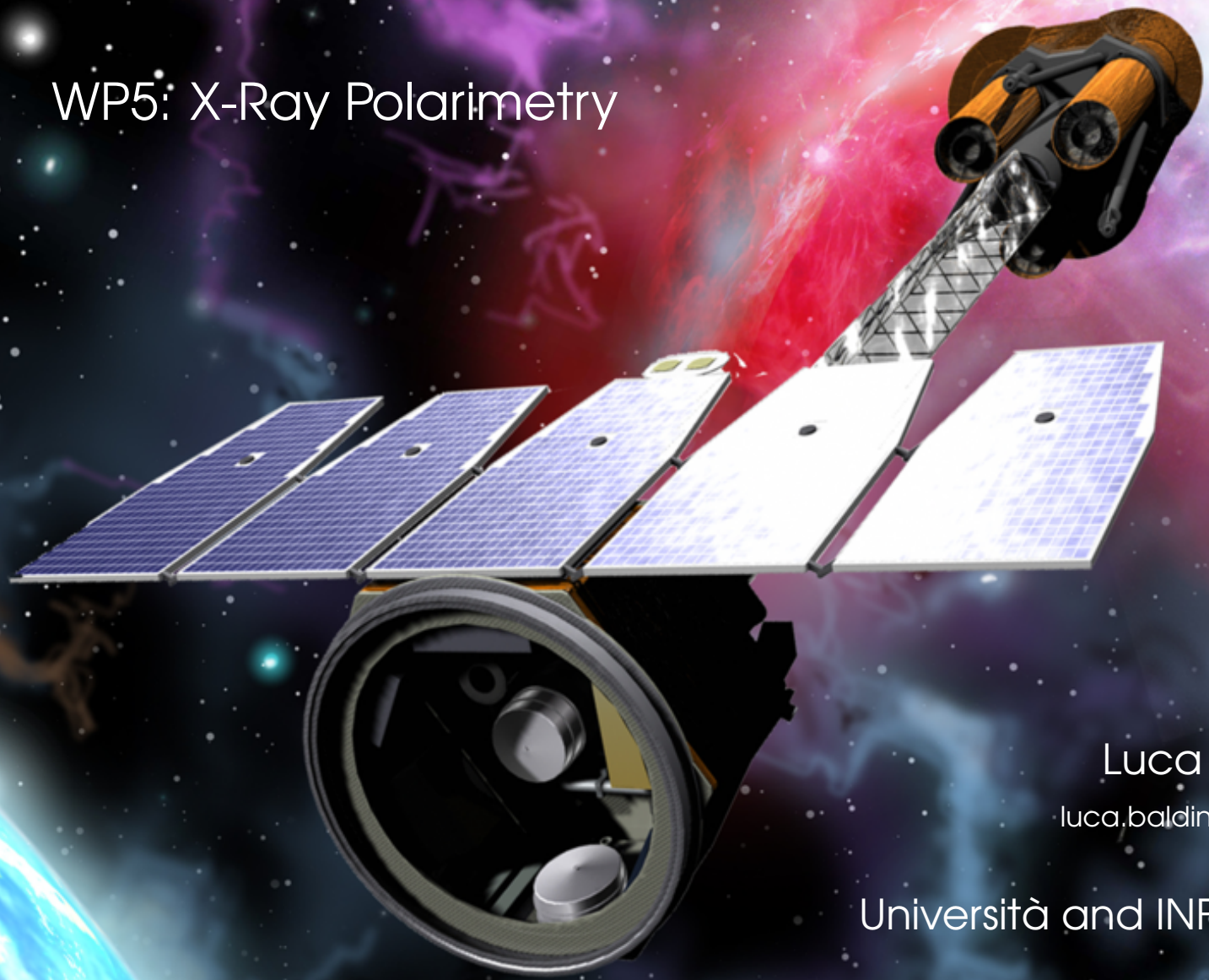
# WP5: X-Ray Polarimetry



Luca Baldini

luca.baldini@pi.infn.it

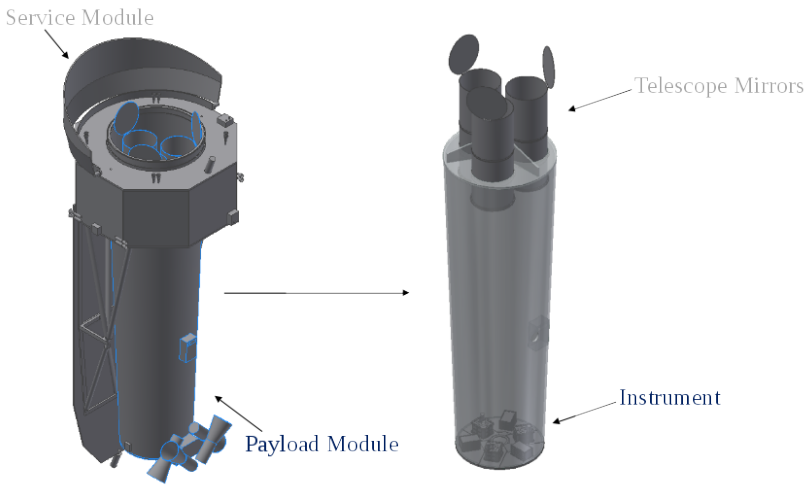
Università and INFN–Pisa

NEWS mid-term review

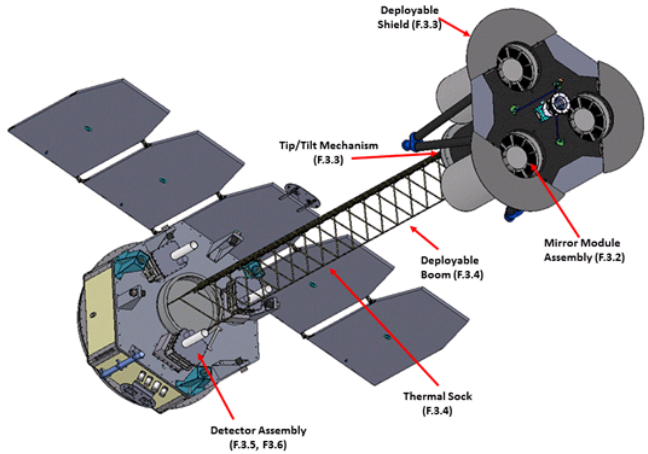
# Background information

## The landscape at the time of the proposal submission

### —XIPE (ESA M4)




### —IXPE (NASA SMEX)




| | | |
|---|---|---|
| P. Soffitta (INAF/IAPS)<br>R. Bellazzini (INFN) | Principal Investigator<br>Co-Investigators | M. Weisskopf (MSFC)<br>P. Soffitta (INAF/IAPS)<br>R. Bellazzini (INFN) |
| 400 Meuro | Cost envelope | 125 M$ |
| 2000 kg (Vega) | Mass envelope | 400 kg (Pegasus) |
| 450 $cm^2$ | Eff. area @2 keV | 200 $cm^2$ |
| April 2017 | Down-selection date | February 2017 |
| 2025–2026 | Launch date | 2020–2021 |
| $>$ 3 years | Duration | $>$ 2 years |

