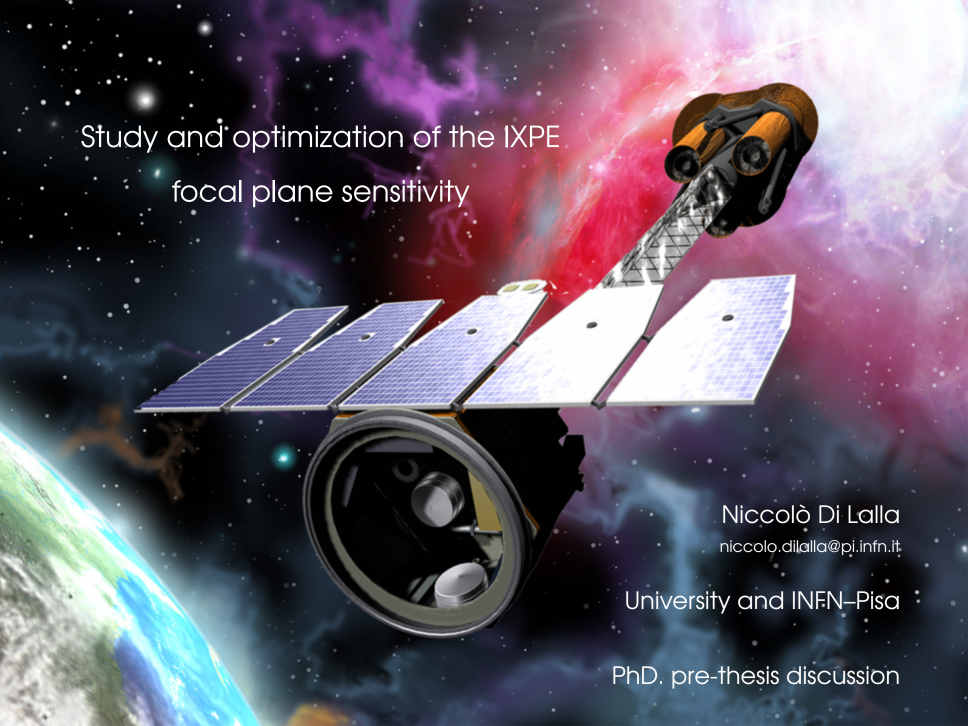


Study and optimization of the IXPE focal plane sensitivity

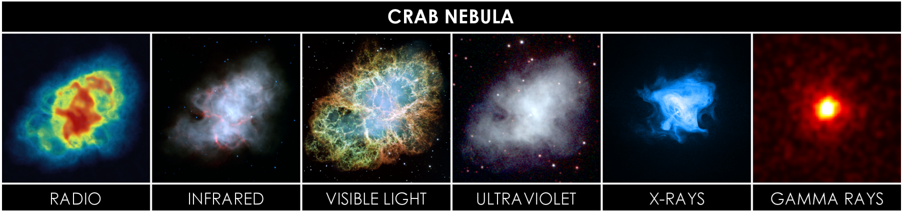
Niccolò Di Lalla
niccolo.dilalla@pi.infn.it

University and INFN–Pisa

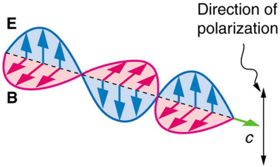
PhD. pre-thesis discussion

The four facets of light

Four different ways to look at the electromagnetic Universe



- Light carries four different types of information:
  - direction;
  - energy;
  - time;
  - polarization.



- Imaging, spectroscopy, timing and polarimetry are routine observational techniques across the entire electromagnetic spectrum.
- High-energy (X-ray and γ-ray) polarimetry is possibly the most notable exception.

The last X-ray polarimeter. . .

Weisskopf et al., ApJ **220**, 1978 (L117)

THE ASTROPHYSICAL JOURNAL, 220:L117–L121, 1978 March 15

A PRECISION MEASUREMENT OF THE X-RAY POLARIZATION OF THE CRAB NEBULA WITHOUT PULSAR CONTAMINATION

M. C. WEISSKOPF, E. H. SILVER, H. L. KESTENBAUM, K. S. LONG, AND R. NOVICK
Columbia Astrophysics Laboratory, Columbia University
Received 1977 November 15; accepted 1977 December 22

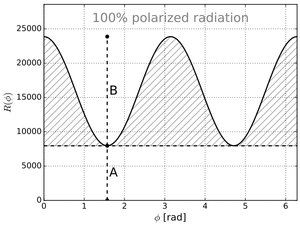
ABSTRACT

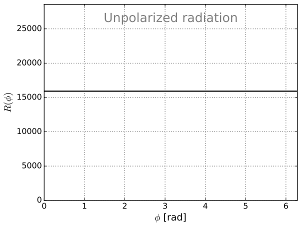
The linear X-ray polarization of the Crab Nebula has been precisely measured at 2.6 keV and 5.2 keV with the *OSO* 8 graphite crystal polarimeters. The 1.4 ms time resolution of these instruments permitted the removal of any contribution to the polarization from the pulsar. The nebular polarization is 19.2% ± 1.0% at a position angle of 156°.4 ± 1°.4 at 2.6 keV. At 5.2 keV the corresponding results are 19.5% ± 2.8% at 152°.6 ± 4°.0.
Subject headings: nebulae: Crab Nebula — polarization

