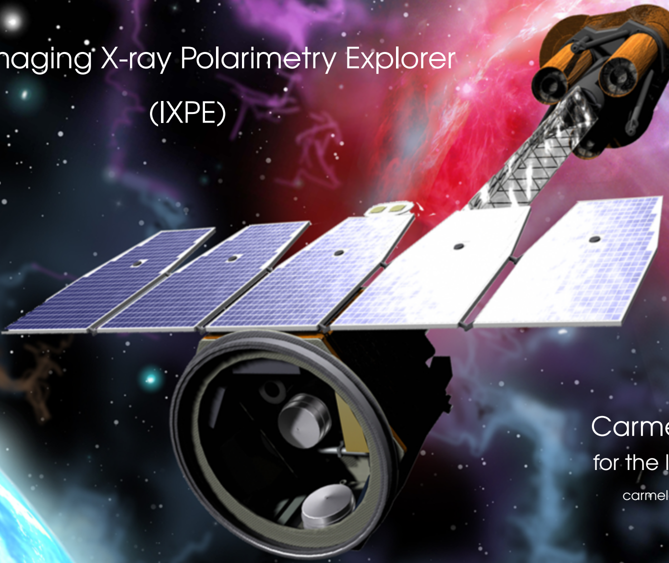
The Imaging X-ray Polarimetry Explorer (IXPE)



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The IXPE mission

- Imaging X-ray Polarimetry Explorer
  - Imaging and polarimetry in the 2–8 keV band
  - The observation technique and the mission were made possible by the introduction of a polarization-sensitive detector developed at INFN-Pisa
    - 2 order of magnitude increase of sensitivity wrt previous measurements
- Recently selected by NASA as the next SMall EXplorer (SMEX) mission
  - Launch in early 2021
- International partnership:

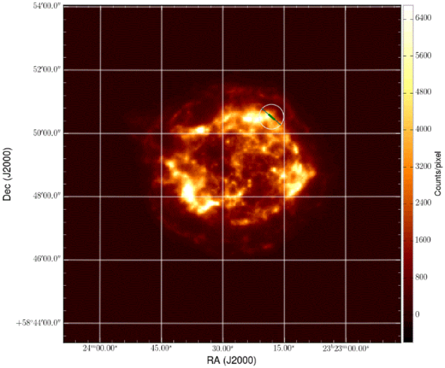
- X-ray Mirror by NASA/MSFC
- X-ray Instruments by INFN, IAPS/INFN and ASI
- Spacecraft, payload structure and integration by Ball Aerospace

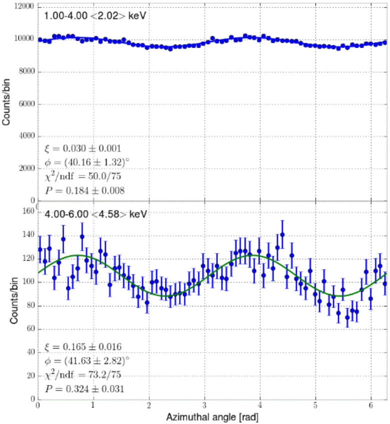
A new exploration window

- Spectroscopy, imaging and timing are routine techniques in X-ray astronomy
- Polarimetry adds two parameters to the phase space:
  - (linear) polarization degree
  - polarization angle (phase)
- Significant X-ray linear polarization expected in most classes of non-thermal X-ray sources:
  - Emission processes
    - Synchrotron radiation and Inverse Compton
    - Acceleration phenomena (supernova remnants, pulsar wind nebulae, jets)
  - Geometry
    - Photon scattering in aspherical geometries (accretion disks, X-ray reflection nebulae)
    - Photon propagation in magnetized plasmas (accreting pulsars, magnetars)
  - Fundamental physics
    - Quantum electrodynamics (photon propagation in strong magnetic fields)
    - General relativity (photon propagation in strong gravitational fields)

Map magnetic field of bright extended source

Example: Cassiopeia A (Cas A) Supernova Remnant (SNR)

