Probing the Universe with X-ray Polarimetry

Technological Advances for Satellite-Based Observations

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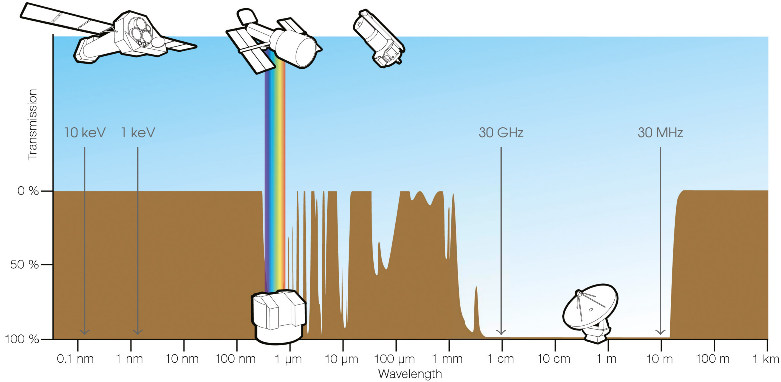
Some context

What do we astrophysicists do?

The Universe as a source of electromagnetic waves

(And the opacity of the Earth atmosphere)

18 decades (or 60 octaves) in energy



γ rays

X-rays

(particle detectors)

Optical

(lenses, mirrors)

Radio

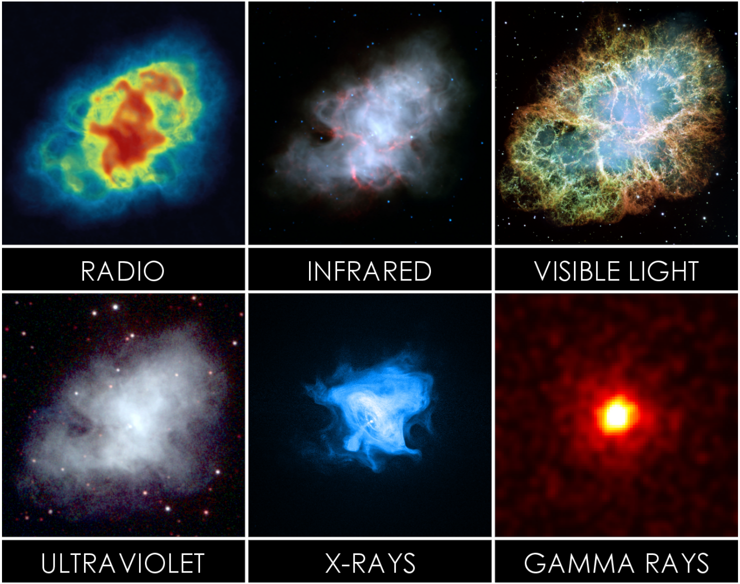
(antennas)

Single photons

Waves

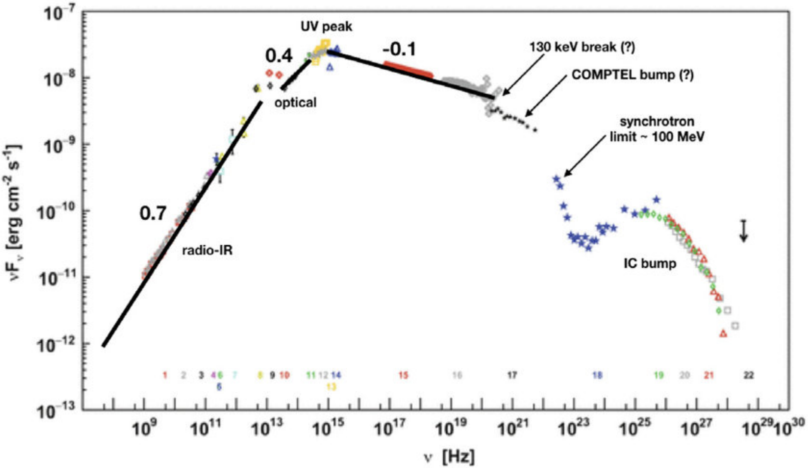
How do we study the Universe?

1. By images



How do we study the Universe?

