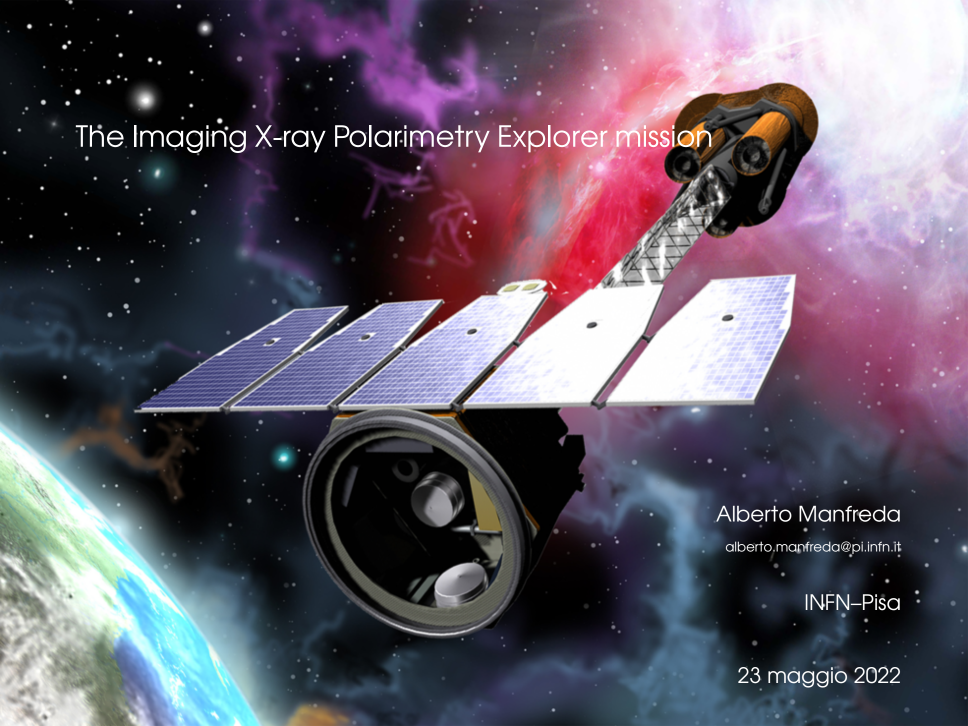

The Imaging X-ray Polarimetry Explorer mission

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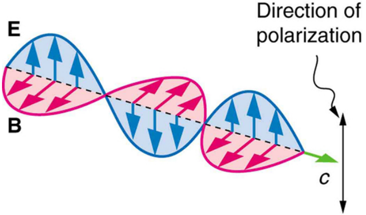
INFN–Pisa

23 maggio 2022

The four ways of astronomy

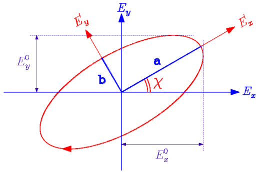
Light carries four different observables, corresponding to the four classical branches of astronomy:



- ▷ Direction → *Imaging*
- ▷ Energy → *Spectroscopy*
- ▷ Time → *Timing*
- ▷ **Polarization** → ***Polarimetry***

- ▷ Polarimetry complements other observations and provides essential information to understand the nature of celestial objects

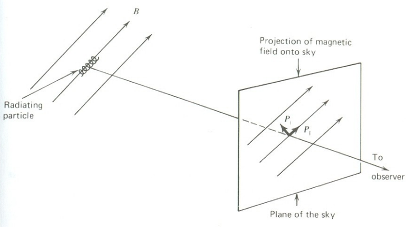
Polarization

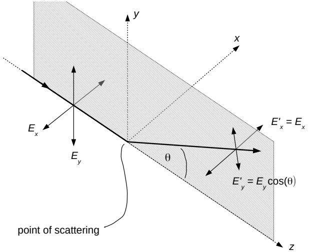


- General case for a single e.m. wave: elliptical polarization
- Special cases:
  - Circular Polarization
  - **Linear polarization**: this is what we will be dealing with in this talk
- What about an ensemble of photons?
  - If their polarization are completely random the net result of averaging over a sufficient time is zero
  - If their polarization are all the same we measure the same polarization as in the ideal case
  - In general we will have a partial polarization → polarization degree (a number between 0 and 1)
- **Polarization degree** → level of asymmetry of a system
- **Polarization angle** → preferred direction of the system

Polarigensis

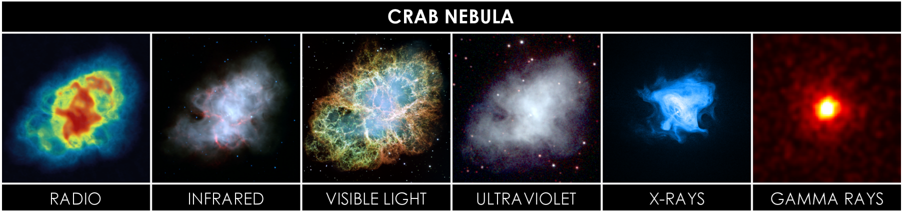
- ▷ Non-thermal emission processes (e.g. Synchrotron radiation, Inverse Compton)
- ▷ Scattering in aspherical geometries (matter or magnetic fields)
- ▷ Propagation in extreme environments (e.g. QED effects, GR effects – more on this later)