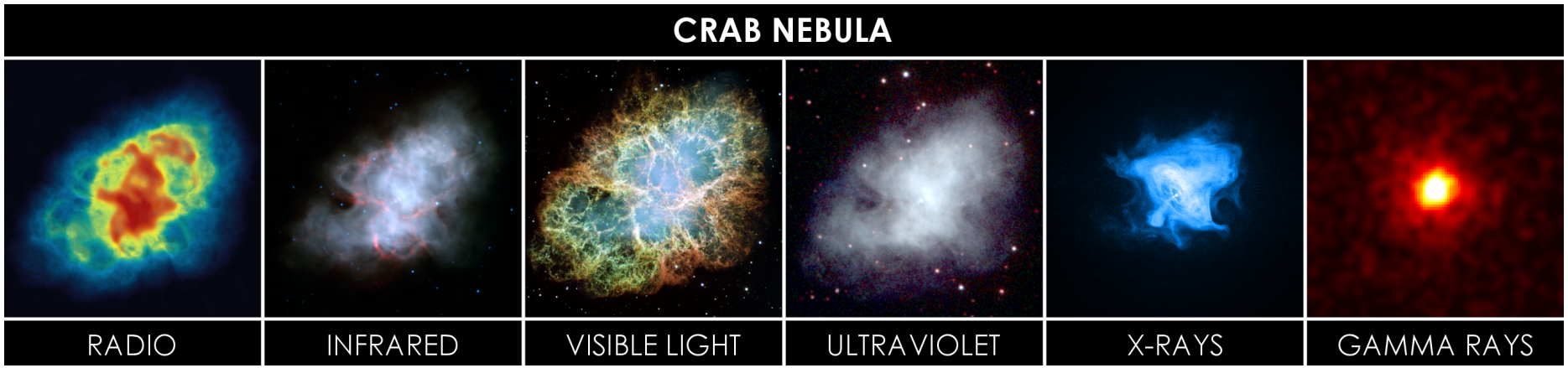
▷ Three (out of 6) missions in phase study for the last ESA and NASA calls are specifically devoted to X-ray polarimetry.

# Current status and timeline

- January 2017: IXPE selected as the next NASA SMall EXplorer (SMEX) mission
  - Launch date no earlier than april 2021
- Instrument milestones
  - System Requirement Review (I-SSR), October 2017
  - Preliminary Design Review (I-PDR), March 2018
  - Critical Design Review (I-CDR), May 2018
  - I-CDR provides the final green light for the production of the flight hardware
- Mission milestones
  - Preliminary Design Review (PDR), June 2018
  - Key Decision Point C (KDP-C), September 20, 2018
  - KDP-C signals the final mission adoption by NASA and the start of phases C/D
  - Critical Design Review (CDR), May 2019
- No margins for delaying the schedule

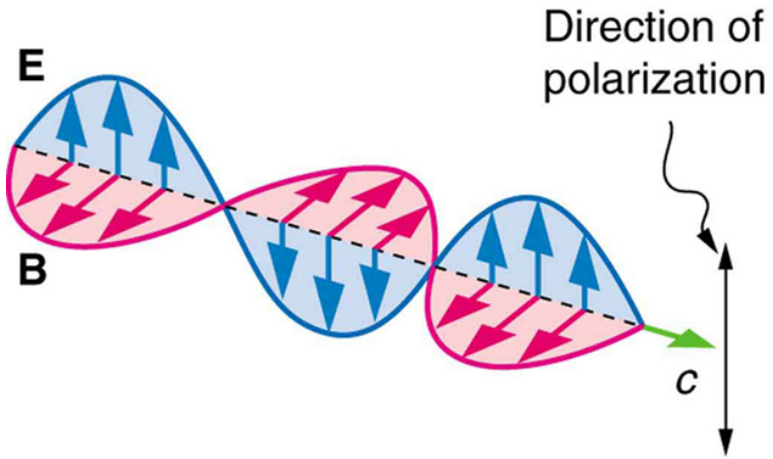
# The four facets of light

## 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 $\gamma$-ray) polarimetry is possibly the most notable exception.

# And what is polarization, after all?




- EM waves are oscillations of electric and magnetic fields propagating at the speed of light (in vacuum).
  - Polarization has to do with the orientation of the fields and its complete description is non trivial.
- $\vec{E}$, $\vec{B}$ are mutually perpendicular and perpendicular to the direction of propagation $\vec{k}$, i.e., ($\vec{E} \perp \vec{B} \perp \vec{k}$).
- When the $E$ direction is fixed, the wave is linearly polarized.
  - The orientation of the $E$ field is the polarization angle.
  - The superposition of many different wave trains (of photons), can exhibit an arbitrary polarization degree from 0 to 1.
  - (And linear polarization is all we'll be dealing with today.)

# Is X-ray polarization interesting? Yes!

## And especially in conjunction with the other observables

- Significant X-ray linear polarization expected in a variety of astronomical X-ray source classes.
  - Acceleration phenomena and non-thermal emission processes.
  - Geometry/propagation (e.g., scattering in aspherical geometries).
- X-Ray polarimetry would add two parameters to the phase space where models are confronted with observations:
  - polarization degree;
  - polarization angle.
- 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;
  - strong magnetic fields and QED effects;
  - photon propagation over cosmological distances.
- Potential for an otherwise inaccessible wealth of information on a wide variety of galactic and extra-galactic sources.

# Great expectations, meager results...

## 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*

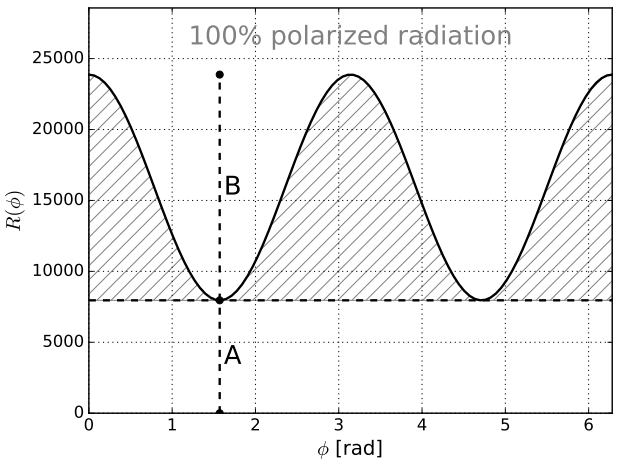
ABSTRACT

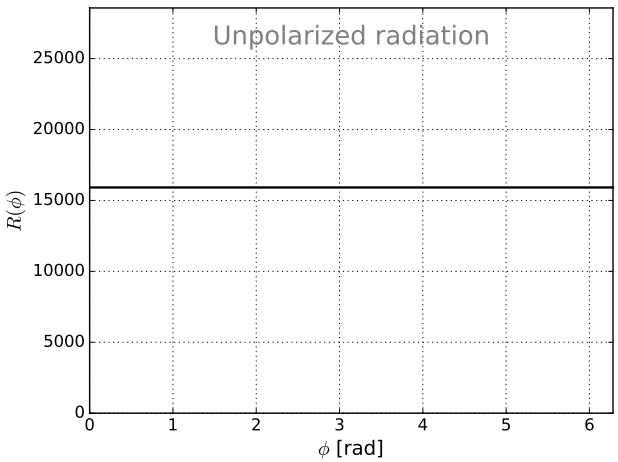
The linear X-ray polarization of the Crab Nebula has been precisely measured at 2.6 keV and 5.2 keV with the *OSO* 8 graphite crystal polarimeters. The 1.4 ms time resolution of these instruments permitted the removal of any contribution to the polarization from the pulsar. The nebular polarization is 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