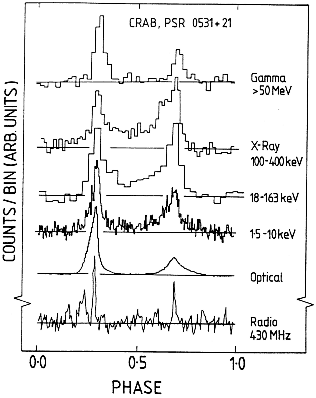
2. With spectroscopy



- ▷ Energy spectrum of the Crab Nebula from radio to γ-rays
  - ▷ Dozen of instruments with different observational techniques

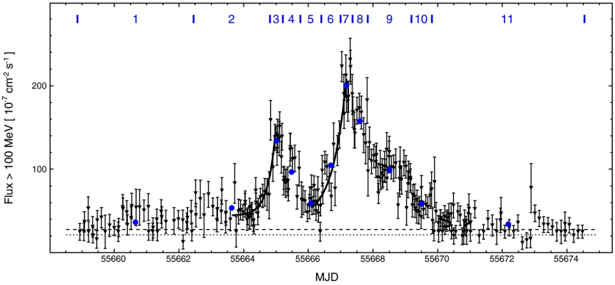
How do we study the Universe?

3. With *timing*



Pulsar (33 ms period)

Flares from the nebula (days, weeks)



That's it? No: how about polarization

Have you ever heard the word *polaroid*?

32.46 €

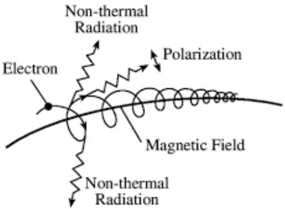
Without Filter   With Filter

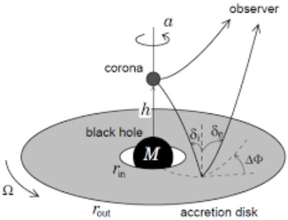
The problem (and its solution)

What do we want to measure? (And how?)

X-ray polarimetry

Interesting and challenging

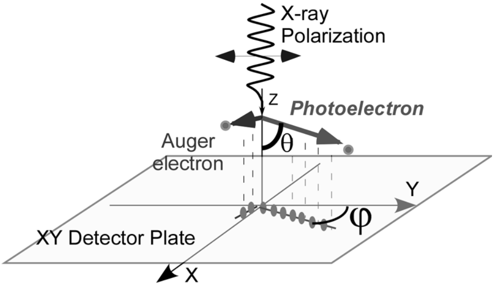




- Some degree of polarization expected in most classes of X-ray sources
  - Non-thermal emission (e.g., synchrotron radiation)
  - Re-processing and propagation in aspherical geometries
- That is: measuring polarization is potentially interesting
  - In fact this is routinely done in optical and radio
  - Problem: not trivial to make a polaroid film for X-rays...
  - ...mismatch between the needs and the sensitivity of the standard techniques
- Polarimetry has been traditionally the most underdeveloped branch of X-ray astronomy

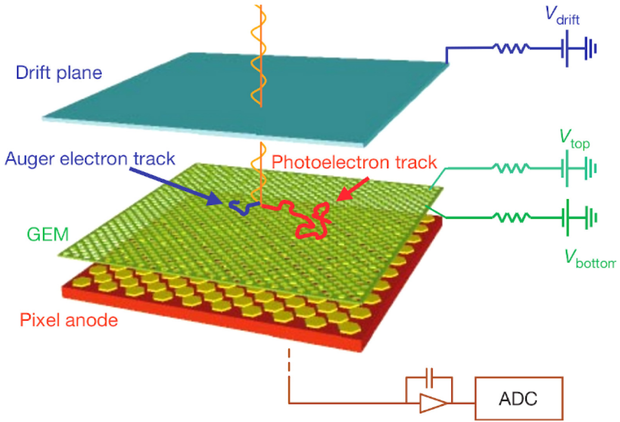
The physical principle

Expliting the photoelectric effect to measure X-ray polarization



- ✓ Direction of emission of the photoelectron preferentially around the electric field (aka polarization) of the incoming photon
- ✓ The (photo) electron is a charged particle and we can measure it through its ionization
- ✗ Problem: a few-keV electron only travels a few hundreds of nm in a solid. . .
  - ▷ At least an order of magnitude smaller of the pixel in the camera of your smartphone