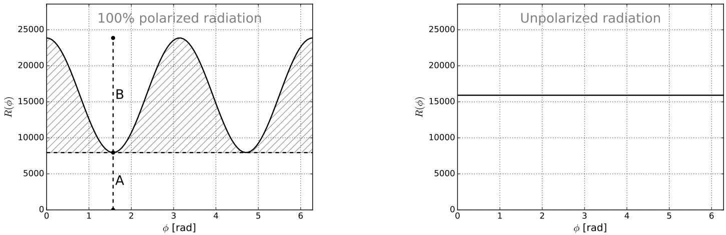
- ▷ Polarimetry allow studying the geometry of the sources and of the fields involved in emission processes, **even when internal structures are unresolved**

X-ray polarimetry



- Putting together information from different wavelengths is a cornerstone of modern astrophysics
- Unfortunately X-ray (and γ-ray) polarimetry are still relatively undeveloped compared to lower frequencies:
  - Experimentally challenging, as high energy particles are harder to detect
  - Earth atmosphere is not transparent to X-rays: need to go to space
  - Statistically limited – **typical number of photons for polarimetry is** $> 10^5$
- The polarization of a single, very bright, source – the Crab Nebula – was the only significantly before IXPE
- And this was originally done in 1975! (Weisskopf et al., ApJ **220**, 1978 (L117))

Basic polarimetry formalism



- A polarimeter essentially measures the azimuthal modulation around the polarization direction ϕ_0 of the incident photon beam:

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

- Modulation factor: Response to 100% polarized radiation

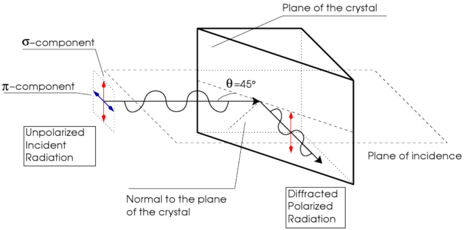
$$\mu = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} = \frac{B}{B + 2A}$$

- Minimum Detectable Polarization (MDP):

$$MDP_{99\%} = \frac{4.29}{\mu R_S}\sqrt{\frac{R_S + R_B}{T}}$$

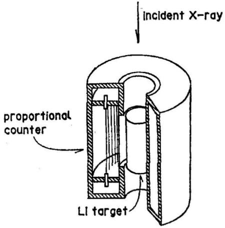
Conventional X-ray polarimetry techniques

—Bragg diffraction at 45°



- ✓ Excellent modulation factor
- ✘ Low efficiency (narrow band-pass)
- ✘ Dispersive (one angle at a time)
- ✘ Requires detector rotation

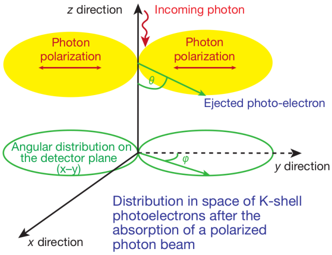
—Thomson/Compton scattering



- ✓ Suitable for hard X-rays
- ✓ Decent efficiency
- ✘ Compton scattering not 100% modulated
- ✘ Background rejection challenging
- ✘ Rotation to reduce systematics

Photoelectric-based X-ray polarimetry

Concept



- Dominant interaction in the soft X-ray band (< 10 keV).
- Photo-electron emission in K-shell 100% modulated for incoming linearly polarized radiation:

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

- Requires reconstructing the electron emission direction
- Typical 5 keV e^- track is $\sim \mu m$ in a solid: **need a gas detector!**

The turning point

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

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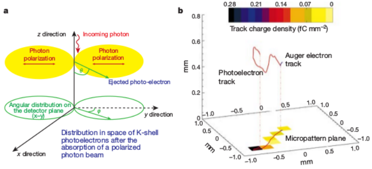
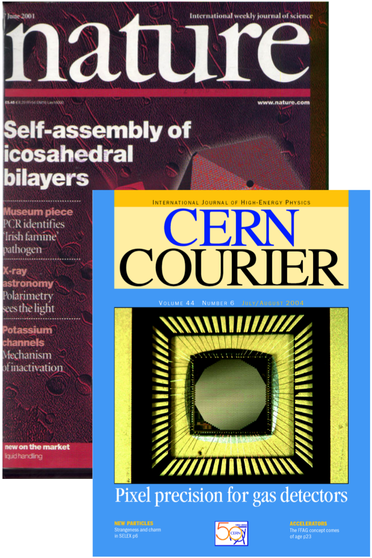
The study of astronomical objects using electromagnetic radiation involves four basic observational approaches: imaging, spectroscopy, photometry (accurate counting of the photons received) and polarimetry (measurement of the polarizations of the observed photons). In contrast to observations at other wavelengths, a lack of sensitivity has prevented X-ray astronomy from making use of polarimetry. Yet such a technique could provide a direct picture of the state of matter in extreme magnetic and gravitational fields[1–6], and has the potential to resolve the internal structures of compact sources that would otherwise remain inaccessible, even to X-ray interferometry[7]. In binary pulsars, for example, we could directly 'see' the rotation of the magnetic field and determine if the emission is in the form of a 'fan' or a 'pencil' beam[1,8]. Also, observation of the characteristic twisting of the polarization angle in other compact sources would reveal the presence of a black hole[9–12]. Here we report the development of an 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. However, Bragg polarimetry[21] is dispersive (one angle at one time) and very narrow-band. Thomson polarimetry[22] is non-imaging and band-limited (>5 keV). This limits the sensitivity of SXRP to a few bright, galactic sources only.