- This is all great, but where do we stand?
- 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 $\phi_0$ of the incident photon beam:

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

- Modulation factor: response to 100% polarized radiation:

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

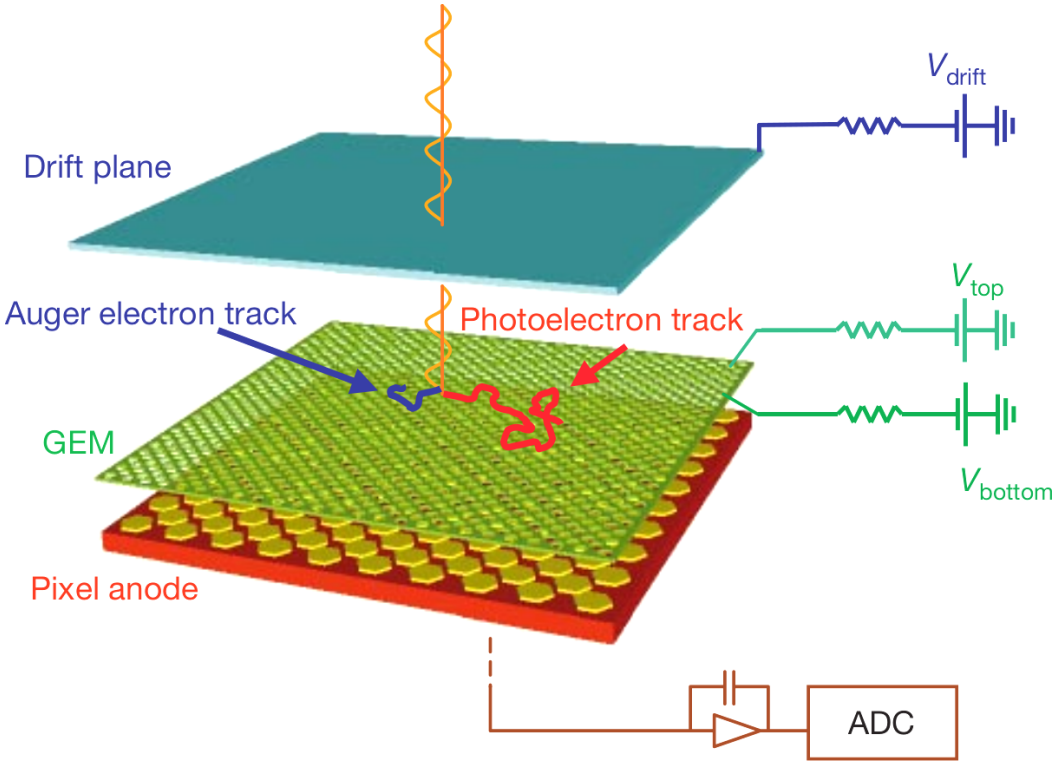
- Minimum Detectable Polarization (MDP)[1] with no background:

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

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

# Photoelectric X-ray polarimetry

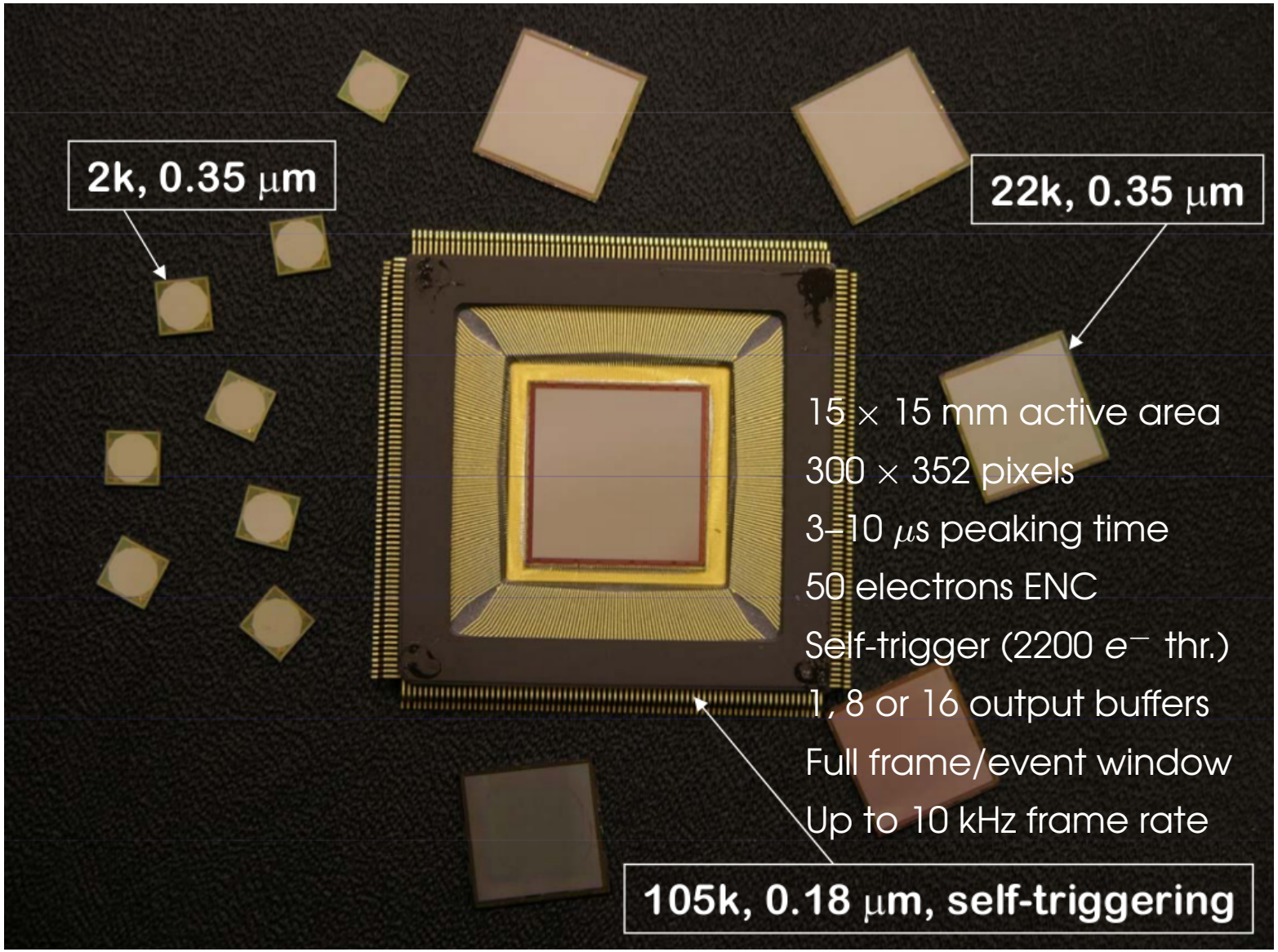
## The Gas Pixel Detector (GPD) as a polarimeter




- 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
- Basic GPD components:
  - gas-filled absorption gap acting as detection medium;
  - Gas Electron Multiplier (GEM) providing gas amplification;
  - finely pixelized readout anode for signal collection.