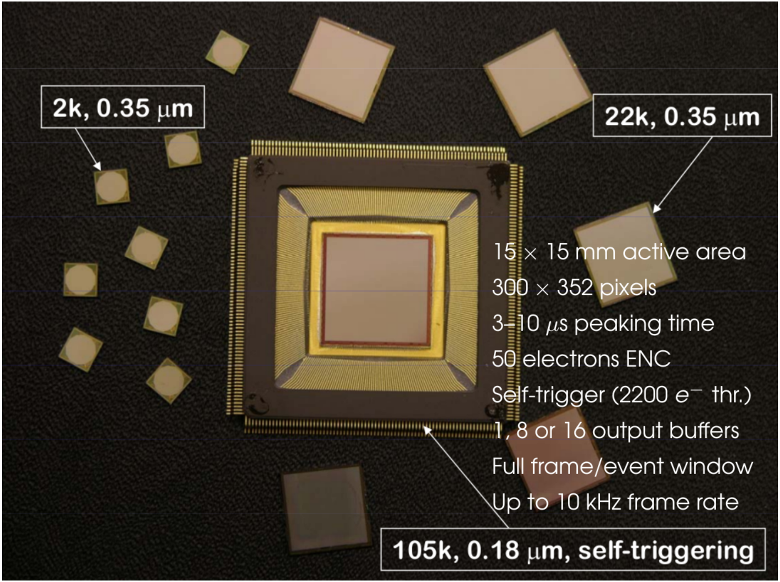
The Gas Pixel Detector (GPD)



- By using a gas as the active medium we gain a factor of 10^3 in track length, i.e., 100 nm $\rightarrow$ 100 μm

XPOL: a custom CMOS chip

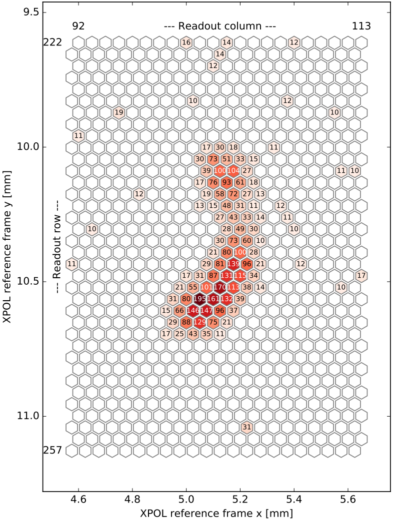
The heart of the Gas Pixel Detector

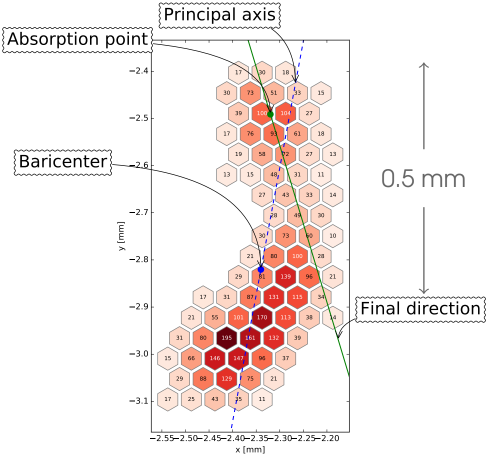


- 15×15 mm active area
- 300×352 pixels
- 3–10 μs peaking time
- 50 electrons ENC
- Self-trigger (2200 e^- thr.)
- 1, 8 or 16 output buffers
- Full frame/event window
- Up to 10 kHz frame rate

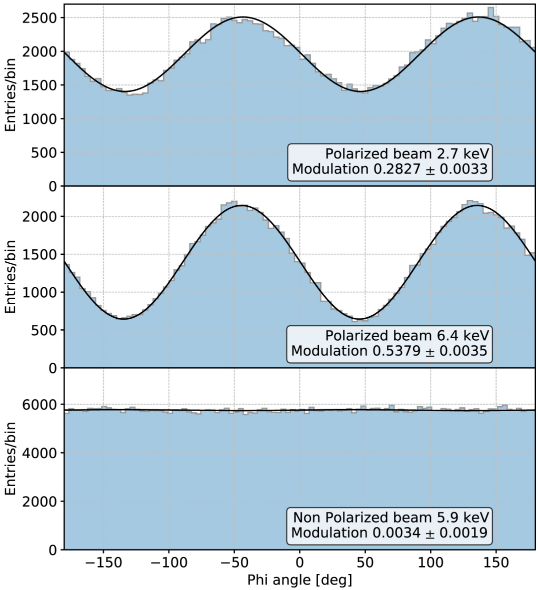
The measurement principle. . .

