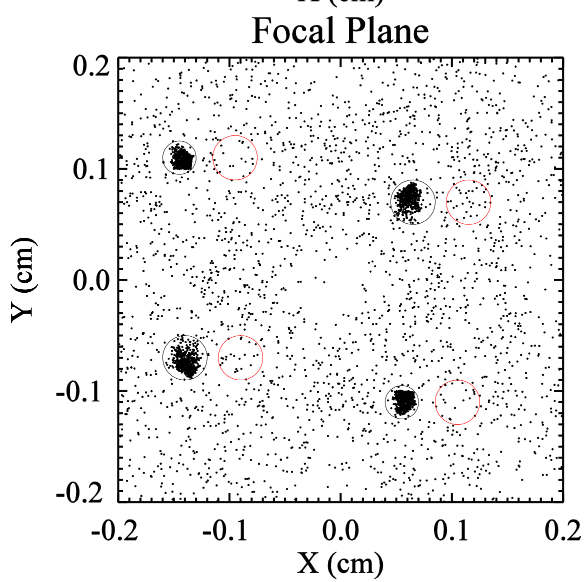
Test of reflectivity (Cr/C ML) at the Diamond light source: meet requirements

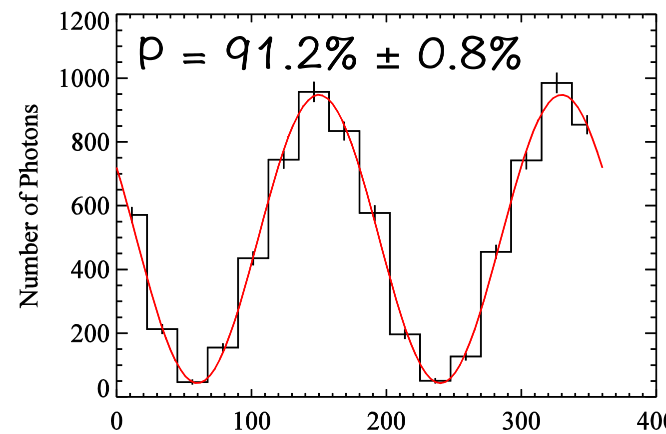


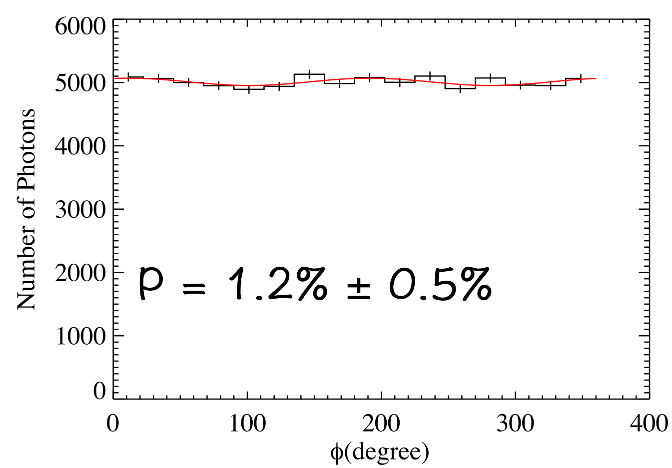
- Mirror base
  - Slumped glass (ready in Tongji University)
  - electroformed Nickel (ready in MLT)