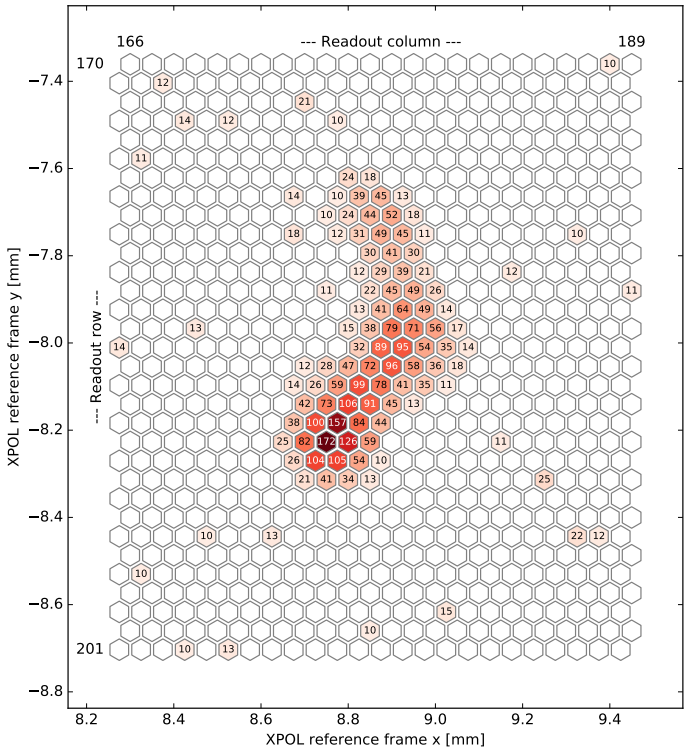
# The Italian fundamental contribution to the mission