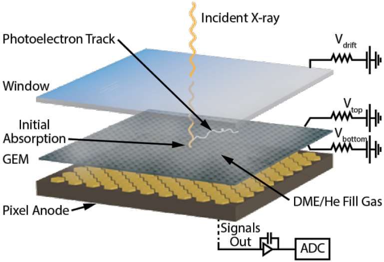
The photoelectric effect is very sensitive to polarization. The electron is ejected from an inner shell with a kinetic energy which is the difference between the photon energy and the binding energy. The direction of emission is not uniform but is peaked around that of the electric field of the photons (see Fig. 1a). This photoelectron





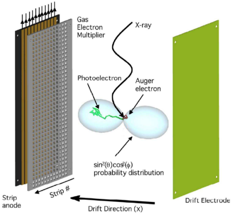
Photoelectric-based X-ray polarimetry

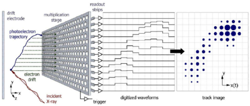
—Gas Pixel Detector



- ✓ Imaging
- ✓ Spectroscopy
- ✓ Low systematics (no detector rotation required)
- ✘ Trade-off efficiency/modulation factor

—Time Projection Chamber





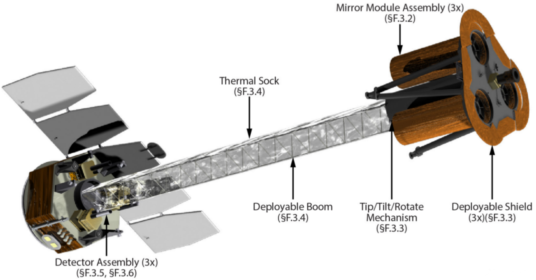
- ✓ Efficiency decoupled from modulation factor
- ✓ Spectroscopy
- ✘ No imaging
- ✘ Requires rotation to keep systematics under control

Polar Light

The X-ray polarimetry window reopens

- Demonstrative mission PolarLight: a Gas Pixel Detector on a CubeSat (no x-ray optics), launched in October 2018
- Successfully proved the detector concept works in space environment
- A new measurement of the Crab polarization (consistent with OSO-8)
- Detected a polarization drop after a glitch of the Crab in July 2019

The Imaging X-Ray Polarimetry Explorer mission



- ▷ Selected in 2017 by NASA as its next SMEX (SMall EXplorer) mission, launched on 9 December 2021
- ▷ For the first time simultaneously perform imaging, spectrometry, polarimetry and timing of tens of x-ray sources
- ▷ 3 identical telescopes, each comprised of:
  - ▷ A Mirror Module Assembly (MMA) for light collection
  - ▷ A Detector Unit (DU) equipped with a GPD
- ▷ DUs are rotated by 120° respect to each other (reduce systematic effects)

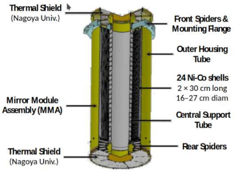
The IXPE mission

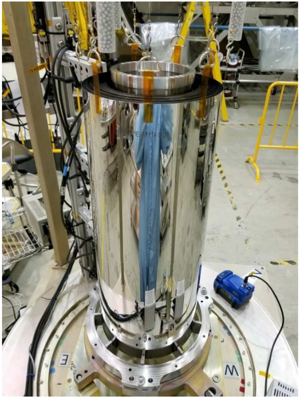
Overview

- 2 years of on-orbit operations + possible extension
- Point-and-stare observation mode towards predefined targets
  - Long duration - from days to week(s)
  - Data are made public after validation
  - No-repointing, but Targets of Opportunity possible in a few days
- Equatorial orbit, 600 Km nominal altitude
  - Minimize charged particle background
  - $\sim$ 13% off-time due to South Atlantic Anomaly

The X-ray optics

- ▷ Wolter I type grazing incidence mirrors
- ▷ Manufactured at NASA/MSFC with replica from mandrels technique
- ▷ Nickel-cobalt alloy shells, 24 shells/module
- ▷ 4000 mm focal length
- ▷ Shell thickness: 178-254 μm
- ▷ Mass: 93 kg for three mirrors
- ▷ Measured total collecting area: 540 cm^2 at 3 keV
- ▷ Measured angular resolution < 30 arcsec

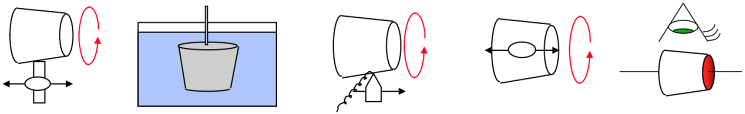




Mirror modules assembly

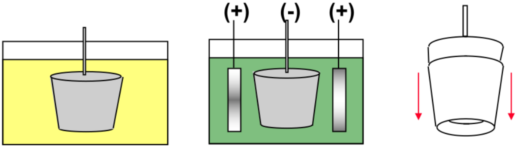
Mandrel fabrication

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

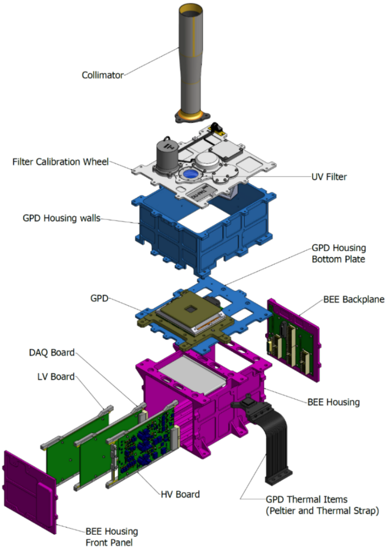
6. Passivate mandrel surface to reduce shell adhesion
7. Electroform Ni–Co shell onto mandrel
8. Separate shell from mandrel in chilled water