- A crystal X-ray polarimeter flown onto the OSO-8 satellite in 1975.
  - $\sim 20\,\sigma$ measurement averaged over the Crab nebula.
  - Still the state of the art in the soft X-ray band.
- Polarimetry still largely underdeveloped, compared to the other branches of X-ray astronomy.
  - No soft-X-ray polarimeter flown in the last 40 years.

Basic formalism

What is a polarimeter and why polarimetry is photon-greedy?





- ▷ Any polarimeter ultimately measures an azimuthal modulation around the polarization angle ϕ_0 of the incident photon beam:

$$R(\phi) = A + B\cos^2(\phi - \phi_0)$$

- ▷ Modulation factor: response to 100% polarized radiation:

$$\mu = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} = \frac{B}{B + 2A}$$

- ▷ Minimum Detectable Polarization (MDP)[1] with no background:

$$\text{MDP} = \frac{4.29}{\mu\sqrt{N}} \quad (99\% CL)$$

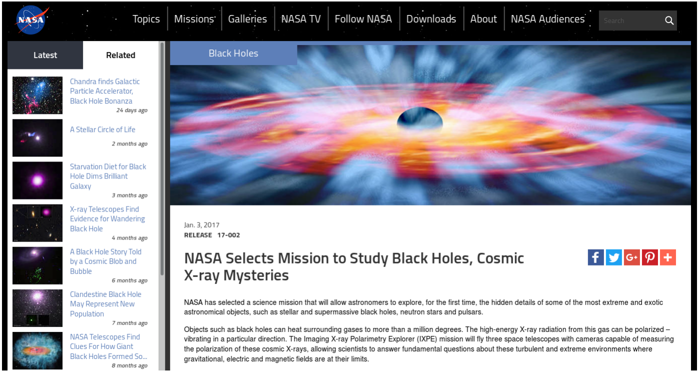
[1] Need 184,000 photons to reach a MDP of 1% even for $\mu = 1$!

Why is the X-ray polarization interesting?

Especially in conjunction with the other observables

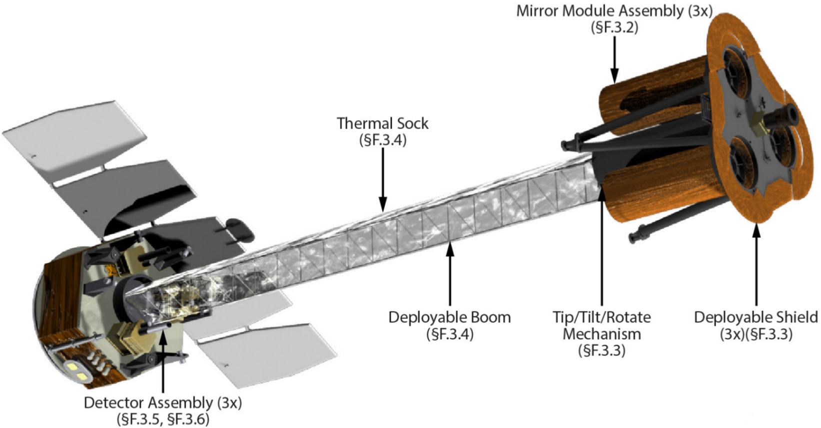
- X-ray polarimetry would add two parameters to the phase space where models are confronted with observations:
  - polarization degree;
  - polarization angle.
- Significant X-ray linear polarization expected in a variety of astronomical X-ray source classes, galactic and extra-galactic:
  - Acceleration phenomena and non-thermal emission processes.
  - Geometry/propagation (e.g., scattering in aspherical geometries).
- Direct information on the geometry of the source and the configuration of the magnetic field.
- Study of systems under extreme conditions and implications for fundamental Physics:
  - strong gravitational fields and General Relativity effects;
  - strong magnetic fields and QED effects;
  - photon propagation over cosmological distances.

NASA selects IXPE

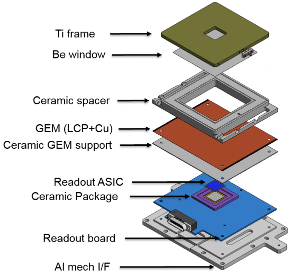


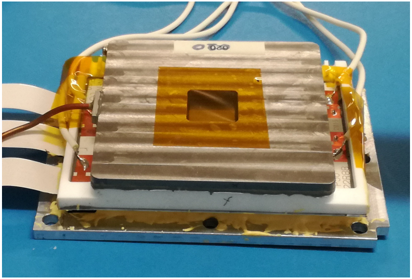
- IXPE stands for Imaging X-ray Polarimetry Explorer.
- Recently selected by NASA as the next SMall EXplorer (SMEX) mission for a launch in late 2020 and duration of at least 2 years.
- First space mission entirely dedicated to X-ray polarimetry.