## Three generations of ASICs



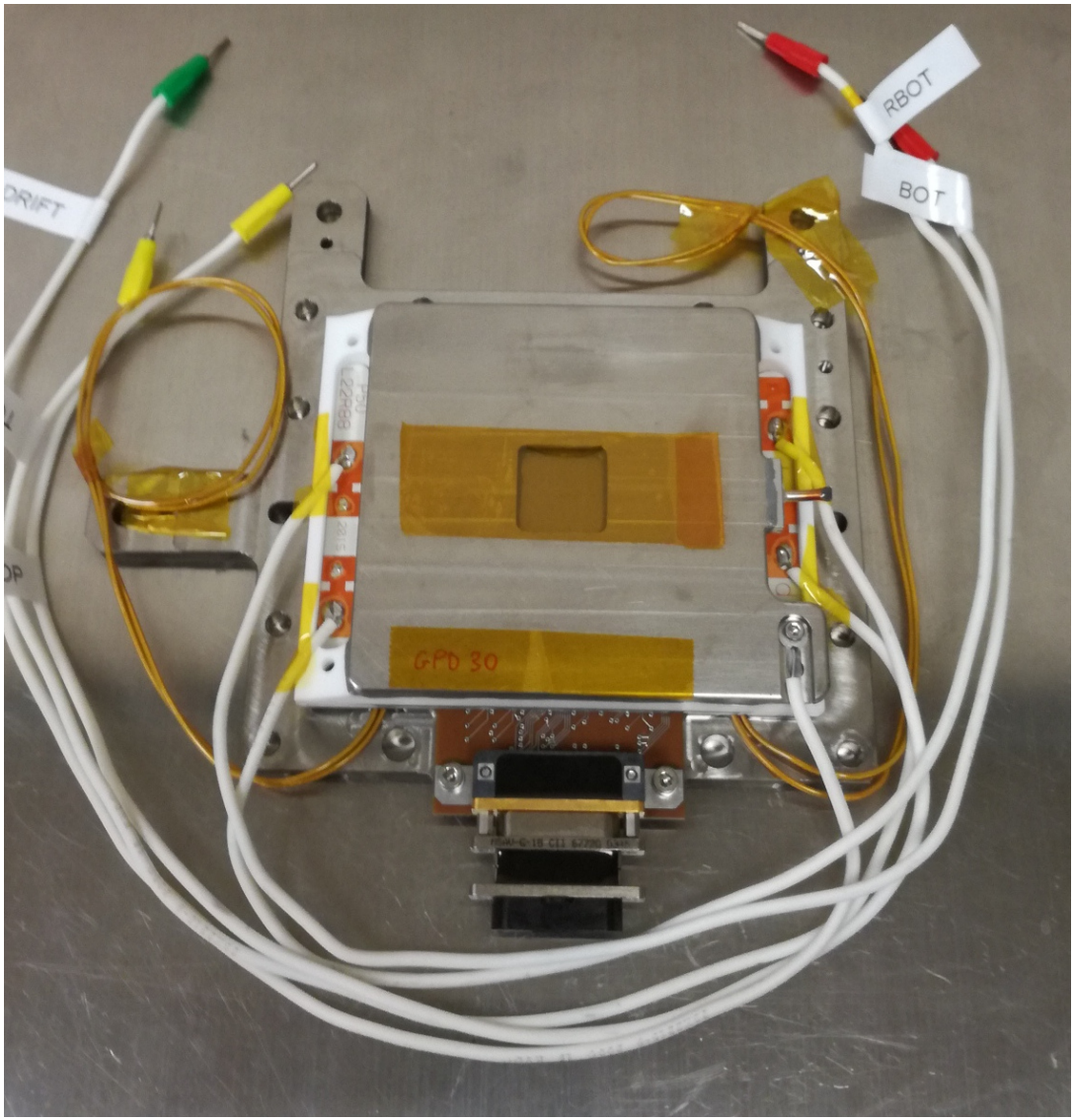
# ASIC salient features

## Image: real 5.9 keV photoelectron track

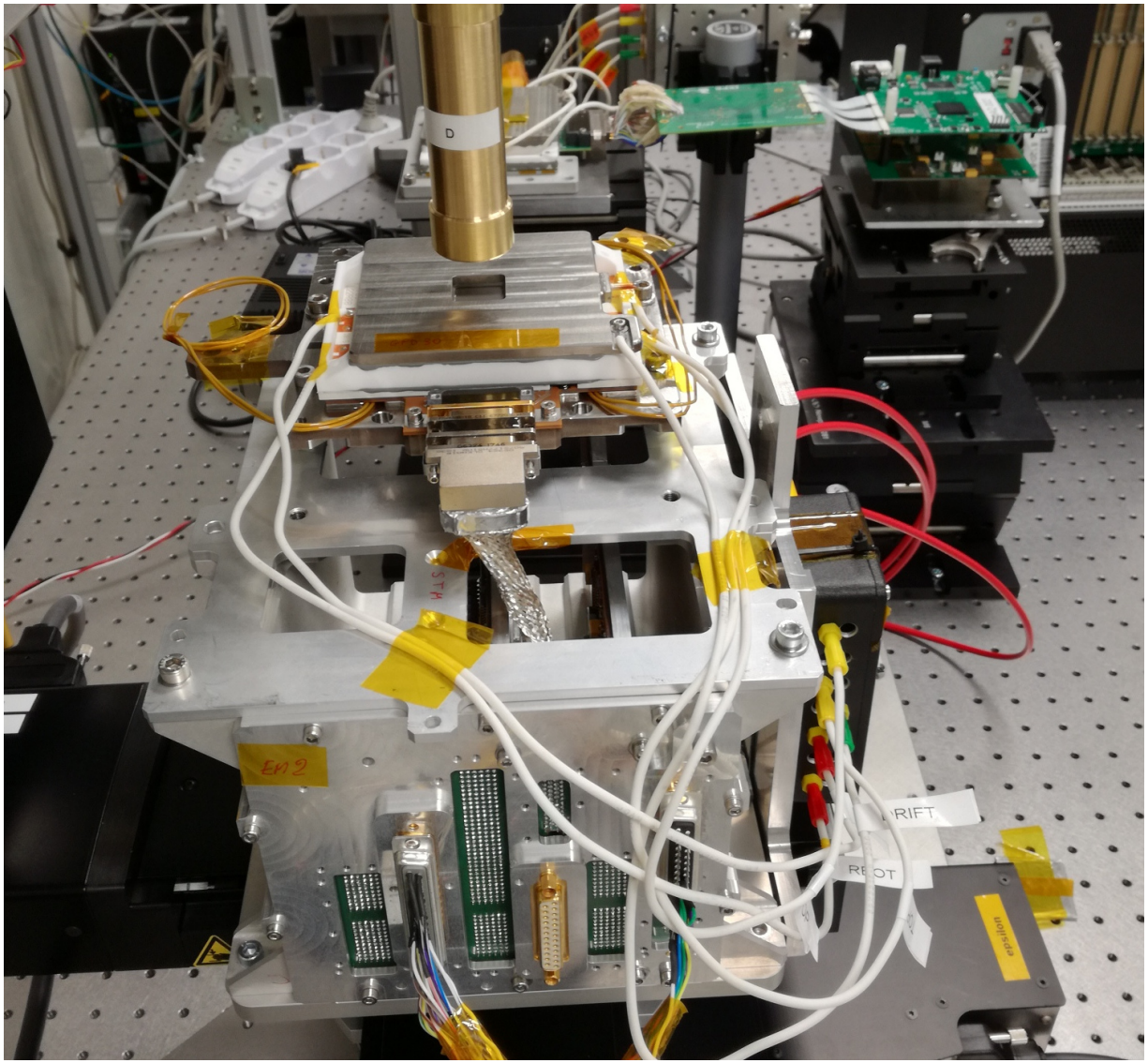



- Self-triggering.
- Internal definition of the region of interest for the event readout.
  - Typical window size $<$ 1 k pixels.
  - Multiple window readout for event-by-event pedestal subtraction.
- Serial readout via an external ADC.