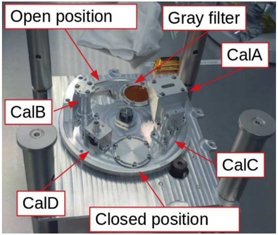


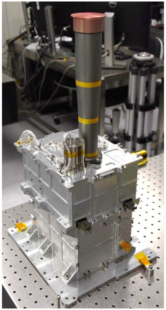
Ni–Co electroformed mirror shells

The Detector Unit (DU)

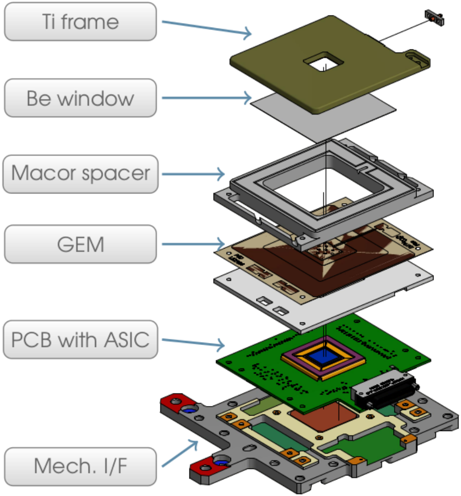
Exploded view



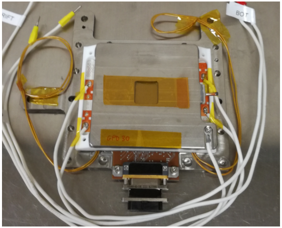




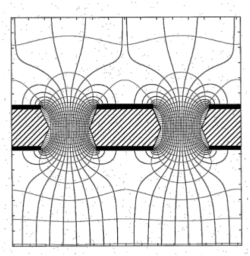
GPD exploded view

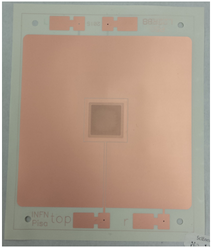


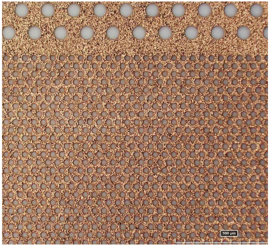
- ▷ Sealed detector, no gas system needed
  - ▷ Requirement on leak rate: $< 1 \cdot 10^{-9}$ mbar l/s
  - ▷ Major design challenge!
- ▷ X-ray window in Be
  - ▷ 50 μm thick
  - ▷ 15×15 mm^2 aperture, match the anode size
- ▷ Gas cell thickness 1 cm
- ▷ Gas mixture DME @ 0.8 bar
  - ▷ Optimized for 2-8 keV energy range



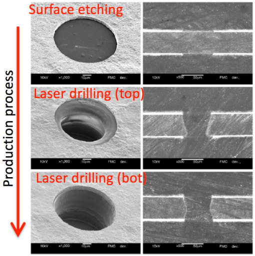
The GEM





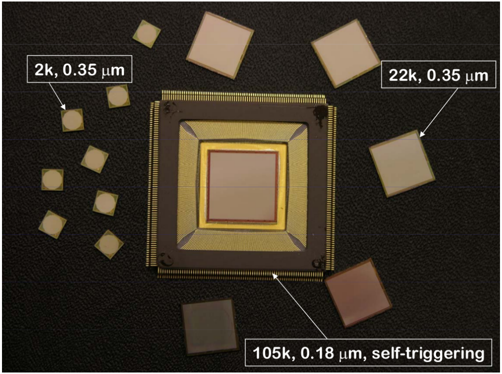


- Produced by RIKEN and SciEnergy in Japan
- 50 µm thick Liquid Crystal Polymer (LCP) insulator, 5 µm copper layer
- Hexagonal hole pattern, with 50 µm pitch, diameter of 30 µm
  - photo-lithographic copper etching
  - CO_2 laser drill in the insulator
  - wet etching to cleanup

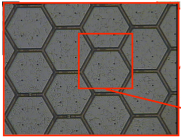


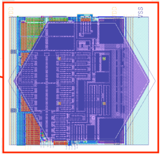
The readout ASIC

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



Technology	CMOS 0.18 μm
Active area	$\sim$ 15 $\times$ 15 mm
Fill factor	92 %
Number of pixels	300 $\times$ 352
Pixel pitch	50 μm
Pixel density	$\sim$ 470/mm 2
Pixel noise	$\sim$ 20 ENC
Shaping time amplifiers	3 - 10 μs
Readout clock	typically 5 MHz
Dead time	$\sim$ 1 ms

