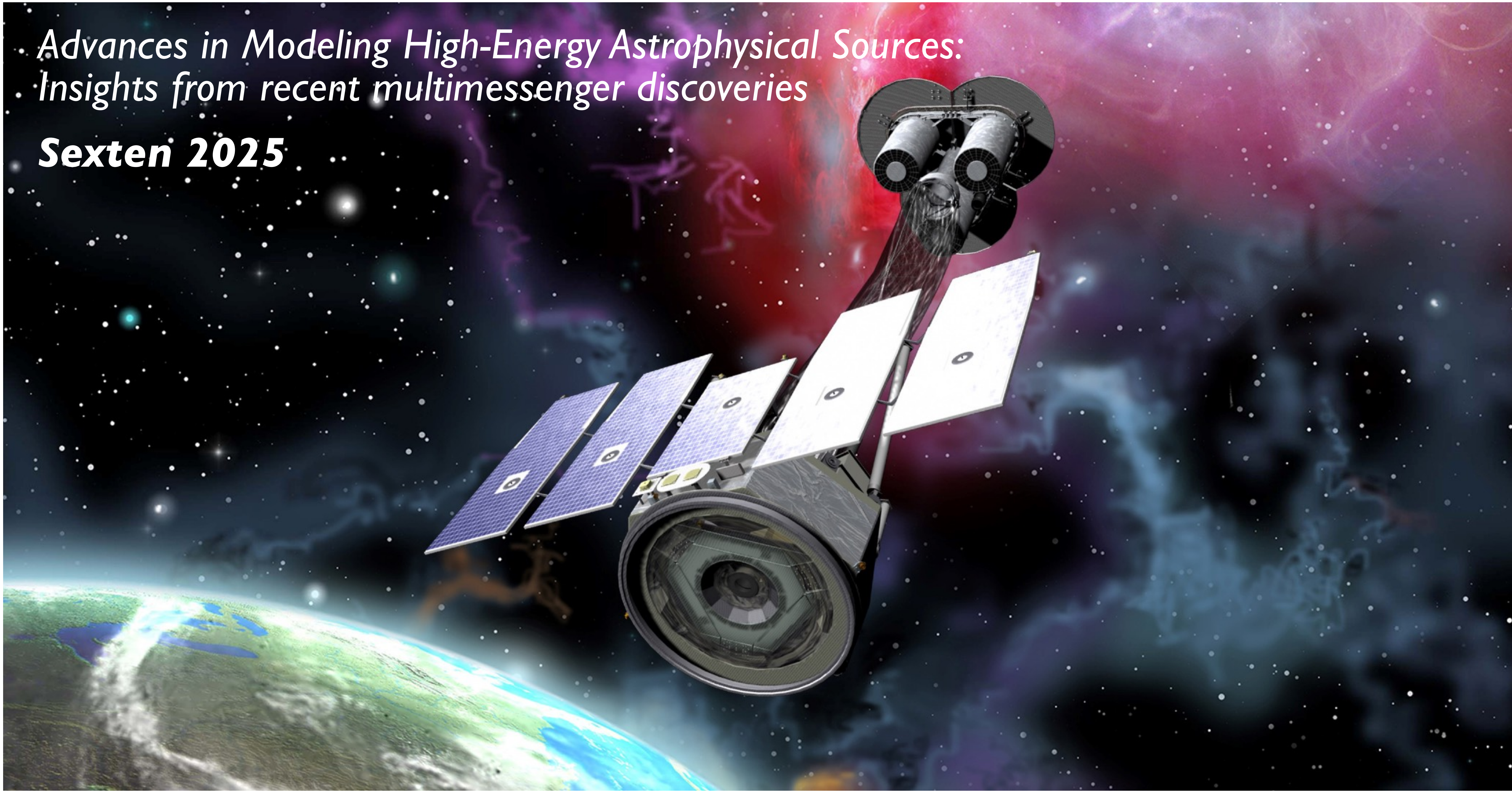
Advances in Modeling High-Energy Astrophysical Sources:
Insights from recent multimessenger discoveries