The IXPE mission
Artistic rendering



The Gas Pixel Detector (GPD)

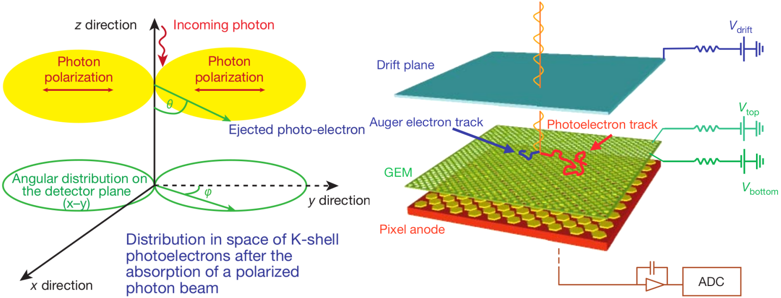




- Basic components:
  - gas-filled absorption gap acting as detection medium;
  - Gas Electron Multiplier (GEM) providing gas amplification;
  - finely pixelated readout anode for signal collection.
- Sensitive down to very low energy ($\sim$ 1 keV).
- Fully two-dimensional (imaging).
- Coronation of a 20-year long R&D activity entirely carried out in Pisa under the lead of Ronaldo Bellazzini.

Photoelectric X-ray polarimetry

The detection principle of the GPD



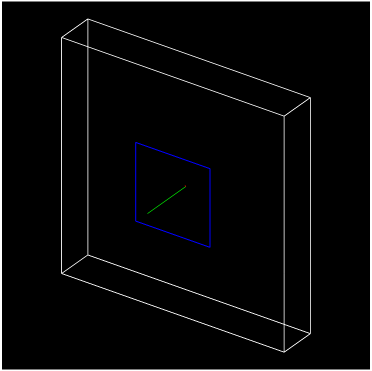
- ▷ Dominant interaction process at low energy (< 10 keV).
- ▷ Distribution of the direction of emission of a K-shell photoelectron 100% modulated for linearly polarized radiation:

$$\frac{d\sigma_C^K}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta \cos^2\phi}{(1+\beta\cos\theta)^4}$$

- ▷ Need to reconstruct the emission direction of the photoelectron.

GPD Monte Carlo simulation (*ixpesim*)

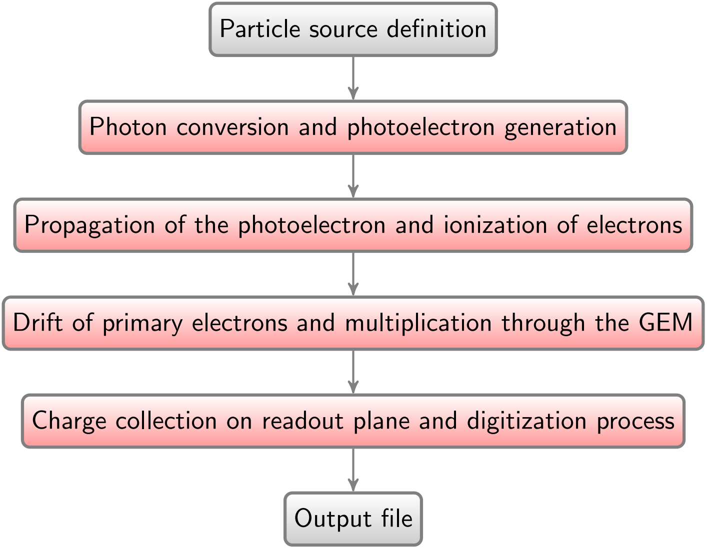
The implemented detector geometry



- ▷ Completely rewritten from scratch in the Geant4 framework.
- ▷ Simulate the response of the GPD to a generic particle source.
- ▷ Produce output files virtually identical to those produced by the actual hardware.