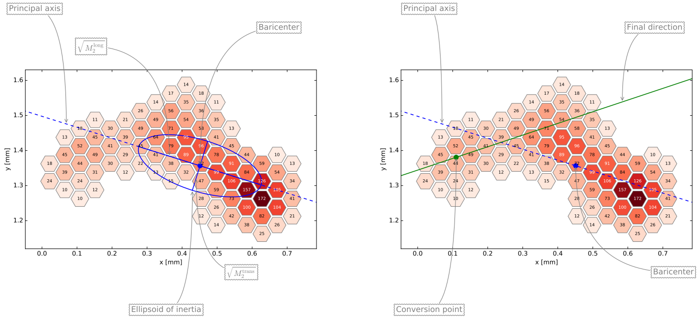




- Self-triggering, with ROI definition
  - Key concept: only a small subsample (500-700) of the pixels is read upon triggering
- Metal top layer acting as a charge collecting anode
- Serial readout via external 14 bits ADC

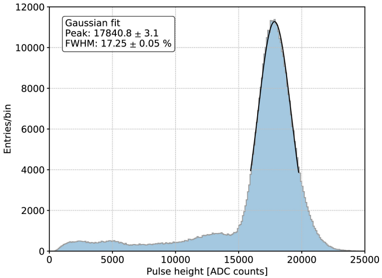
Event reconstruction

A typical 5.9 keV track (Fe55)

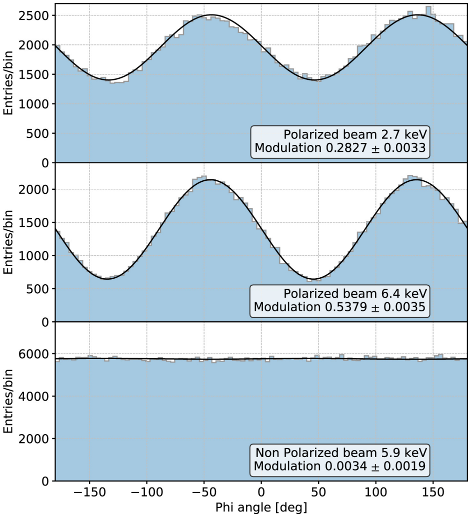


- Clustering stage to identify main track
- Moments analysis to get the ellipsoid of inertia of the charge distribution
- Exploit the Bragg peak to identify conversion point
- A second, weighted moments analysis, to improve direction estimate (especially helpful for high-energy events)

GPD Performance

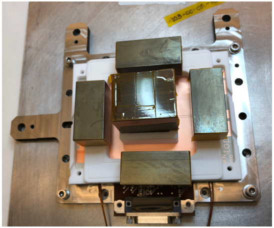


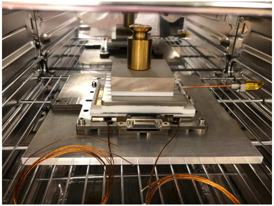
- ▷ 17% FWHM @5.9 keV
- ▷ μ = 54 % @6.4 keV
  28% @2.7 keV
- ▷ 90 µm spatial resolution
- ▷ ∼10 µs time resolution
- ▷ **Allow to perform polarimetry resolved in space, energy and time!**

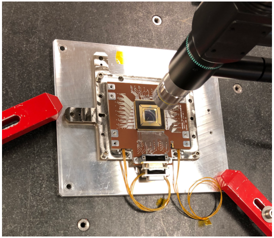


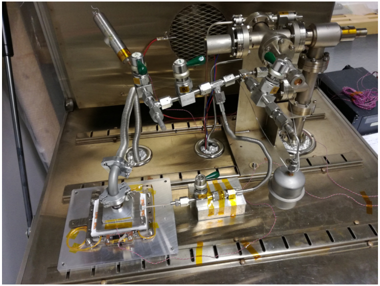
GPD assembly and filling

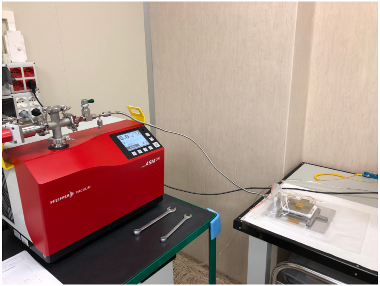
At INFN, Pisa and Oxford Instruments, Finland