Rautracing simulation: RX J1856.5-3754









Sensitivity

Minimum detectable polarization

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

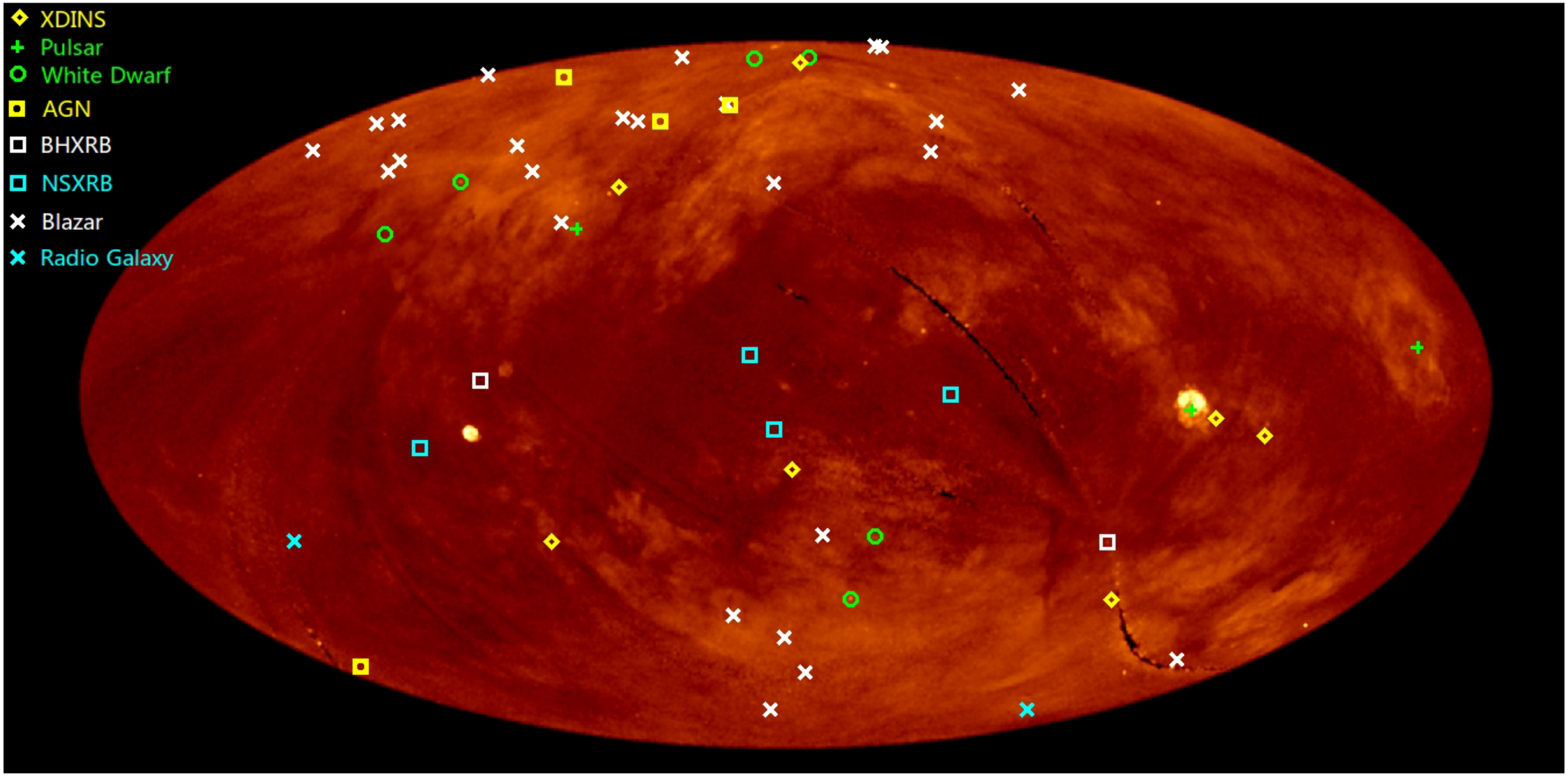
MDP ~ 1% for brightest objects

$T = 10^6$ 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
Radio quiet AGN	100	408