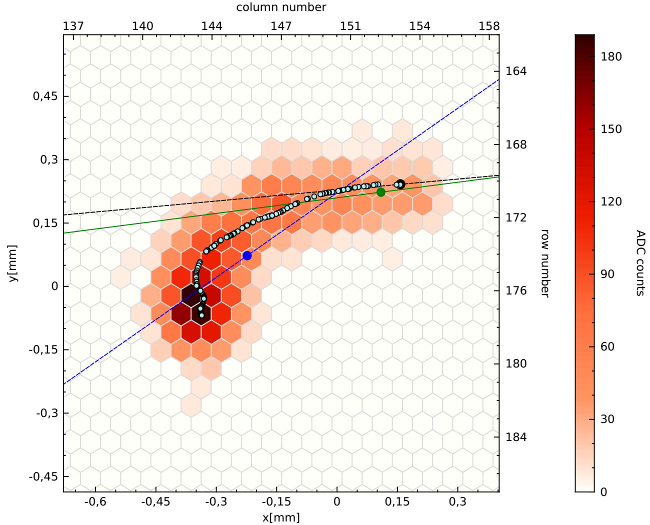
GPD Monte Carlo simulation

Simulation flow

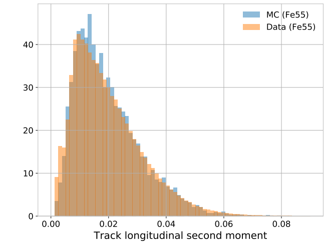


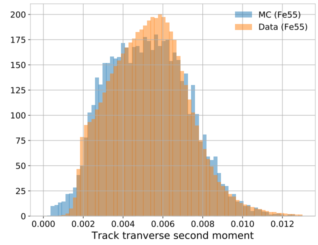
GPD Monte Carlo simulation

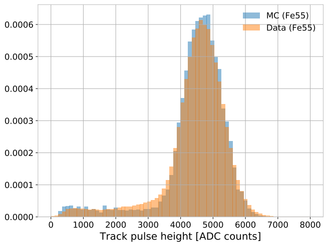
A simulated event

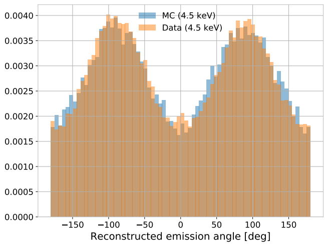


Data–Monte Carlo comparison



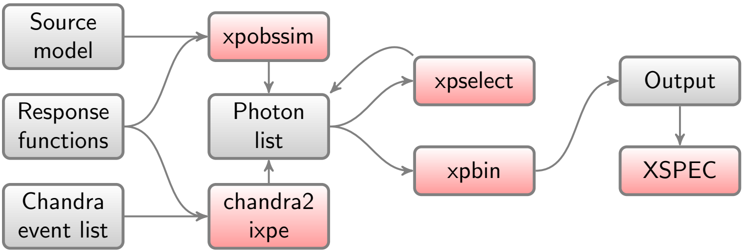






Observation simulation (*ixpeobssim*)

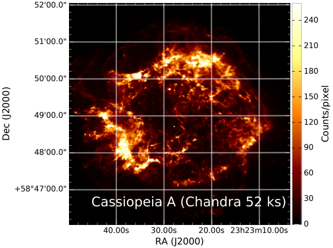
Architectural overview

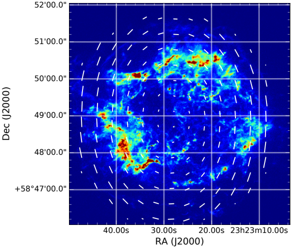


- Simulation framework specifically developed for the IXPE mission
- Produce realistic observation-simulations using the instrument response functions
- The output files can be directly analyzed with standard analysis tools (such as XSPEC and HEASARC ftools)

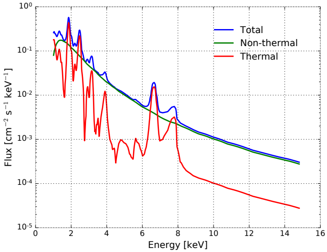
Source model definition

Cassiopeia A



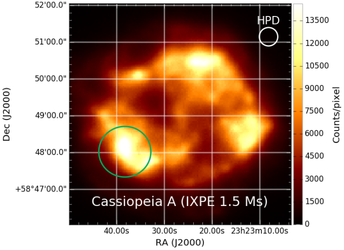


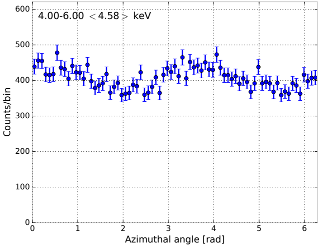
- ▷ Support for phase-dependent periodic sources;
- ▷ Can overlay an arbitrary number of components in the same input model.



Observation–simulation

Cassiopeia A

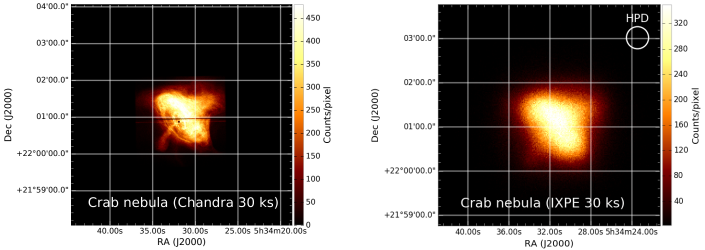




- ▷ Simulate a realistic observation starting from an arbitrary source model:
  - ▷ Calculate the expected number of events convolving the source spectrum with the IXPE effective area.
  - ▷ Extract energies and positions in the sky and smear them with the IXPE response functions.
  - ▷ Generate the angular distribution of the photoelectrons according to the polarization model.