Sexten 2025



X-RAY POLARIMETRY WITH IXPE

FROM DETECTOR DESIGN TO SCIENTIFIC DISCOVERIES

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OUTLINE

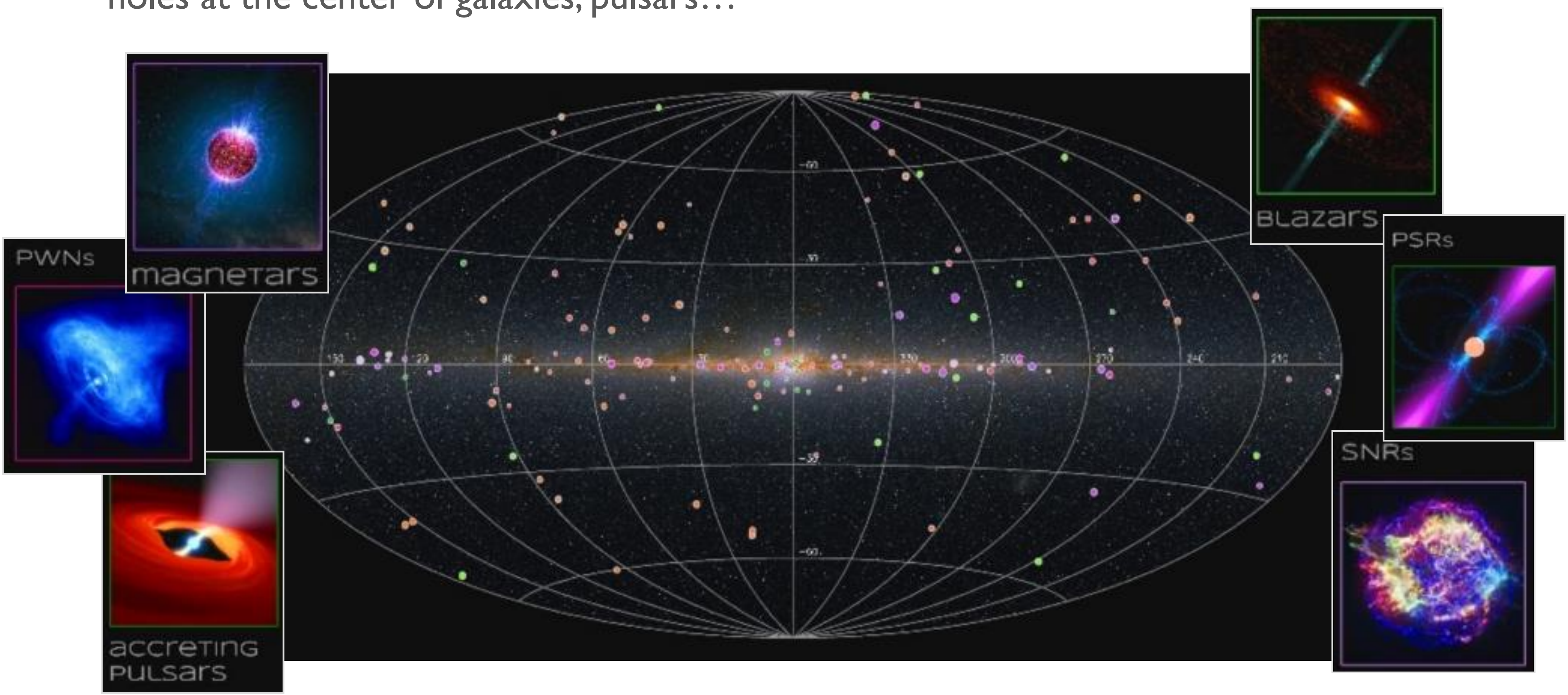
- **X-ray polarimetry** and **astrophysical context**

- **IXPE**
  - Gas Pixel Detector (GPD)
  - Track reconstruction algorithm
  - Scientific results