# The first flight GPD

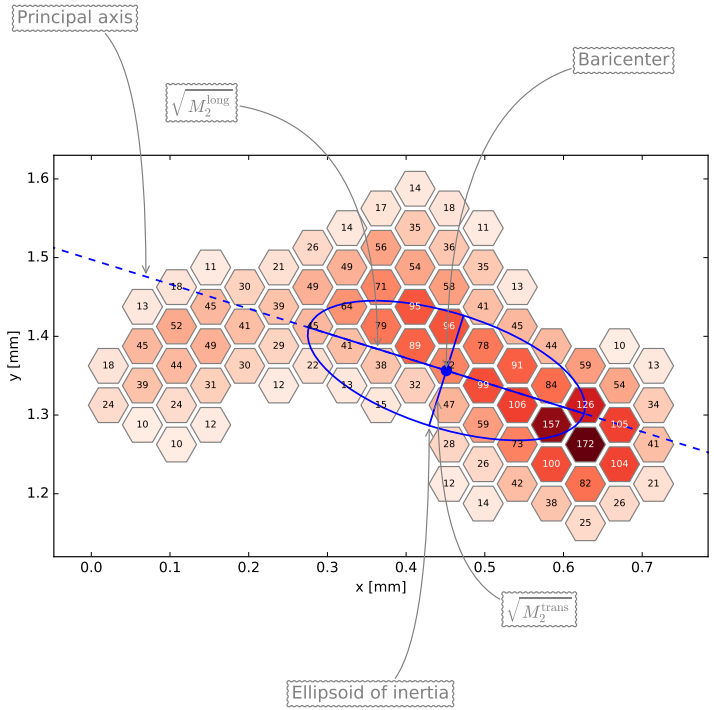


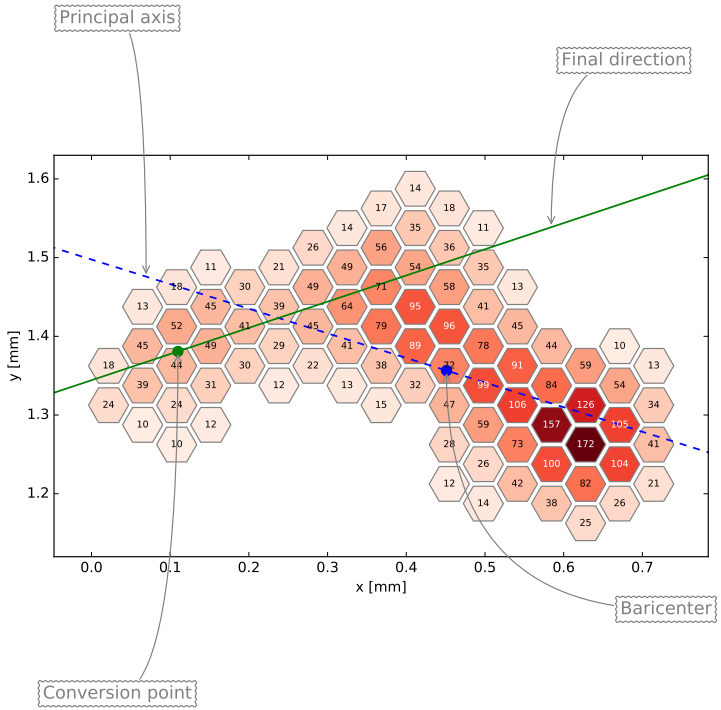
# GPD testing



# Event-level analysis basics

## Real 5.9 keV photoelectron track, colors indicate the pulse height

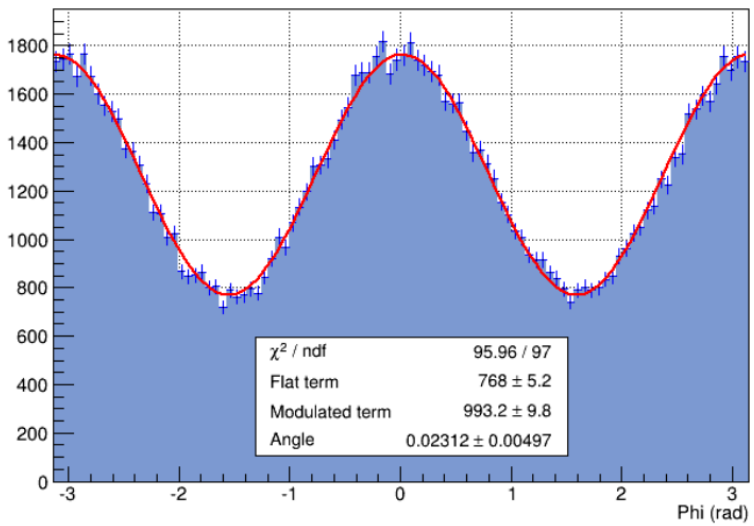


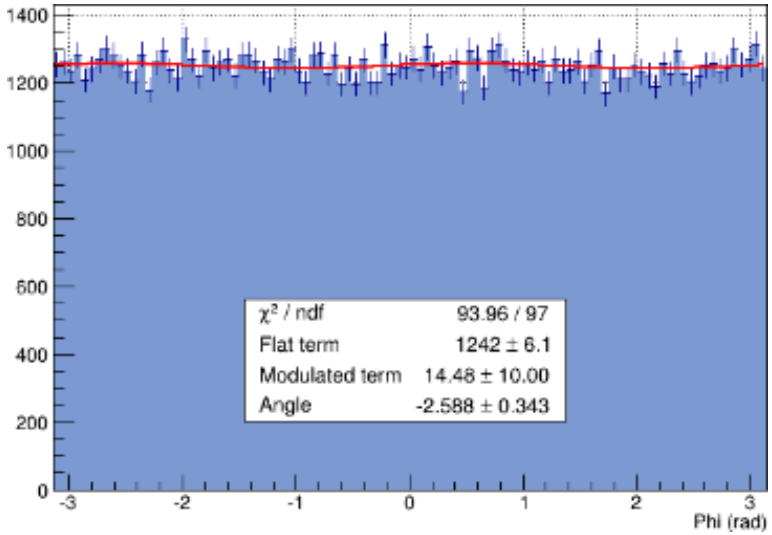




- Analysis is done event-by-event.
- Track reconstruction:
  - First pass: baricenter, basic moments analysis, skewness of the longitudinal projection to identify the Bragg peak.
  - Second pass: determination of the absorption point and weighted moments analysis for a refined estimate of the direction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

# Performance of the GPD as a focal-plane polarimeter

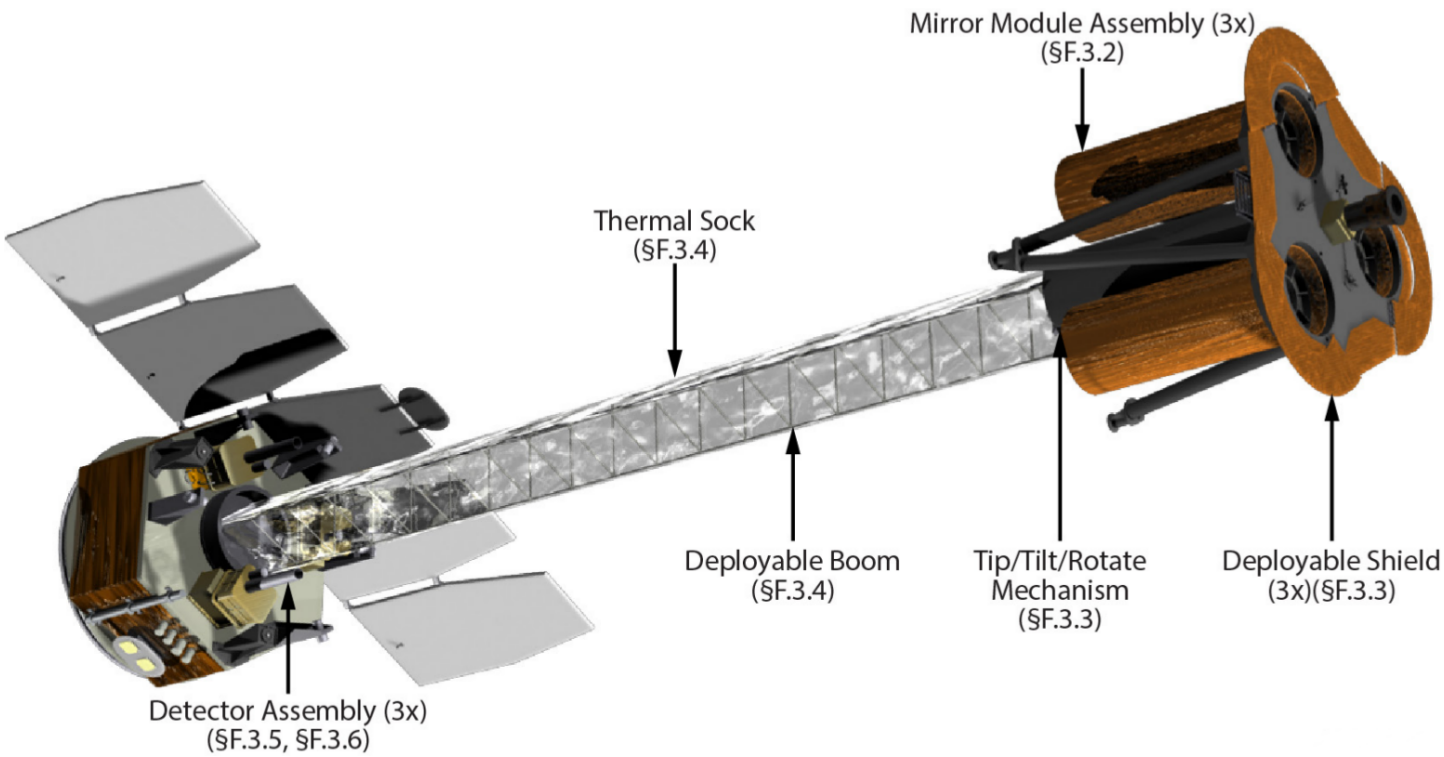
## Measuring four things at once

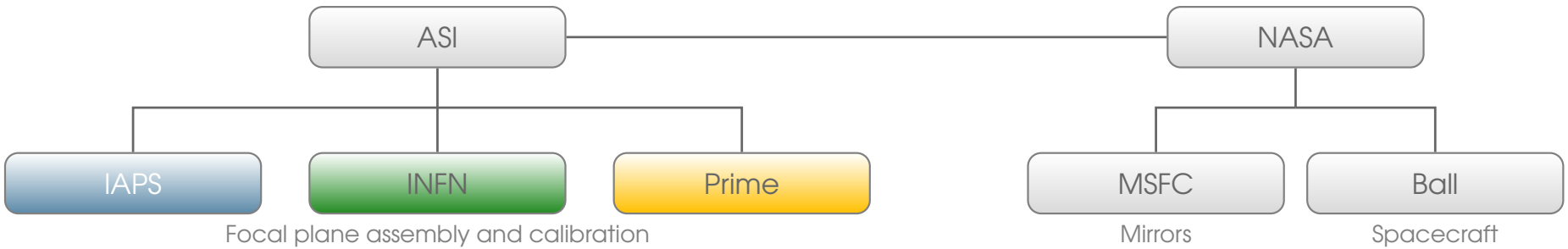



- Modulation factor: 0.2 (0.7) at 2 (8) keV.
  - Stability over $\sim$ 3 years demonstrated with a sealed detector.
- Residual modulation for unpolarized radiation $\sim$ 0.1%.
- $\sim$ 90 $\mu$m spatial resolution at 5.9 keV, measured ($\ll$ track length).
  - Good match for a 20 arcsec-type X-ray optics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

# IXPE


Mirror Module Assembly (3x)
(§F.3.2)
Thermal Sock
(§F.3.4)
Deployable Boom
(§F.3.4)
Tip/Tilt/Rotate
Mechanism
(§F.3.3)
Deployable Shield
(3x)(§F.3.3)
Detector Assembly (3x)
(§F.3.5, §F.3.6)