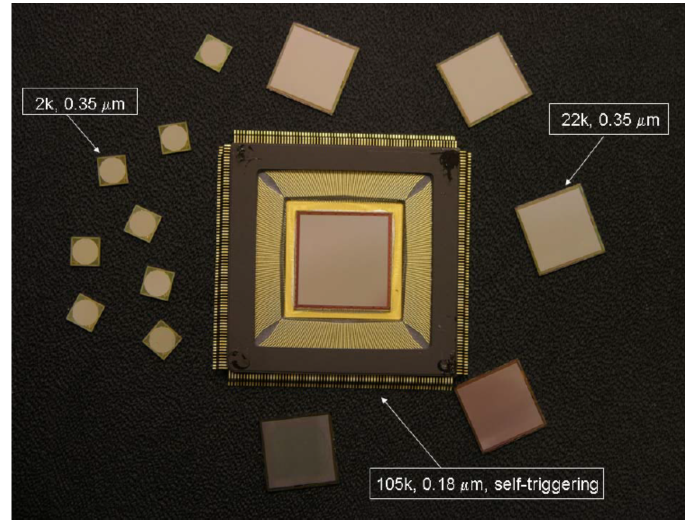
Core program

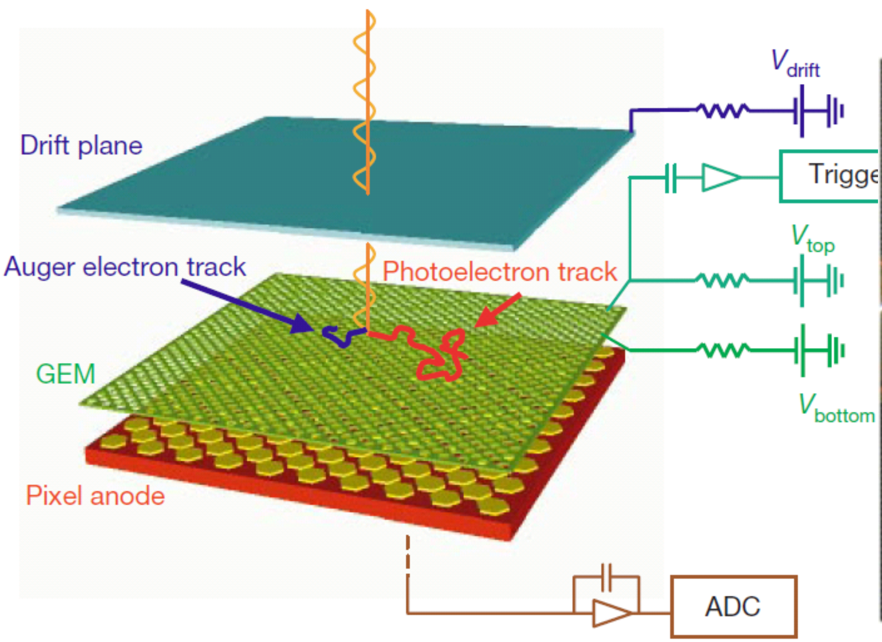
- 1.5-2 years: the brightest of each class