Energy, position, and time on a photon-by-photon basis





. . . and finally: polarization



$N(\phi) \propto 1 + \mu \cos(2(\phi - \phi_0))$

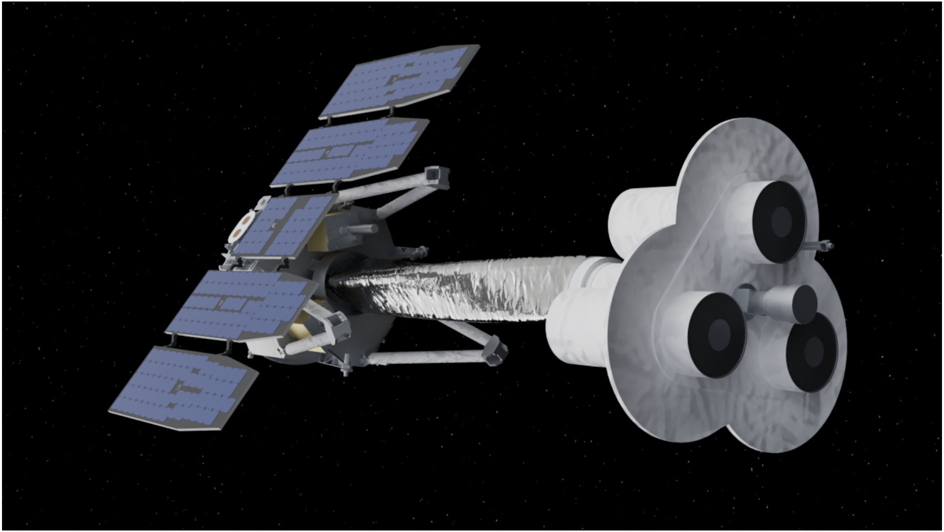
(μ: modulation factor)

How flat is the response to unpolarized radiation?

The Imaging X-ray Polarimetry Explorer (IXPE)

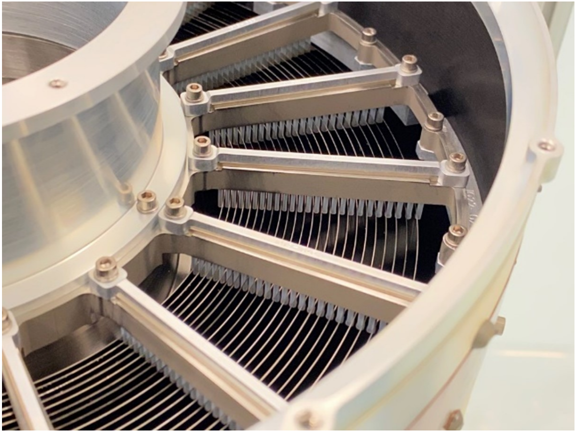
The mission in a nutshell

An artistic impression of the three telescopes



The X-ray mirrors

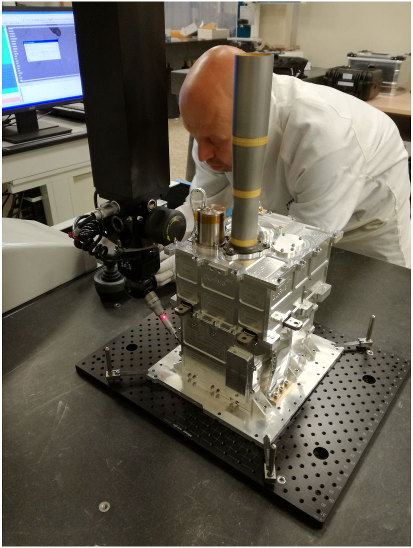
Concentrate X-rays on the focal plane

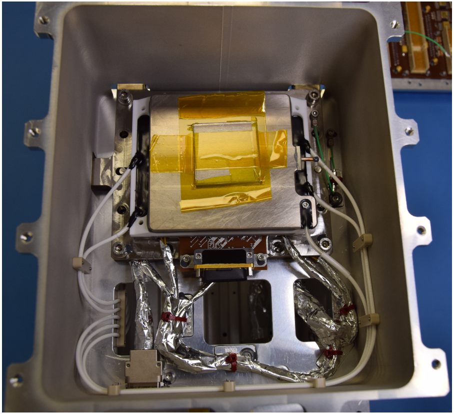


- 24 concentric shells
  - Length: 600 mm
  - Diameter: 162–272 mm
- Focal length: 4 m
- Peak effective area: 200 cm^2