Chandra-to-IXPE converter

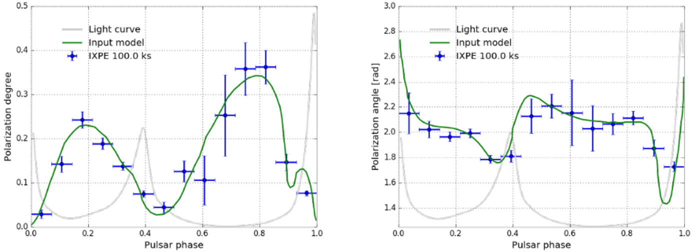
Crab pulsar + nebula



- Process an actual Chandra photon list to produce an IXPE simulation:
  - Chandra measured energies, times and positions taken as MC truth.
  - Events are down- or over-sampled and then smeared with the IXPE response functions.
- Preserve the full correlation between the morphology and the energy spectrum.

Analysis tools

Crab pulsar + nebula



- Some basic analysis tools have been developed in order to:
  - Select subsamples of photons based on event energy, direction, time or phase.
  - Bin and fit the simulated data, producing count maps, spectra, phasograms, light and modulation curves.
- The produced output files can be fed into the standard analysis tools.

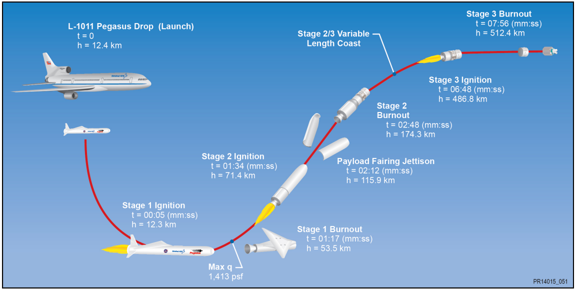
Conclusions and perspective

- The development of the detector Monte Carlo simulation is still underway.
  - Reproduce most of the track features observed in the real data.
  - Fundamental to improve the understanding of the GPD.
  - Creation and study of the IXPE instrument response functions.
  - Validation using Garfield package?
- The observation–simulation software is in a more advanced stage.
  - Successfully used to produce simulations required by NASA for IXPE final approval.
  - Distributed to the IXPE community to support science groups.
  - Important also to develop and test end-to-end analysis chains.
- Start developing analysis and Data Quality Monitoring tools:
  - Analyze and rapidly validate data taken in laboratory.
  - Calibrate the GPD.

BACKUP SLIDES

The IXPE mission

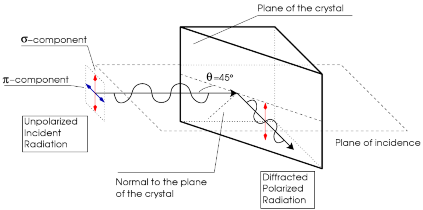
Cheat sheet



- Three identical telescopes, each including GPD and optics:
  - Provide full redundancy
  - Mitigate possible residual systematic effects.
- Mass and power budget (total): $\sim$ 300 kg, $\sim$ 200 W:
- Focal length: 4 m (deployable boom).
- Pegasus launch in stowed configuration from Kwajalein on or after November 20, 2020.
  - 2-year mission on a 540 km circular orbit at nominal 0° inclination.
  - One (simple) operation mode: point-and-stare at known targets.

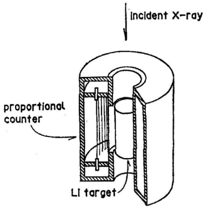
Conventional techniques of X-ray polarimetry

—Bragg diffraction at 45°



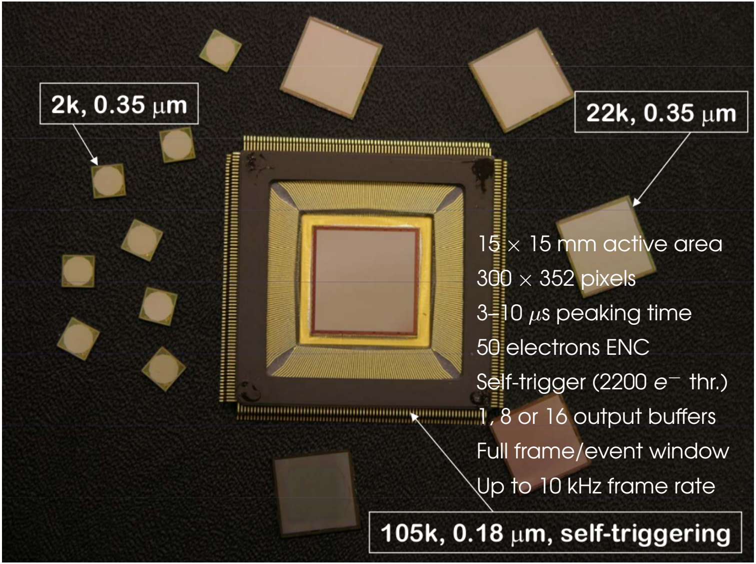
- ✓ Excellent modulation factor.
- ✓ Energy-resolved (discrete harmonics).
- ✘ Limited to low energies.
- ✘ Low efficiency (narrow band-pass).
- ✘ Dispersive (one angle at a time).
- ✘ Needs rotation.