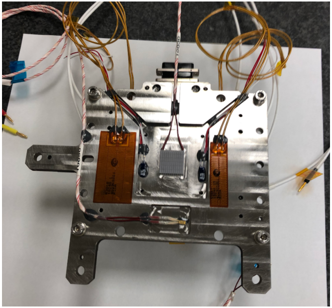


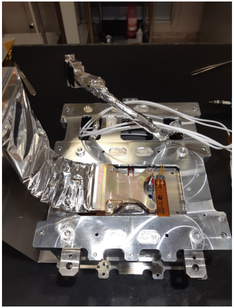


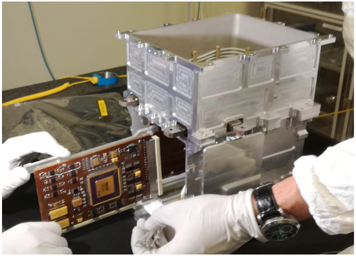


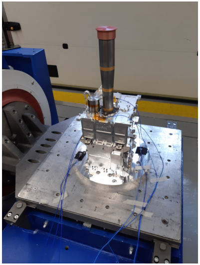


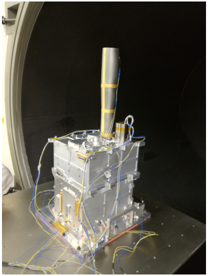
DU integration and testing





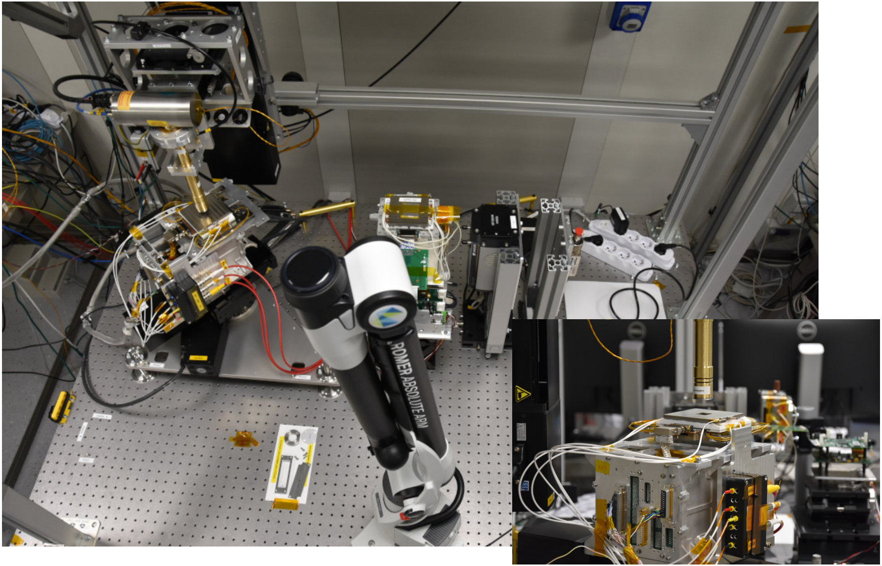




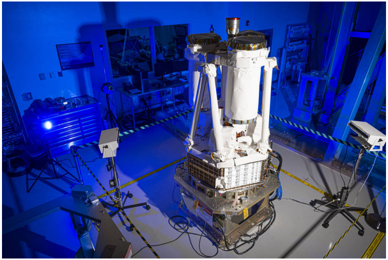


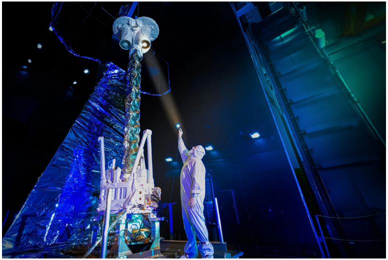
Testing the GPD with x-ray beams

Calibration facility at INAF in Rome



Waiting for launch

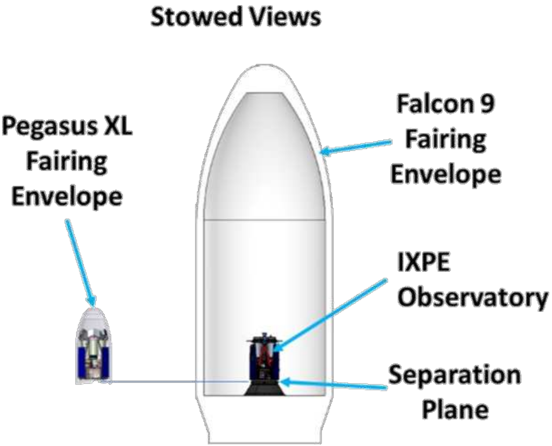




The IXPE spacecraft after integration at Ball Aerospace.

The deployable boom allows reaching the nominal focal length starting from the stowed configuration

Fun fact

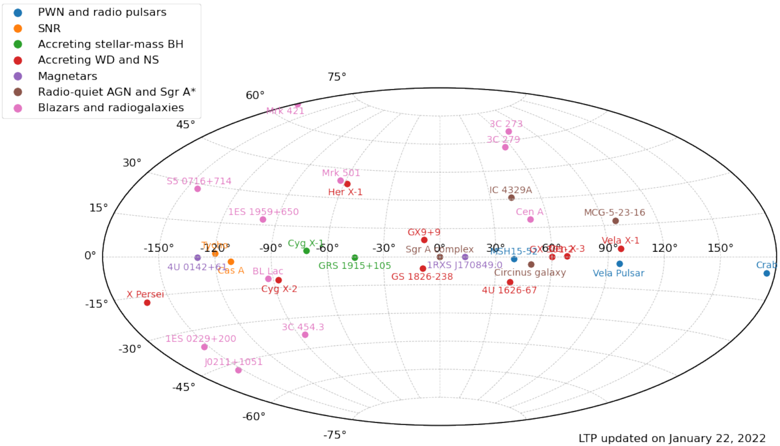


- IXPE payload designed for fitting Pegasus fairing
- Eventually launched by Space-X Falcon IX instead
- A factor 10 our initial mass budget . . .

Launch night!

9th December, 2021 from Cape Canaveral Space Force Station

IXPE Science

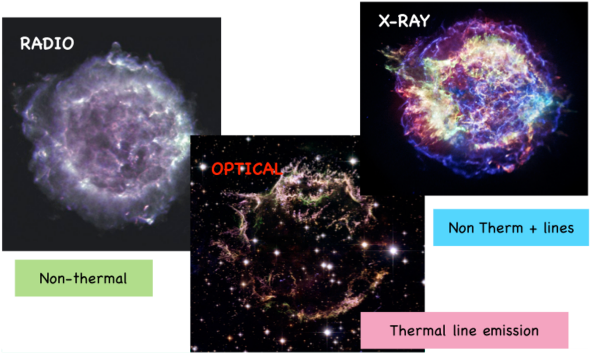


Courtesy of Luca Baldini

Supernova remnants

Galactic accelerators

- Supernova Remnants are shock waves produces by SN events
- Candidate for galactic cosmic rays acceleration up to the knee (10^{15} eV)