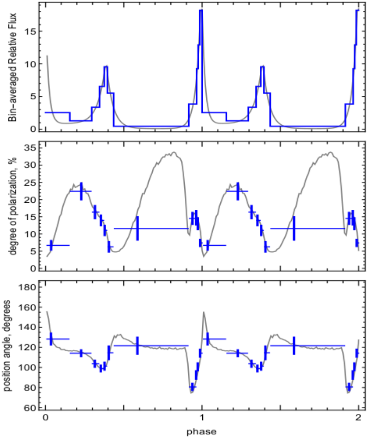




- Probe sites of cosmic-ray acceleration
  - Lines and thermal continuum dominate 1-4 keV
  - Non-thermal emission dominates 4-6 keV
- 1.5 Ms simulated IXPE observation
- See poster by Melissa Pesce-Rollins

Phase-resolved polarimetry

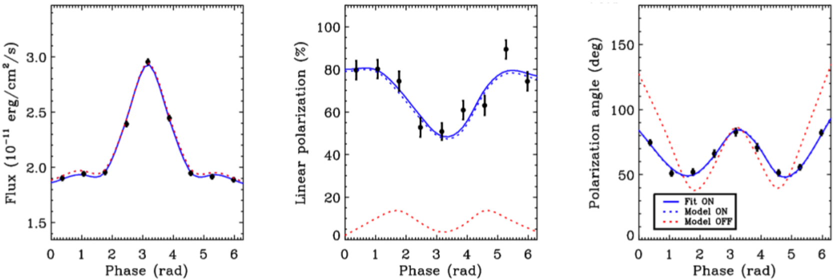
Example: Crab Pulsar



- Isolated pulsar in pulsar wind nebula (PWNe)
- 34-ms period
- 140 ks of simulated observation
  - IXPE expectation (in blue)
  - visible-band profile (in gray)
- The geometry of the system determines the polarization pattern
  - Adding 2 more panels to the phasogram

Test of Quantum Electrodynamic

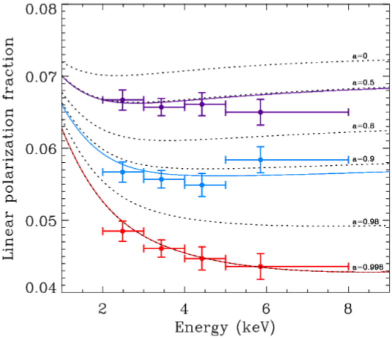
Example: 1RXS J170849.0-400910

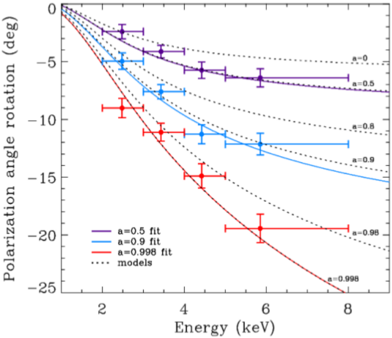


- ▷ Magnetar is a neutron star with magnetic field up to 10^{15} Gauss
- ▷ Non-linear QED predicts birefringence in magnetized vacuum
  - ▷ Impacts polarization and position angle as functions of pulse phase
- ▷ 250 ks simulated IXPE observation to exclude QED-off