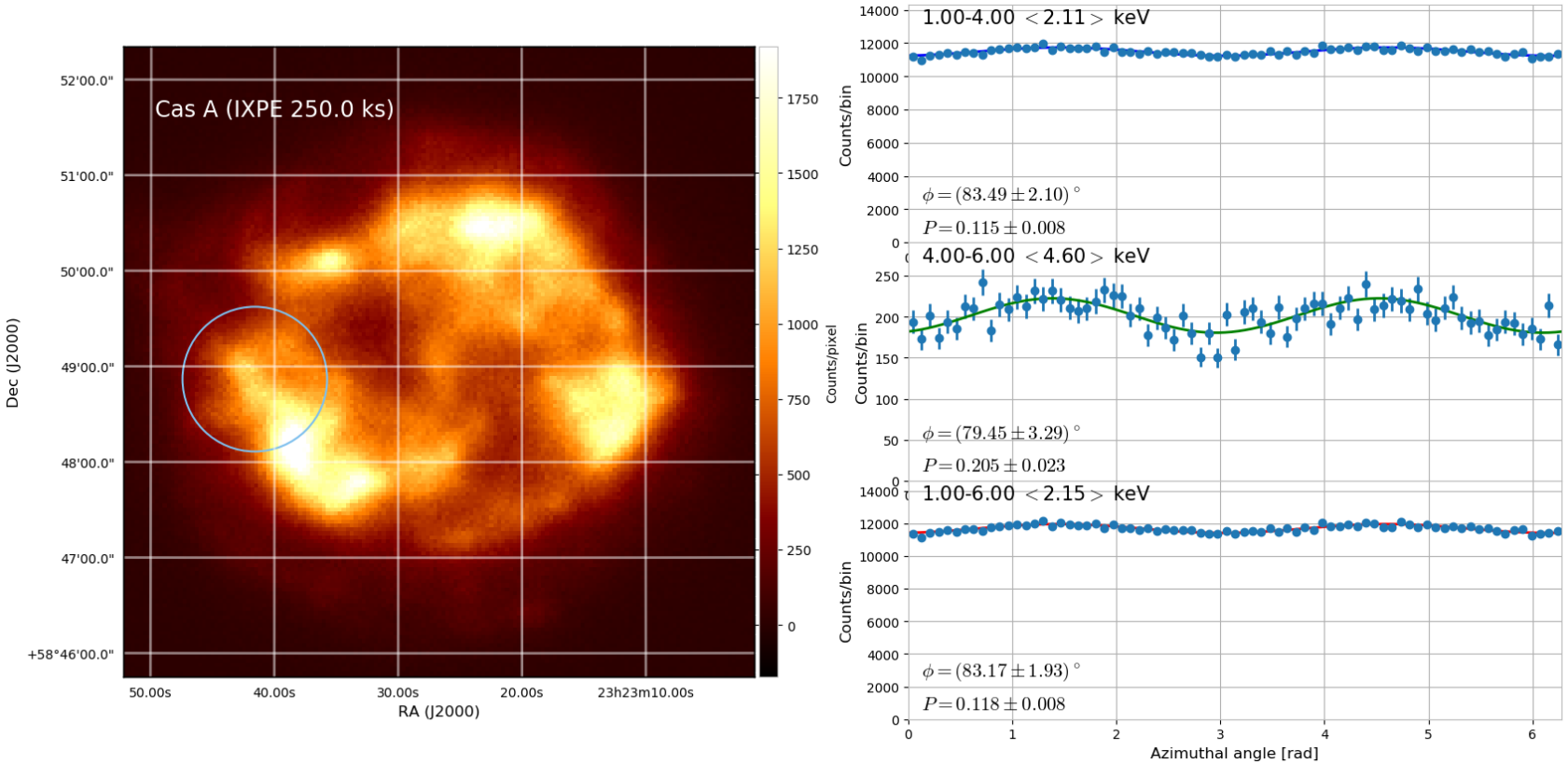

ASI
NASA
IAPS
INFN
Prime
MSFC
Ball
Focal plane assembly and calibration
Mirrors
Spacecraft

# The IXPE mission

## Cheat sheet

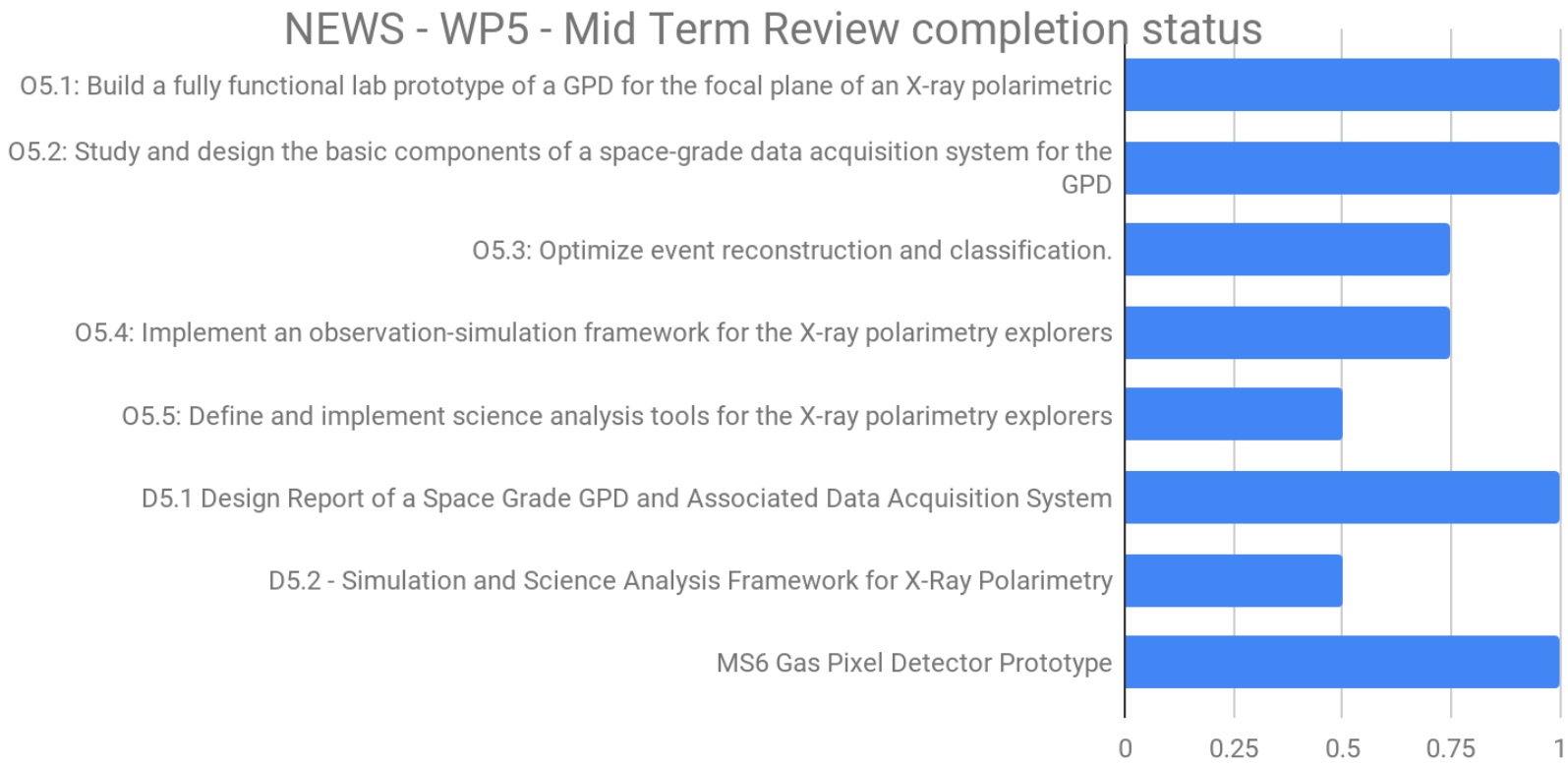
- Three identical telescopes, each including GPD and optics:
  - Provide full redundancy, mitigate possible residual systematic effects.
- Mass and power budget (total): $\sim$ 300 kg, $\sim$ 200 W:
  - $\sim$ 15 kg, $\sim$ 20 W for the three detector units;
  - $\sim$ 85 kg for the mirror module assembly.
- Focal length: 4 m (deployable boom).
- Launched in stowed configuration with three critical events:
  - separation from launch vehicle (free-flying spacecraft);
  - solar array deployment (full power available);
  - payload boom deployment (ready for payload commissioning).
- Pegasus launch 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.