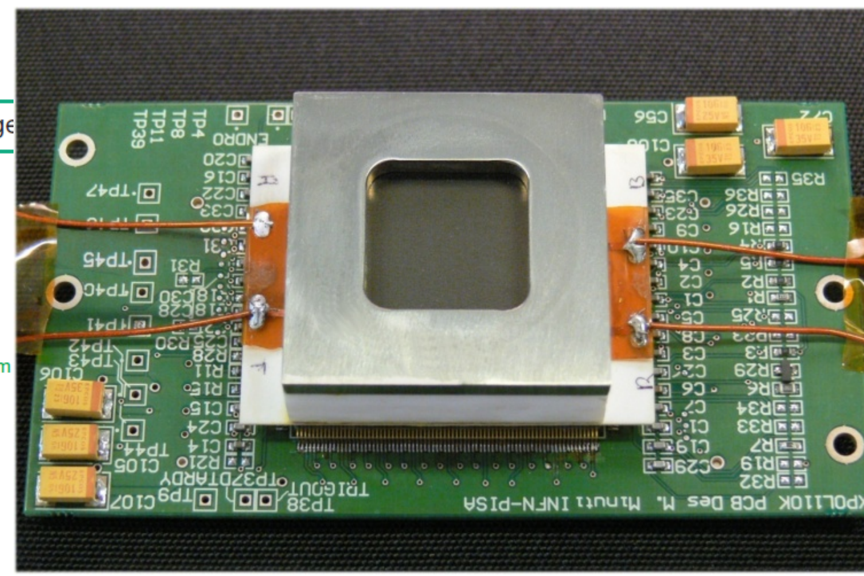


Gas Pixel Detector

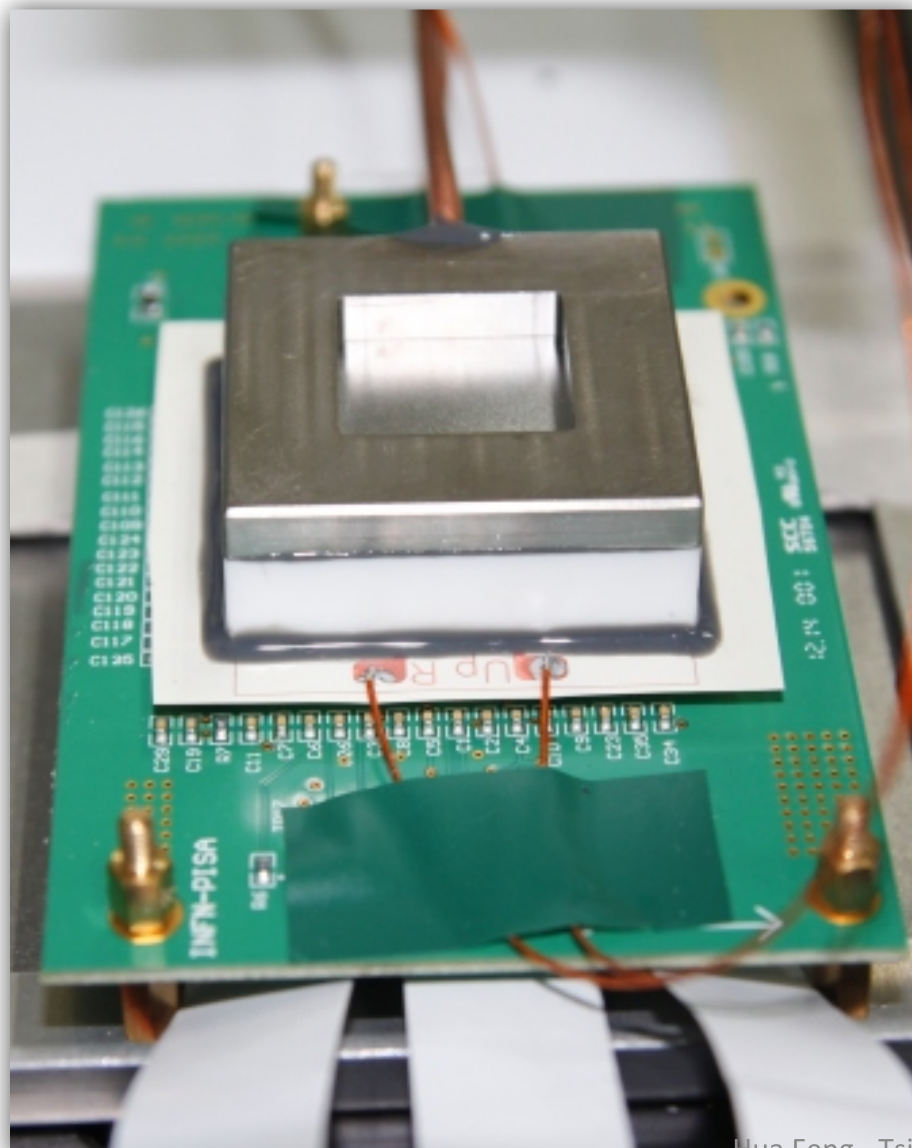
- Direct 2D imaging
  - Pixel size 50μm
  - 110k pixels