The focal plane

Hosting the polarization-sensitive detectors

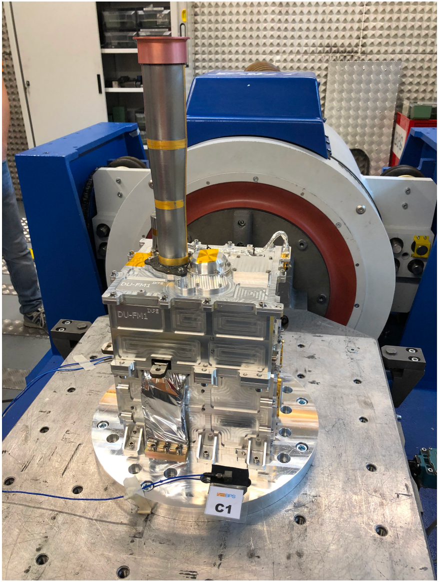




- 3 identical detector units
  - Gas Pixel Detector
  - Readout electronics
  - Filter and calibration wheel
  - Thermal control

Qualification for space

Servicing missions are luxury that only few can afford



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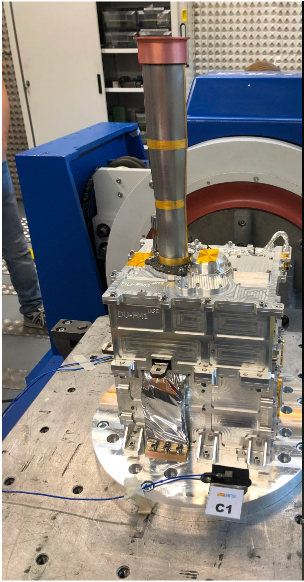

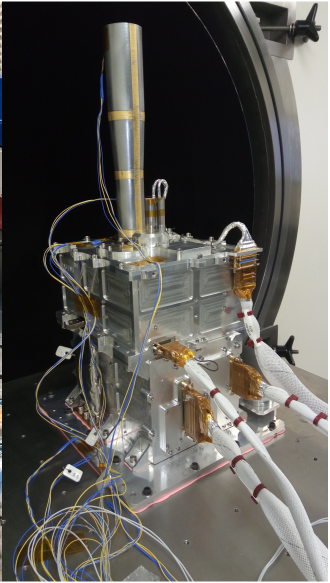

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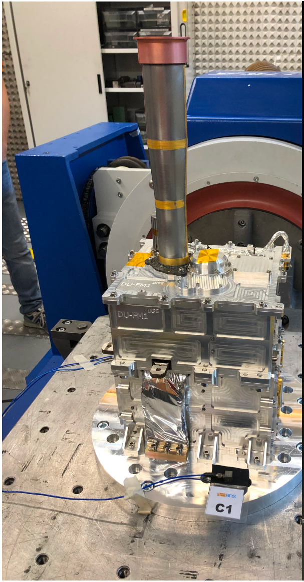
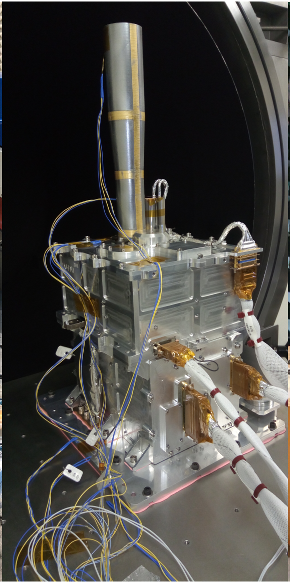
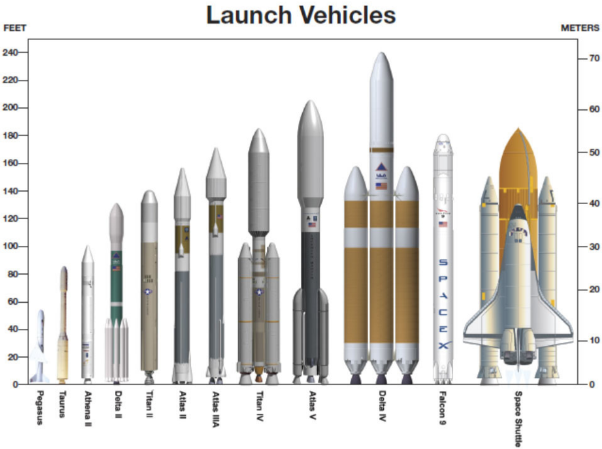




Interlude: one unexpected twist

Did we just get an upgrade in first class?