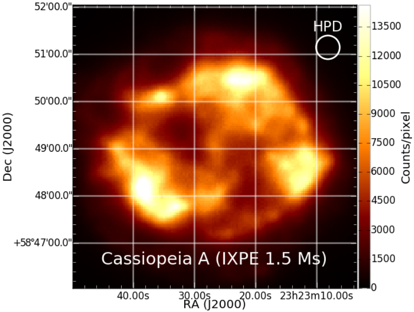


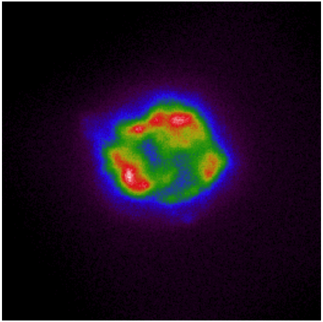
- Expect turbulent magnetic fields
  - What is the orientation of the magnetic field at the site of acceleration?
  - How ordered is it (i.e. level of turbulence)?

Supernova remnants

Space resolved polarimetry

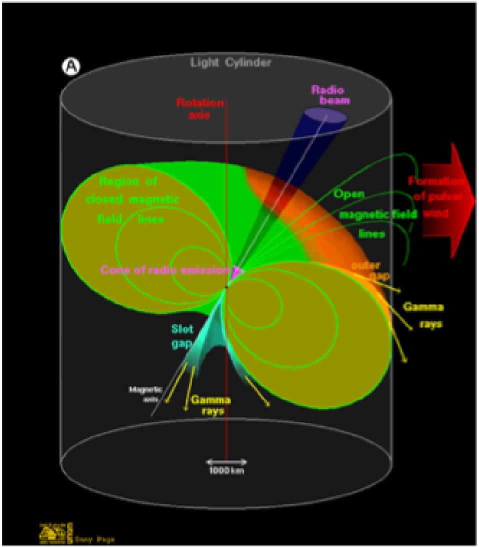
- Cas-A is the rest of a SN exploded ∼400 y ago (last visible by eye from Earth?)
- First IXPE observed target!





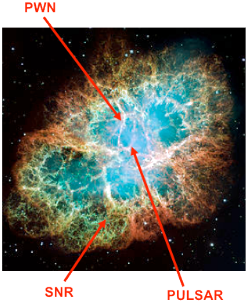
- Long exposition time (1 Ms, roughly 11.5 d) to allow spatially resolved polarimetry
- No net overall polarization (as expected), in depth analysis of sub-regions ongoing

Pulsars



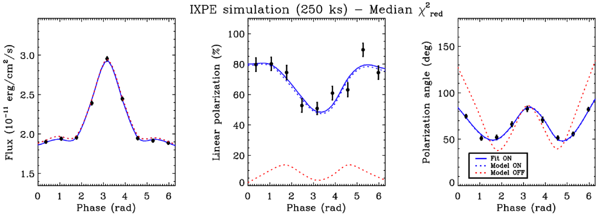
- ▷ Pulsars are rapidly rotating Neutron Stars
  - ▷ M $\sim M_\odot$, R $\sim$ 10 km
  - ▷ P $\sim$ 0.001 - 1 s
  - ▷ Extremely strong magnetic fields, magnetized atmosphere
- ▷ Beamed emission due to misalignment of magnetic axis w.r.t. rotation axis
- ▷ Usually detected in radio but emission may go up to gamma energies (and radio-quiet pulsars do exist)
- ▷ Different classes
  - ▷ **Rotation powered**
  - ▷ **Accretion powered** (in binary systems)
- ▷ IXPE will study pulsars in different contexts: isolated, in binary systems, in Pulsar Wind Nebulæ
- ▷ Phase resolved polarimetry is key!

Pulsar wind nebulæ



- ▷ Generated by the interaction of the pulsar wind with the SNR
- ▷ Ordered magnetic field, high polarization degree expected
- ▷ X-ray polarimetry has the advantage to probe accelerated particles very close or even directly at the injection sites. X-rays are produced close to where the synchrotron electrons are accelerated
- ▷ **Polarization detection confirmed for Vela PWN and Crab**
  - ▷ IXPE imaging capabilities will separate the Crab jet and axis components
  - ▷ Using phase we will also separate pulsar from the brighter nebula emission

1 RXS J170849.0-400910



- Magnetar are ultra-magnetized neutron stars with B $\sim 10^{13}$–10^{15} G.
- In this regime the refraction index of the vacuum depends on the magnetic field intensity:
  - Vacuum birefringency, predicted by Heisenberg e Euler in 1936;

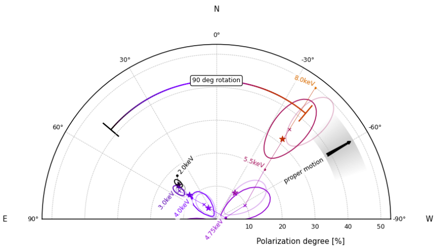
$$n_{\parallel} - n_{\perp} = \frac{\alpha_{QED}}{30\pi}\left(\frac{B}{B_{QED}}\right)^2 \sin\theta^2$$

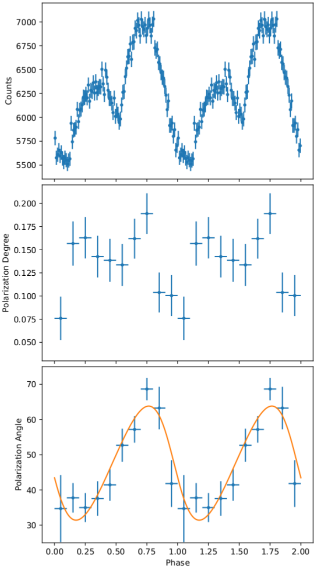
$$B_{QED} = \frac{m_e^2 c^3}{he} = 4.4 \times 10^{13} G$$

- QED may force the PA to adiabatically align to magnetic field direction
- A very large polarization degree would be a smoking gun for vacuum birefringency!