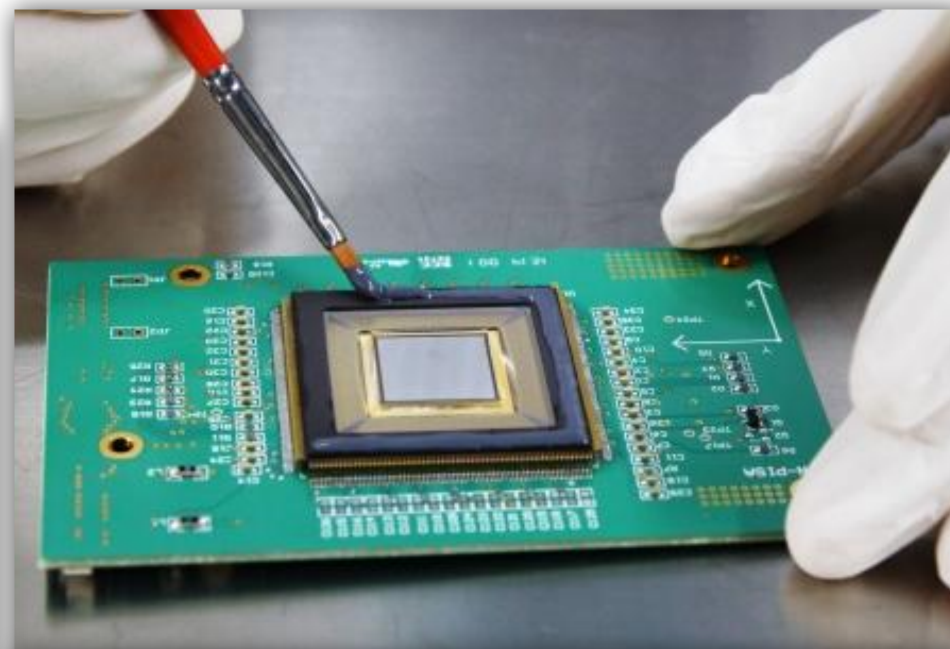


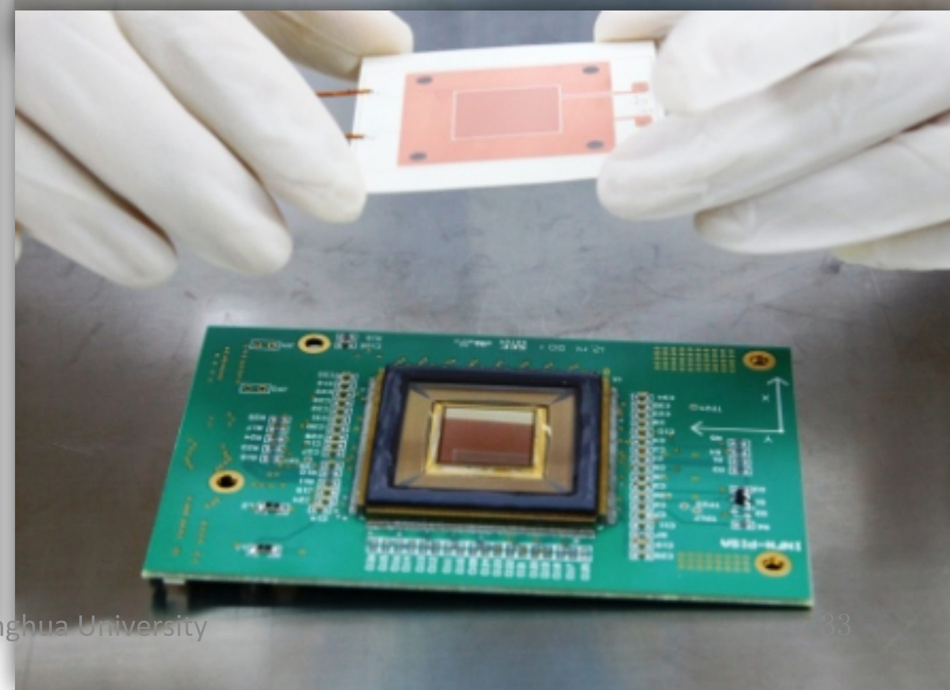




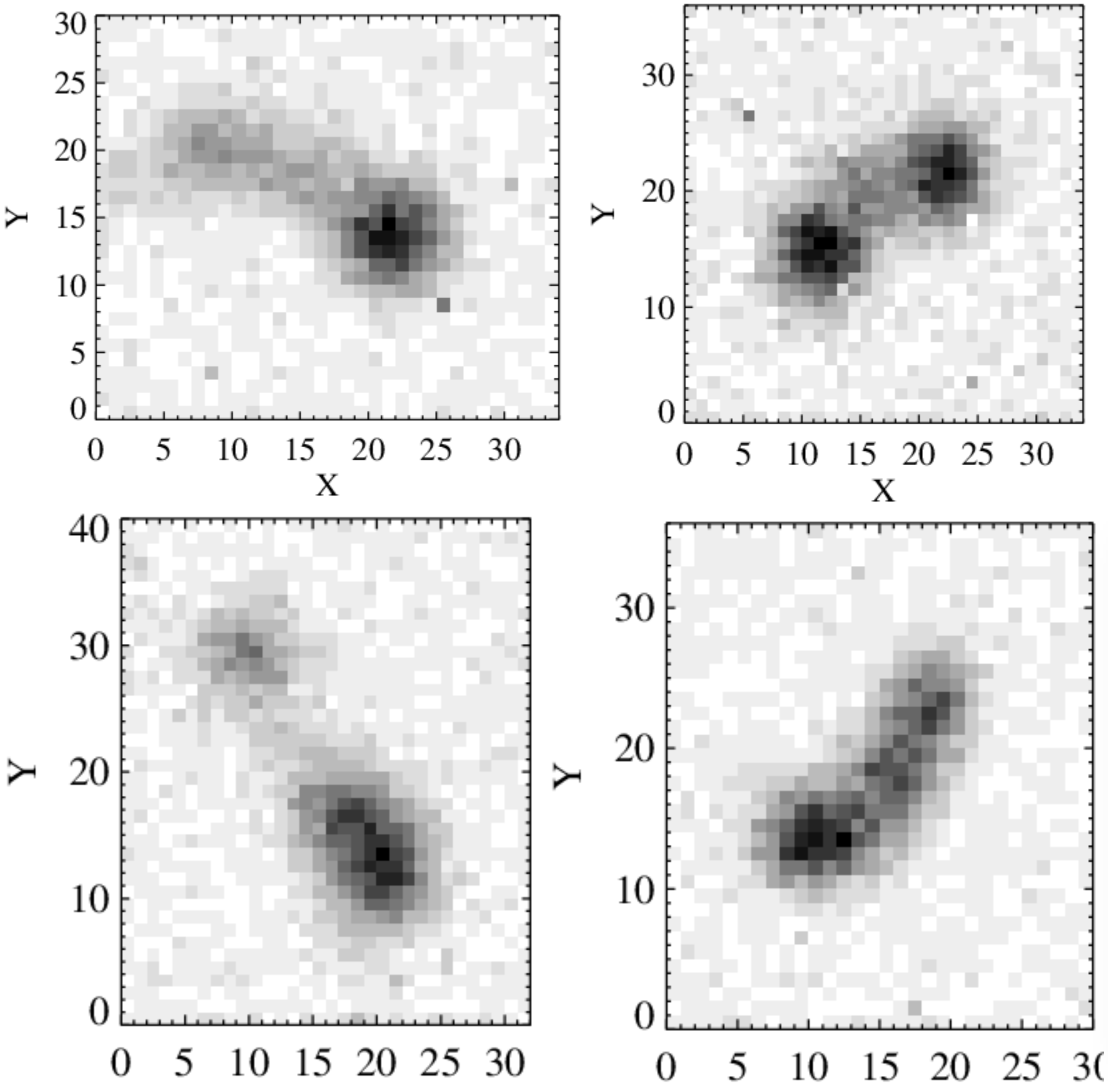
Detector sealing



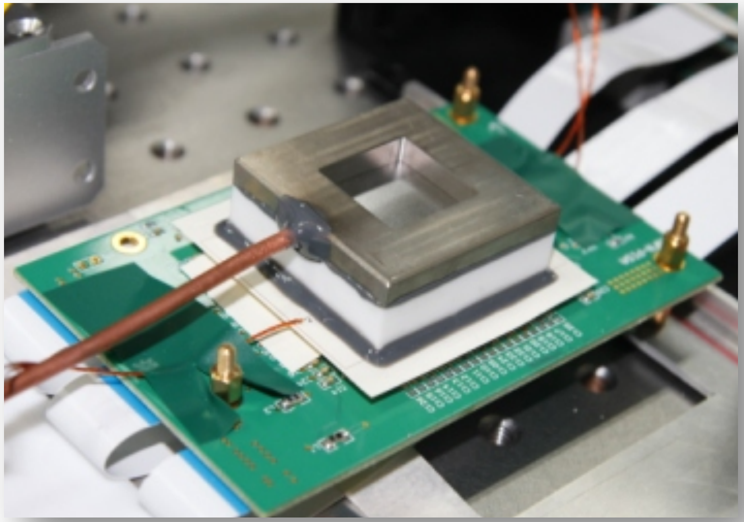




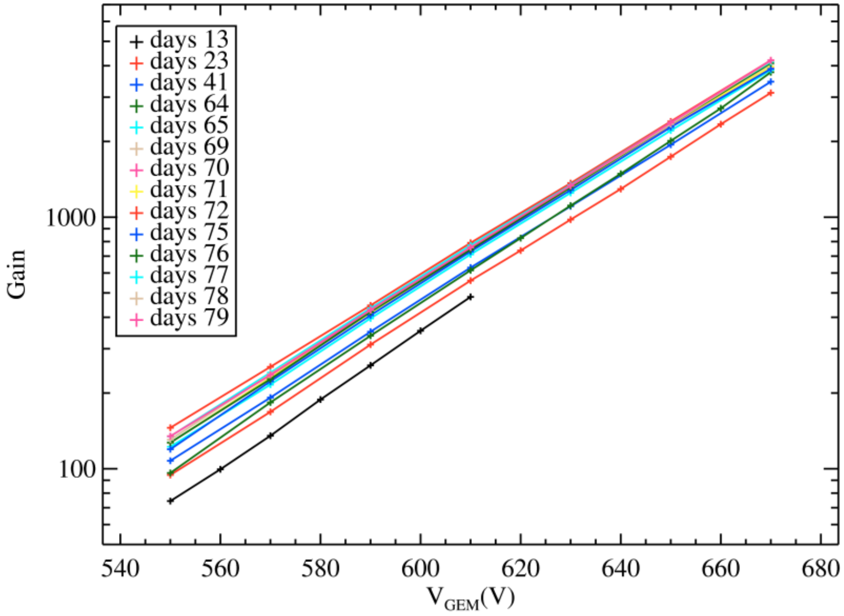
Electron tracks (8 keV)

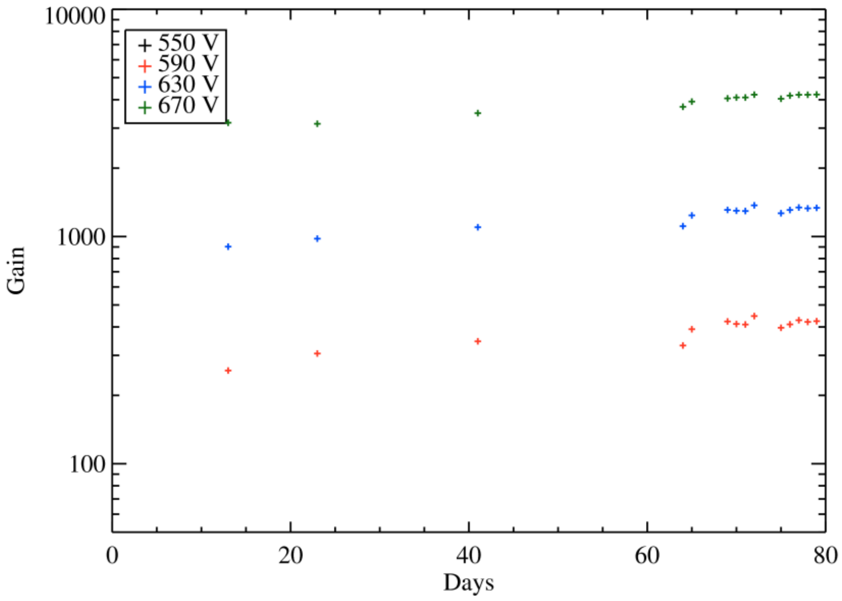


Single GEM
50μm pitch
Ar:CO_2=7:3 @1.1atm



Lifetime test





TPC or GPD?

- Systematics
- Imaging capability
- Pitch
  - 120/140 μm (TPC) vs. 50 μm (GPD)
- Gas mixture
  - ¼ atm DME vs. 1 atm DME or Ne/CO2
- Lifetime
  - TPC is very sensitive to contamination which affects electron transportation
  - DME is the only choice for TPC, which is organic and difficult to use
- Readout
  - TPC: fast electronics, large noise, high gain
  - GPD: slow electronics, small capacitance, low noise, low gain
  - The GPD ASIC is well developed, while the the APV25 chip is not perfect for X-ray polarimetry (the buffer size is not long enough)

Summary

- XTP
  - <4500 kg, under early phase study
- LAMP
  - <100 kg, 3 years for technical demonstration, 5-6 years to launch, high TRL
  - Unique opportunity at Tsinghua University
- Technique for long-lifetime (5-10 years) sealed proportional counters is almost ready in China
- Welcome to contribute to both the science and instrumentation !