- **X-ray Calibration Facility (XCF)** for R&D of future X-ray detectors

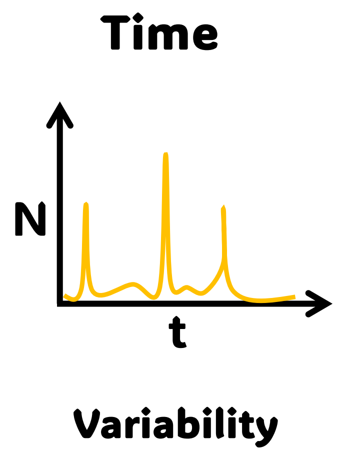
HIGH ENERGY UNIVERSE

- Information on celestial sources are mostly provided by electromagnetic radiation
- X-rays provide info about the **high-energy universe**
- X-rays are produced in:
  - events like **explosions** and high-speed collisions
  - by the **most extreme and mysterious objects**: supernova remnants, supermassive black holes at the center of galaxies, pulsars…



X-RAY POLARIMETRY

- Four basic **observables** to study properties of astrophysical sources:



X-RAY POLARIMETRY

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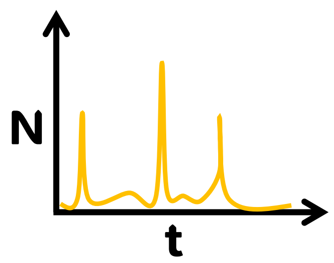
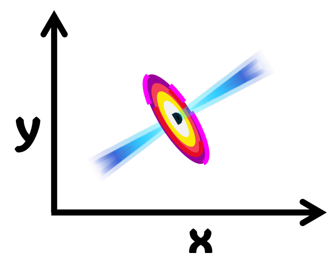


Variability

Image



Topology
Sky map

X-RAY POLARIMETRY

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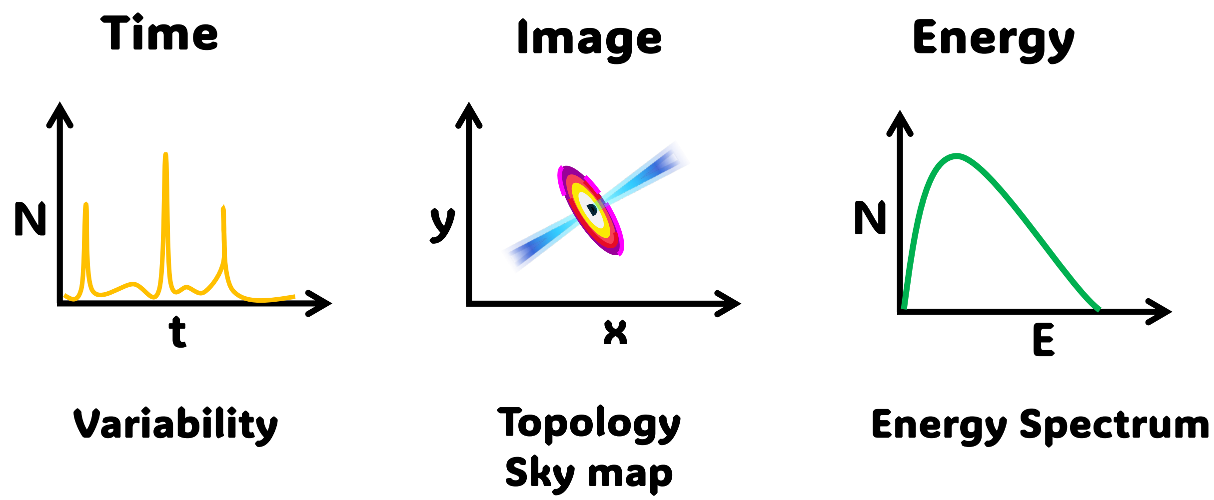

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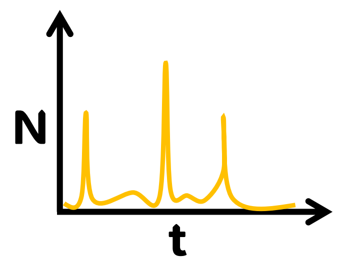