IXPE first detection of magnetar polarization

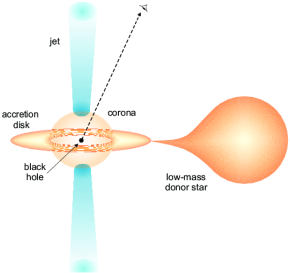
4U 0142+61





- First detection of X-ray polarization from a magnetar `http://arxiv.org/abs/2205.08898`
- Average polarization $(12 \pm 1)\%$ integrated in energy
- Detected a polarization angle swing of 90 degrees between low and high energy
  - **Ordinary** and **Extraordinary** mode components dominating at different energies
- Polarization angle follow phase, polarization degree does not:
  - Inidrect confirmation of QED effects?

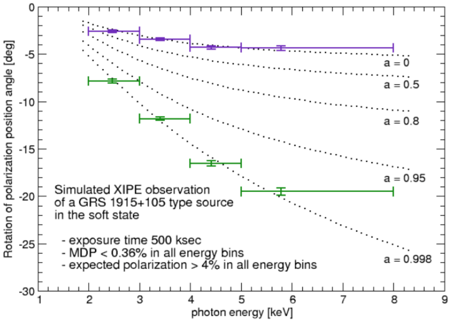
Black-holes systems



- Several variations of 'matter falling onto a Black Hole':
  - Binary systems with low mass BH and low mass companion: LMXRB
  - Binary systems with low mass BH and high mass companion: HMXRB
  - Active galactic nuclei (supermassive BH)
- Highly variable sources, with different states (soft, hard, etc)
- X-ray Polarimetry can:
  - Constrain the geometry of the corona
  - Assess the role of the jet in the X-ray emission
  - Measure the spin of the black hole! (see next slide)

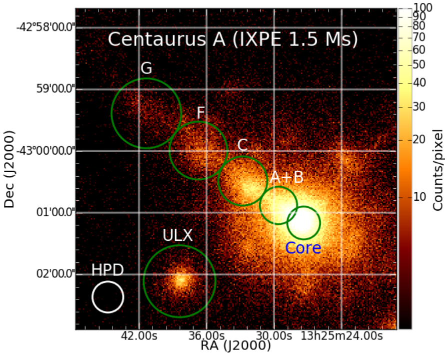
General relativity effects

Energy resolved polarimetry



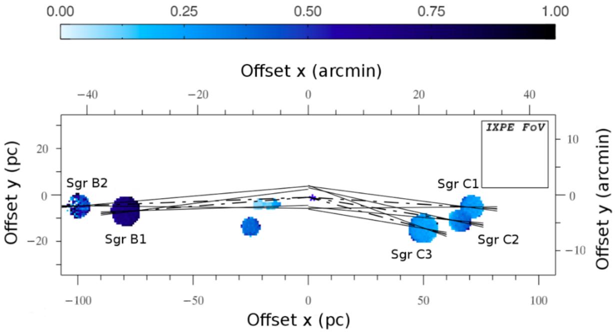
- Thermal emission from the accretion disk can become polarized (up to $\sim$ 12%) by Compton scattering on the Corona
- Including general relativity effects:
  - Black-hole proximity causes a rotation of the polarization angle;
  - Since the disk temperature decreases with the radius, the phase rotation increases with energy.
- An independent technique for measuring the black hole spin a

Active Galactic Nuceli (AGN)



- ▷ AGN unfied model: the same phenomenon seen by different angles
- ▷ Different names based on observed features: Blazar, radiogalaxies, . . .
- ▷ Multiwavelength polarization is a crucial probe of the magnetic field structure and emission processes in such jets
  - ▷ X-ray polarization maps the geometry of the inner regions

Galactic Center



- A number of giant molecular clouds at ∼100 pc projected distance from the Black Hole (SgrA*) with a pure reflection spectrum
- No bright enough sources are in the surroundings. Are they reflecting X-rays from past activity of Sgr A*?
- Polarimetry can tell!
  - PA orthogonal to the direction of the primary source
  - PD measures the scattering angle and determines the true distance of the clouds from Sgr A*

Mission status and conclusions

- 5 months after launch the instrument is fully working, no relevant issues
- Observations currently completed for 19 sources
- Confirmed detections (>6σ) of polarization for 8 of them so far

Name	Class
4U0142+61	Magnetar
Her X-1	Accreating NS, XRB
Crab	Pulsar Wind Nebula
Mrk 501	Blazar
Vela PWN	Pulsar Wind Nebula
Cyg X–2	Low Mass X-ray Binary
Mrk 421	Blazar
Cyg X-1	High Mass X-ray Binary

- Analysis ongoing for other targets
- IXPE has already started to probe source models for different classes of objects
- Ample room for unexpected discoveries!

Thank you for the attention!