Measure Black-hole spin

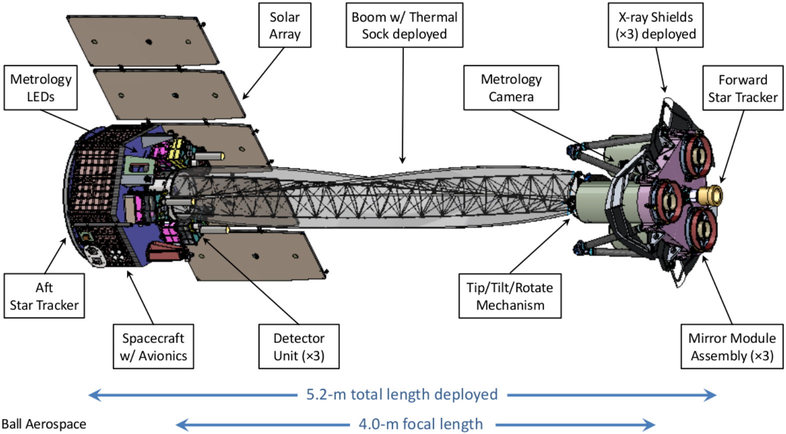
Example: GRX1915+105





- ▷ Microquasar in accretion-dominated state
  - ▷ Scattering polarizes the thermal disk
  - ▷ Polarization rotation is greatest for emission from inner disk
    - ▷ Inner disk is hotter, producing higher energy X-rays
- ▷ 200 ks simulated IXPE observation

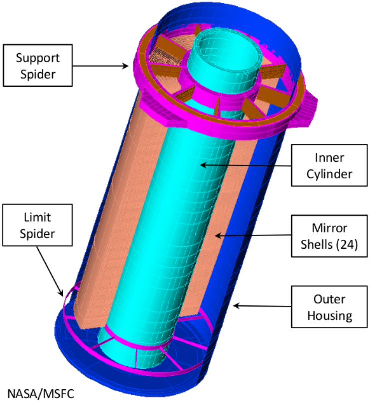
Overview of the observatory



Ball Aerospace

- ▷ Three identical telescopes, each including polarization-sensitive detector and grazing–incidence optics
- ▷ Equatorial circular orbit at $\geq$ 540 km altitude
- ▷ 2-year baseline mission, 1 year extension

Mirror Module Assembly (MMA)



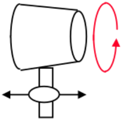
MMA Properties

Number of MMAs	3
Number of shells per MMA	24
Focal length	4000 mm
Shell length	600 mm
Inner–outer shell diameter	162–272 mm
Inner–outer shell thickness	0.18–0.26 mm
Shell material	Nickel–Cobalt alloy
Mass per MMA	30 kg (CBE)
Effective area per MMA	210 cm^2 (2.3 keV) $>$230 cm^2 (3–6 keV)
Angular resolution	$\leq$ 25 arcsec HPD
Field of view (detector-limited)	12.9 arcmin

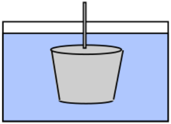
Mirror Production Process

Mandrel fabrication

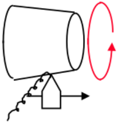
1. Machine mandrel from aluminum bar



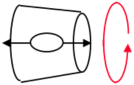
2. Coat mandrel with electroless nickel (Ni–P)



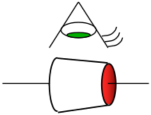
3. Diamond turn mandrel to sub-micron figure accuracy



4. Polish mandrel to 0.3-0.4 nm RMS

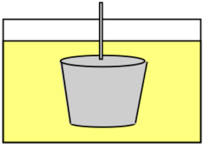


5. Conduct metrology on the mandrel

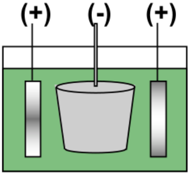


Mirror-shell forming

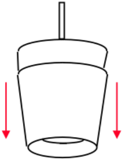
6. Passivate mandrel surface to reduce shell adhesion