- ▷ IXPE was designed to be launched on a Pegasus—1 m, 300 kg...
- ▷ ...and we got a Falcon 9, instead—5 m, 3 ton

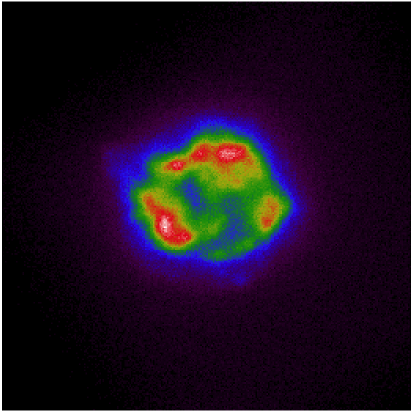
Final tests before moving on the launch pad

IXPE lauch makes it to the astronomy picture of the day

https://apod.nasa.gov/apod/ap211222.html

And, finally: Science!

IXPE first light



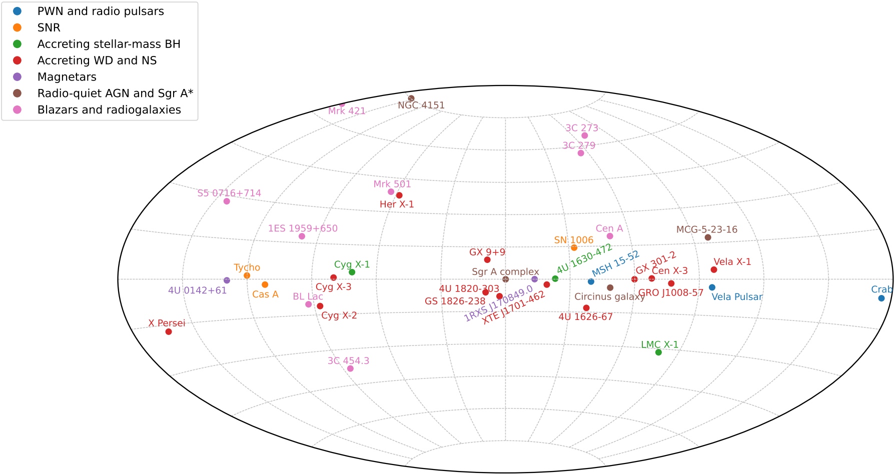
Imaging X-ray Polarimetry Explorer

- Approved in 2017
- Launched on Dec. 9, 2021
- 330 kg, 200 M$

James Webb Space Telescope

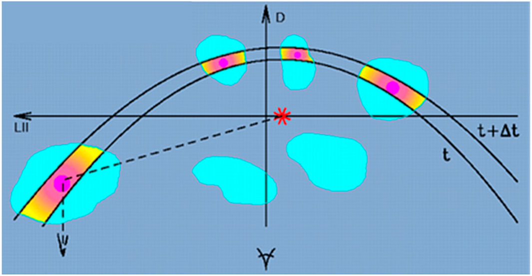
- Design started in 1996
- Launched on Dec. 25, 2021
- 6,500 kg, 10 G$

The observing plan for the first year



One selected science target

Archeology of the Galactic Center



- The center of our galaxy is a very complex region
  - Super-massive black hole (Sgr A*)
  - Surrounded by molecular clouds
- Molecular cloud has a characterstic reflection spectrum
  - Keep in mind: reflection = polarization
  - But what are they reflecting?
  - Sgr A* (as we know it) not bright enough. . .
  - . . . but maybe it was brighter in the past?
- X-ray polarimetry in this case enables astro-archeology
  - The galactic center was much brighter 200 years ago!

Conclusions

- 40 years after the first (and only) polarization measurement of the Crab, IXPE is providing the first systematic study of polarization from astrophysical sources in the 2–8 keV energy range
  - Well into the third year of the mission
  - marching towards 100 observed sources. . .
  - . . . about a half of which are indeed polarized to a measurable level
- Some of the findings are in line with expectation, some are surprising
  - Clear indications that some commonly-accepted models need to be revised
- IXPE now operating as a general observer (GO) facility
  - Not only data are public—the community is driving the observational program
- Good example of a new technology that is enabling great science
  - And a relatively small group of person can make a difference!