# An observation simulation



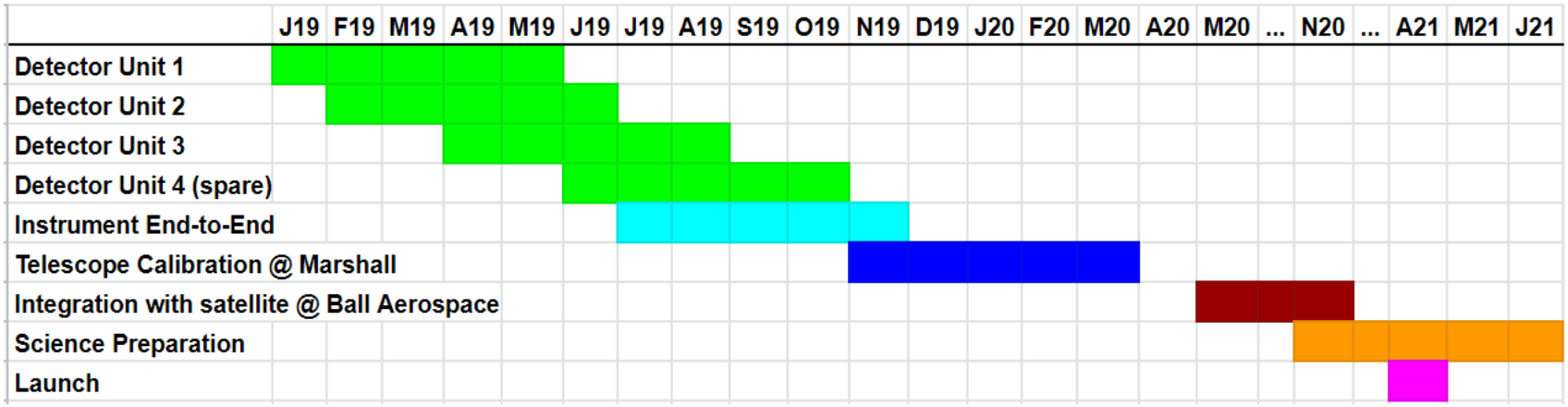

▷ Observation-simulation framework under active development

# NEWS milestones: status



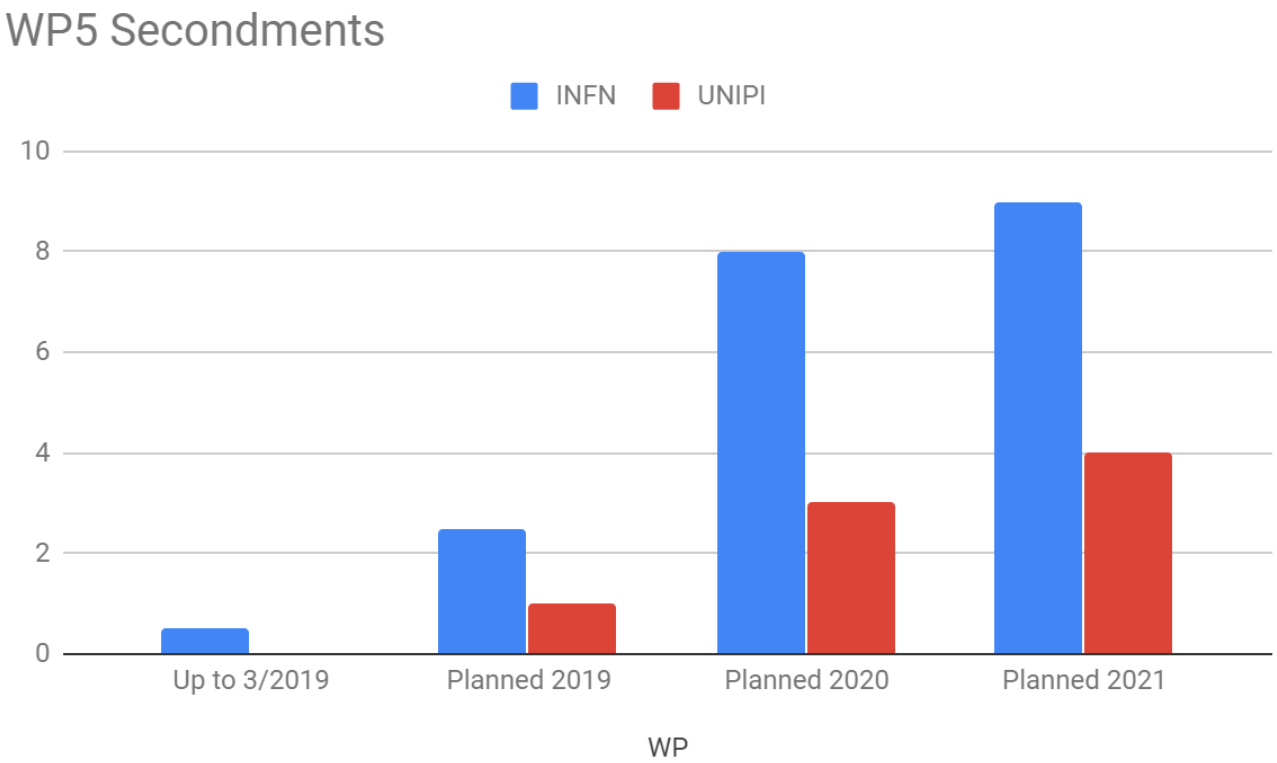

- Hardware development nearing completion
  - Characterization and test will continue through 2019 and 2020
- Software development well on its way
  - Will continue (with increasing emphasis) through the operational life of the mission

# IXPE schedule and secondment status




- IXPE team has focused on the hardware development, so far
  - Both in Italy (instrument) and in the U.S.A (mirrors)
- Time for secondments extremely reduced
  - Limited to supporting a few individuals at key mission level events

# Secondment plans




- Plan to start a vigorous program of secondments starting in 2020
  - Support the telescope end-to-end calibrations
  - Continue the work to prepare for science exploration