—Thomson scattering around 90°



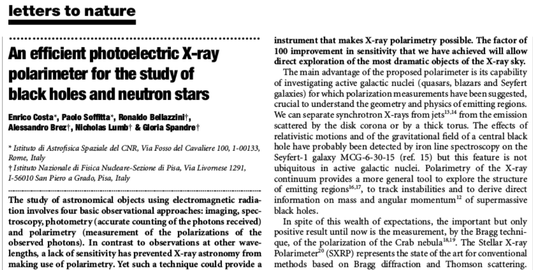
- ✓ Suitable for hard X-rays.
- ✓ Decent efficiency and modulation factor.
- ✓ Decent energy resolution.
- ✘ Limited at low energy.
- ✘ Background can be important.
- ✘ Rotation to reduce systematics.

Three generations of ASICs



X-ray polarimetry becomes reality

Costa et al., Nature **411**, 662–665 (2001)



letters to nature

An efficient photoelectric X-ray polarimeter for the study of black holes and neutron stars

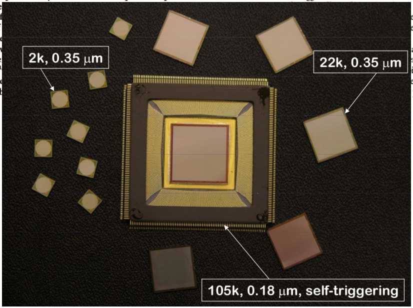
Enrico Costa*, Paolo Soffitta*, Ronaldo Bellazzini†, Alessandro Brez†, Nicholas Lumb† & Gloria Spandre†

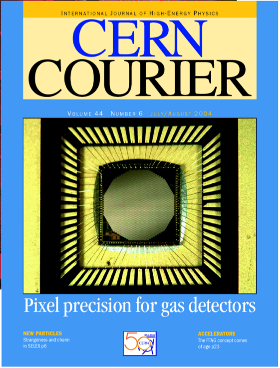
* *Istituto di Astrofisica Spaziale del CNR, Via Fosso del Cavaliere 100, I-00133, Rome, Italy*
† *Istituto Nazionale di Fisica Nucleare-Sezione di Pisa, Via Livornese 1291, I-56010 San Piero a Grado, Pisa, Italy*

The study of astronomical objects using electromagnetic radiation involves four basic observational approaches: imaging, spectroscopy, photometry (accurate counting of the photons received) and polarimetry (measurement of the polarizations of the observed photons). In contrast to observations at other wavelengths, a lack of sensitivity has prevented X-ray astronomy from making use of polarimetry. Yet such a technique could provide a direct picture ... gravitational f... structures of ... inaccessible, ... for example, ... field and dete... 'pencil' beam... the polarizati... presence of a b... instrument that makes X-ray polarimetry possible. The factor of 100 improvement in sensitivity that we have achieved will allow direct exploration of the most dramatic objects of the X-ray sky.

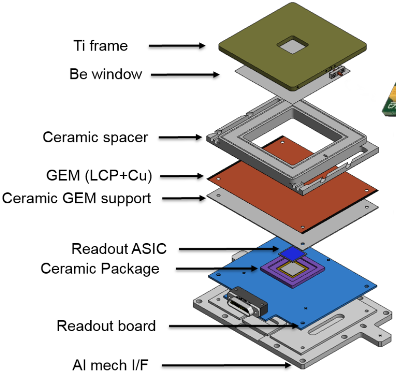
The main advantage of the proposed polarimeter is its capability of investigating active galactic nuclei (quasars, blazars and Seyfert galaxies) for which polarization measurements have been suggested, crucial to understand the geometry and physics of emitting regions. We can separate synchrotron X-rays from jets[13,14] from the emission scattered by the disk corona or by a thick torus. The effects of relativistic motions and of the gravitational field of a central black hole have probably been detected by iron line spectroscopy on the Seyfert-1 galaxy MCG-6-30-15 (ref. 15) but this feature is not ubiquitous in active galactic nuclei. Polarimetry of the X-ray continuum provides a more general tool to explore the structure of emitting regions[16,17], to track instabilities and to derive direct information on mass and angular momentum[12] of supermassive black holes.