7. Electroform Ni–Co shell onto mandrel

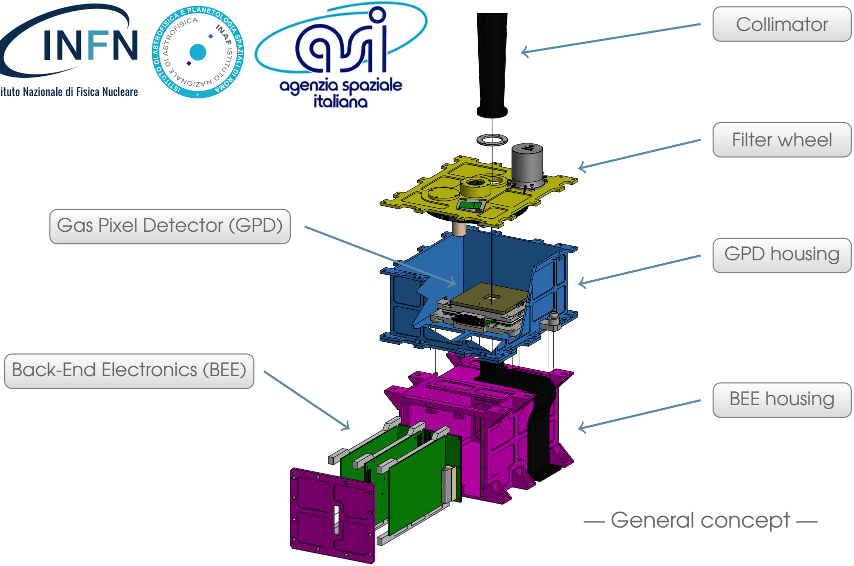


8. Separate shell from mandrel in chilled water



Ni–Co electroformed mirror shells

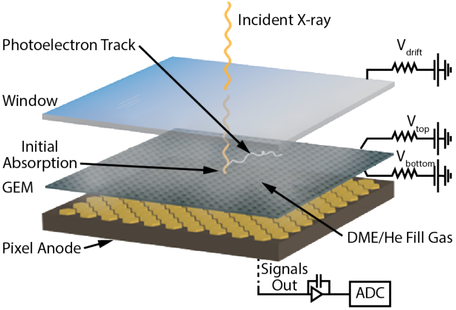
The Detector Unit (DU)



— General concept —

The Gas Pixel Detector (GPD)

Invented by Ronaldo Bellazzini at INFN-Pisa



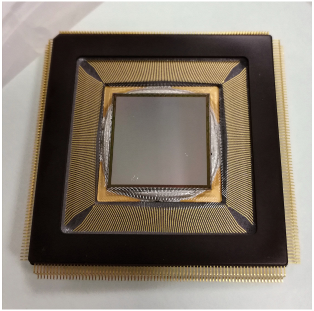
- Distribution of the direction of emission of a K-shell photoelectron 100% modulated for linearly polarized radiation:

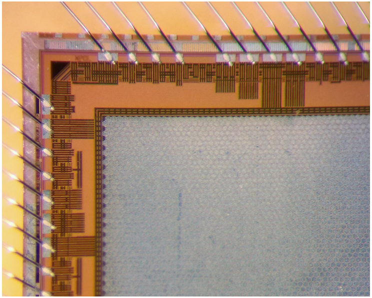
$$\frac{d\sigma_C^k}{d\Omega} \propto Z^5 E^{-\frac{7}{2}} \frac{\sin^2\theta\cos^2\phi}{(1+\beta\cos\theta)^4}$$

- Need to reconstruct the direction of emission of the photoelectron, i.e., a granularity significantly smaller than the typical range

- Detector concept
  - X-ray absorption in a gas gap
  - Signal amplification via a Gas Electron Multiplier (GEM)
  - Finely pixelized ASIC as readout anode
- Sensitive down to very low energy ($\sim 2-8$ keV)
- Fully two-dimensional (imaging)