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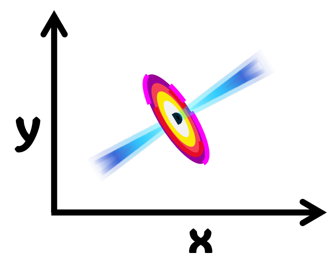

Topology
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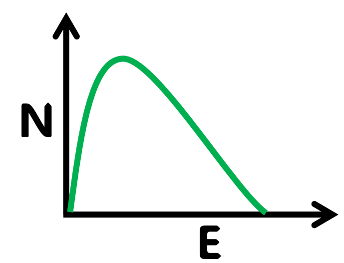
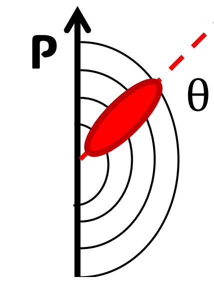
Energy



Energy Spectrum

Polarization



Adds 2 parameters to the phase space**: polarization degree and angle**

X-RAY POLARIMETRY

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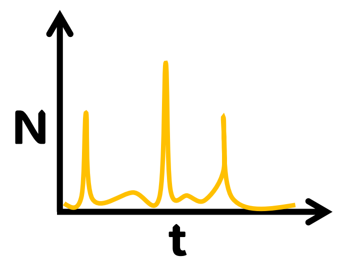

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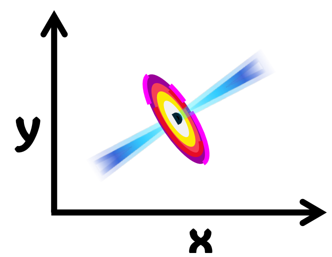

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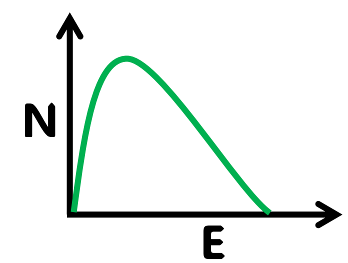

Energy Spectrum

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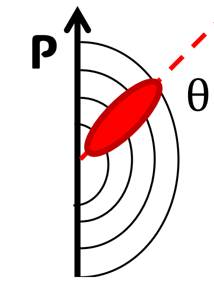
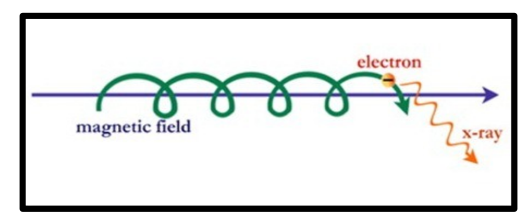


Adds 2 parameters to the phase space**: polarization degree and angle**

- Significant linear polarization expected in a variety of astrophysical X-ray sources

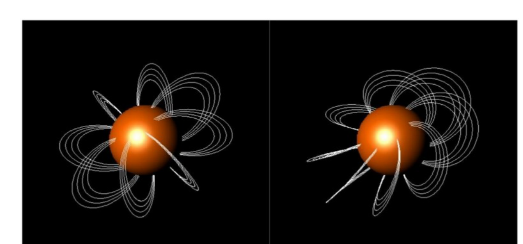
Polarization arises when there is a **preferred direction**

Non-Thermal emission processes: e.g. synchrotron



Geometrical Asymmetries e.g. accretion disk, jets, columns, blobs, etc...