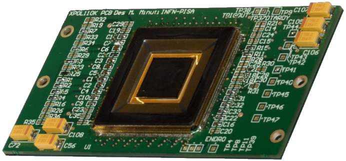
In spite of this wealth of expectations, the important but only positive result until now is the measurement, by the Bragg technique, of the polarization of the Crab nebula[18,19]. The Stellar X-ray Polarimeter[20] (SXRP) represents the state of the art for conventional methods based on Bragg diffraction and Thomson scattering. ... angle at one ... etry[22] is non- ... e sensitivity of ... arization. The ... energy which is ... inding energy. ... ed around that ... photoelectron

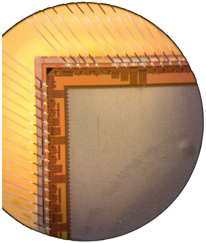


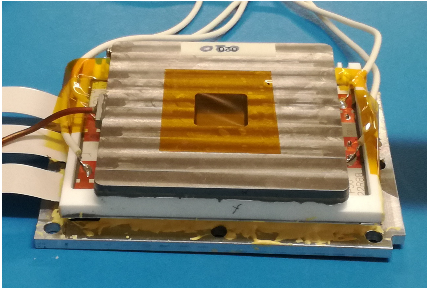


The GPD assembly



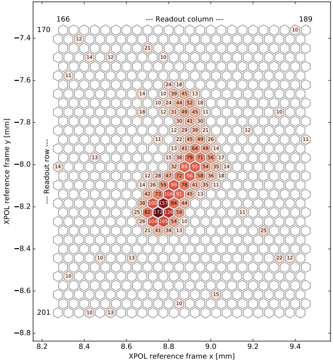






Salient features of the ASIC

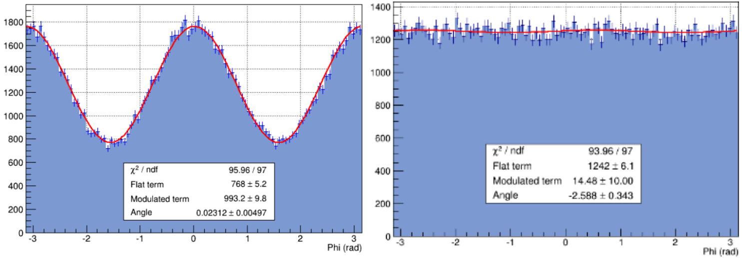
Image: real 5.9 keV photoelectron track



- Self-triggering.
- Internal definition of the region of interest for the event readout.
  - Typical window size < 1 k pixels.
  - Multiple window readout for event-by-event pedestal subtraction.
- Serial readout via an external ADC.

Performance of the GPD as a polarimeter

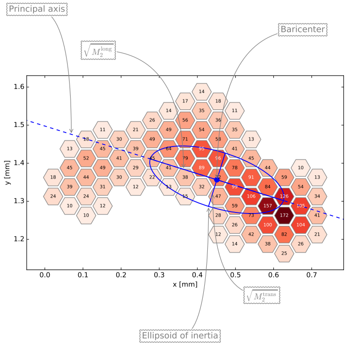
Measuring four things at once

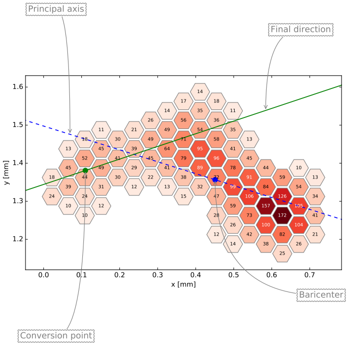


- Modulation factor: 0.2 (0.7) at 2 (8) keV.
  - Stability over $\sim$ 3 years demonstrated with a sealed detector.
  - Residual modulation for unpolarized radiation $\sim$ 0.1%.
- Spatial resolution: $\sim$ 90 μm at 5.9 keV ($\ll$ track length).
  - Good match for a 20 arcsec-type X-ray optics with $\sim$ 4 m focal length.
- Energy resolution: $\sim$ 15% (FWHM) at 5.9 keV.
  - Enough for spectrally-resolved polarimetry (in a few energy bins) when statistics allow it.
- Time resolution: μs-type .
  - More than adequate for the shortest time scales of interest.

Event-level analysis basics

Real 5.9 keV photoelectron track, colors indicate the pulse height

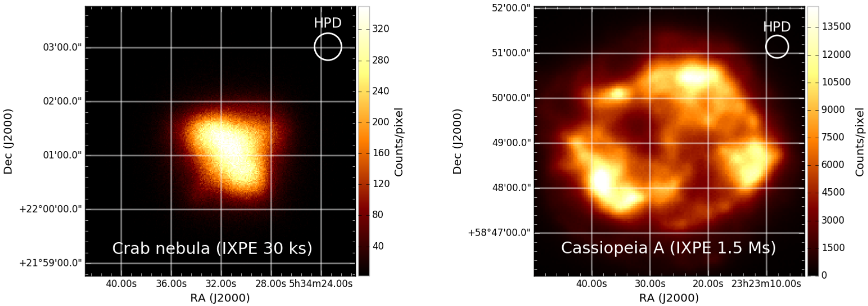




- Analysis is done event-by-event.
- Track reconstruction:
  - First pass: baricenter, basic moments analysis, skewness of the longitudinal projection to identify the Bragg peak.
  - Second pass: determination of the absorption point and weighted moments analysis for a refined estimate of the direction of emission.
- Rich morphological information available.