The core of the detector: the ASIC

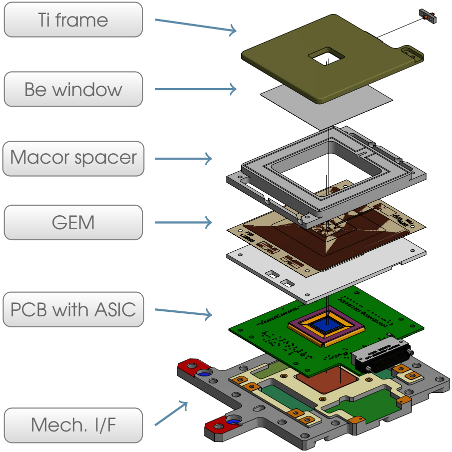




Properties

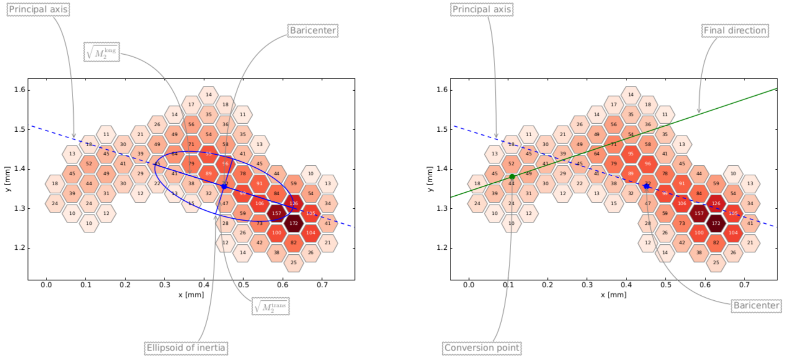
Pixels organization	300×352 pixels in hexagonal pattern
Pixel pitch	50 μm
Active area	15×15 mm^2
Shaping time	3-10 μs
Pixel Noise	$\sim$ 50 electrons ENC
Trigger	internal, with definition of a region of interest
Output	analog (external ADC required)
Technology	CMOS 0.18 μm

The GPD assembly



- Sealed detector
  - No gas system needed
- Gas cell thickness 1 cm
  - Gas based on DME (small lateral diffusion)
  - Optimized in the 2-8 keV range
- A Ti frame acts as “drift” electrode
- X-ray window in Be, 50 μm thick
- GEM holes 50 μm pitch, 50 μm thick
- ASIC in a standard package mounted on a custom PCB
- A Ti frame for mechanical and thermal interface

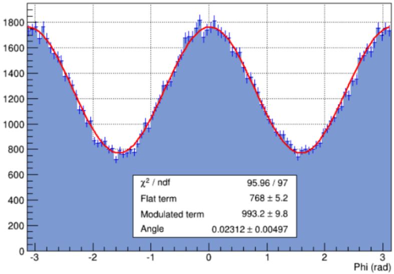
Event reconstruction



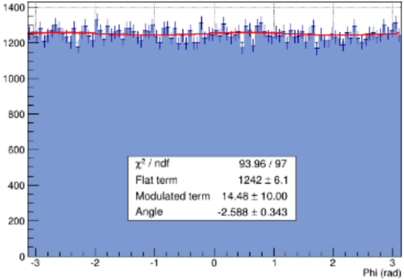
- Event by event reconstruction
- Rich morphological information available
- Iterative moment analysis to reconstruct relevant information
  - Interaction point: imaging
  - Photoelectron direction: polarimetry
  - Trigger output: timing
  - Pixel charge content: spectroscopy

Performance of the GPD as a focal-plane polarimeter

polarized source



unpolarized source



- 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 $<$0.5%
- $\sim$90 μm spatial resolution at 5.9 keV, measured ($\ll$track length)
  - Good match for a $\sim$25 arcsec-type X-ray optics with $\sim$4 m focal length
- $<$20% energy resolution (FWHM) at 5.9 keV
  - Enough for spectrally-resolved polarimetry (in a few energy bins) when statistics allow it
- μs-type time resolution
  - More than adequate for the shortest time scales of interest

Conclusions

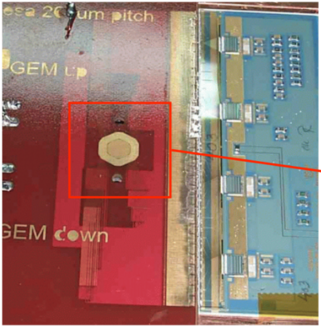
- A new NASA mission dedicated to X-ray polarimetry
  - After 40 years from the last polarimeter in orbit
- The IXPE satellite will explore the polarization of celestial sources in the 2-8 keV energy band
- The Gas Pixel Detector will be at the focal plane of a X-ray optics
  - Will allow spatially-resolved polarimetry
- Design of the flight detector is basically concluded
  - Prototypes under construction and test
  - Flight production will begin soon
- Software activity on-going:
  - Event reconstruction
  - Detector simulation
  - Science analysis tools
- On our way for launch in 2021

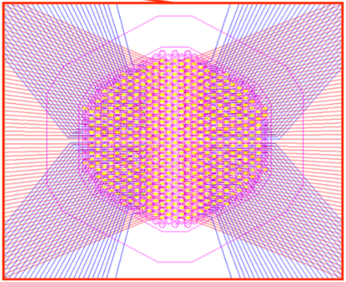
SPARE SLIDES

The proof of concept for the readout plane

circa 2000

- ▷ Main technical challenge: fan-out from the readout anode to the front-end electronics.
- ▷ Yet it worked as a proof of principle.