A new view on the galactic cosmic-ray accelerators

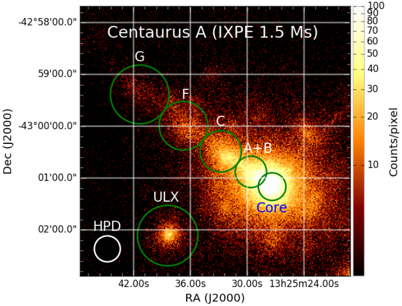
Potential for spatially and phase resolved X-ray polarimetry

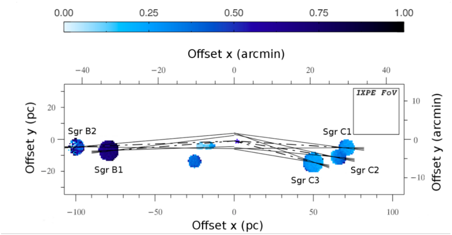


- Pulsar wind nebulæ: ordered magnetic field, high degree of linear polarization expected (and measured).
  - Can we isolate the central pulsar and study the polarization pattern as a function of the pulse phase?
- Shock fronts in supernova remnants: candidate cosmic-ray acceleration sites, turbulent magnetic field.
  - Can we map the polarization degree and angle in these objects on meaningful spatial scales?

AGNs and Galactic Center

Potential for spatially resolved X-ray polarimetry

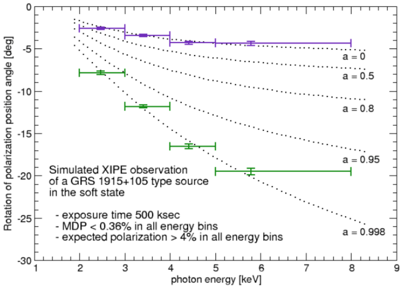




- Blazar and near radio galaxy: study of the jet structure, acceleration and radiation emission mechanisms.
  - True also for X-ray binaries with jet (μQSO).
- Molecular clouds at the Galactic Center: echo of an ancient emission from Sagittarius A*?

Black-hole systems and General Relativity effects

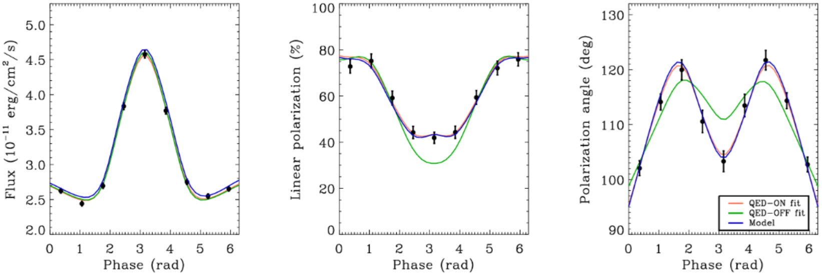
Dovčiak et al., MNRAS **391**, 32-38 (2011)



- In systems with accretion disks the thermal (unpolarized) primary emission can acquire linear polarization via Compton scattering.
- When the central object is a black hole General Relativity comes into play.
  - The proximity of the black hole causes a rotation of the polarization angle of the radiation emitted from the disk.
  - As the temperature of the disk decreases with the radius, the rotation of the position angle increases with energy.
- Effective and independent way to measure the black hole spin a.

Systems with strong magnetic fields and QED effects

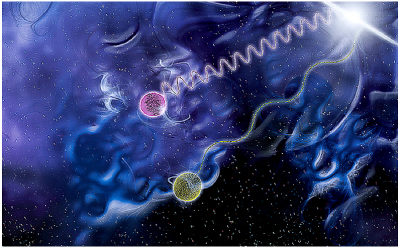
Taverna et al., MNRAS **438**, 1686-1697 (2014)



- Magnetars are magnetized neutron stars with B up to 10^{12}–10^{15} G.
- In the strong-field regime the index of refraction of the vacuum depends on the field intensity.
  - Photon propagation is influenced, and the polarization angle and degree are modified.
- Tiny effect on the intensity, measurable effect on the polarization degree and angle.

Photon propagation over large distances

Study of fundamental physics in space



- Distant astronomical sources are a terrific laboratory to study fundamental physics over length scales not accessible on Earth.
  - Do photons of different energy travel at the same speed *c*?
- X-ray polarimetry allows to test a possible (small) birefringence of the vacuum.
  - Rotation of the polarization angle for nearby sources.
  - Destroy any linear polarization from sources at cosmological distances.
- On the other hand: are there plausible mechanisms that can induce polarization through propagation?
  - What if see evidence of linear polarization where we don't expect it (e.g., galaxy clusters)?