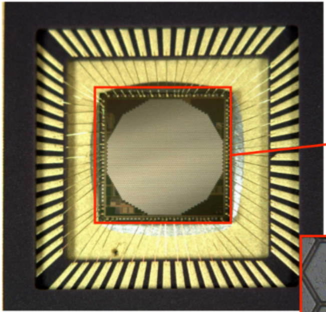


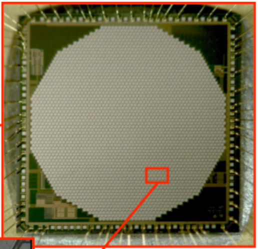


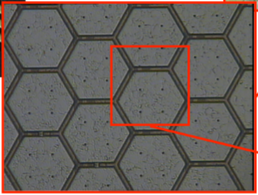
- ▷ Maximum number of channels: ~ 1000 at $\sim 200\ \mu$m pitch.
- ▷ High input capacitance to the preamplifier (high noise).
- ▷ Cross-talk between adjacent lines.

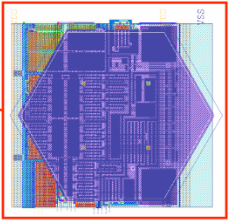
The turning point: a dedicated readout ASIC

Bellazzini et al., NIM A 535, 477–484 (2004)



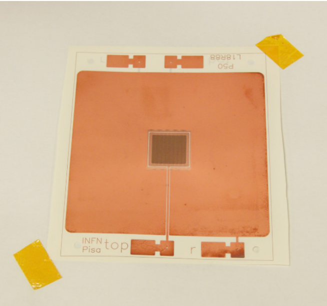


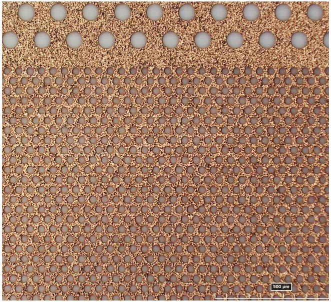




- 2101 hexagonal pixels.
- 80 μm pitch.
- Metal top layer acting as a charge collecting anode.
- Integrating preamplifier, shaper, S/H, multiplexer.
- Serial readout via external ADC.

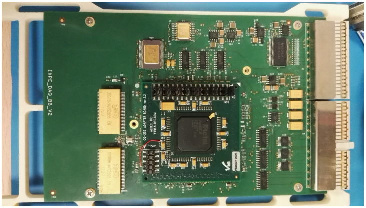
The Gas Electron Multiplier (GEM)

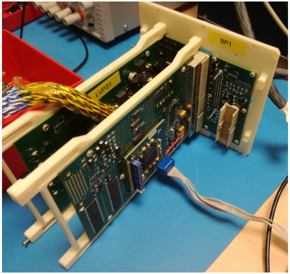




- Produced by RIKEN and SciEnergy in Japan
- Hexagonal hole pattern, with 50 μm pitch, 50 μm thick

The Back-End Electronics (BEE)





- Four PCBs:
  - Data Acquisition board (DAQ)
  - Low Voltage Power Supply, Board (LVPS)
  - High Voltage Supply Board (HVPS)
  - Back Plane (BP)
- FPGA based DAQ, with a 14-bit ADC for GPD data
- Two custom digital interfaces for communication:
  - Command and Control Interface (CCI)
  - Science Data Interface (SDI)
- Event timing via 1-PPS (from spacecraft GPS) and a 1 MHz clock
- Dedicated mechanical frames provide stiffness and thermal control