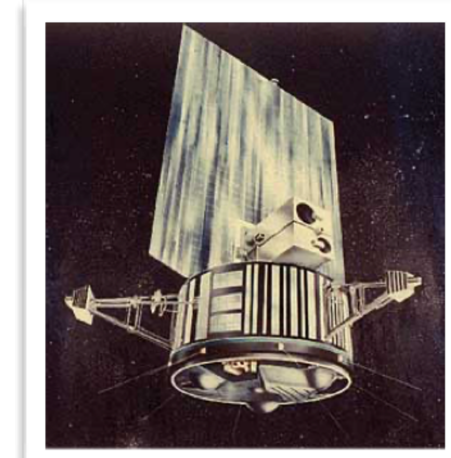
Radiative transfer in strong **gravitational / magnetic field**



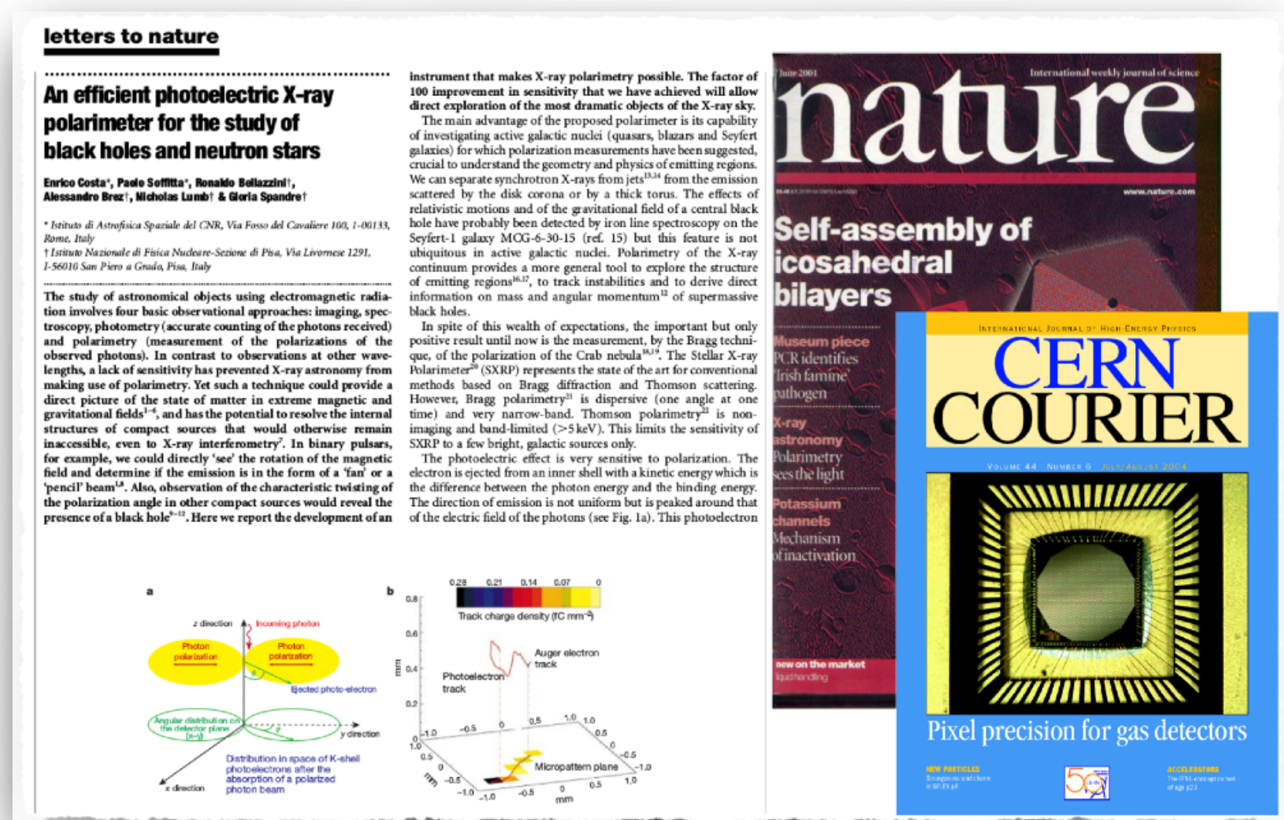
Credit to R. Ferrazzoli

X-RAY POLARIMETRY HISTORY

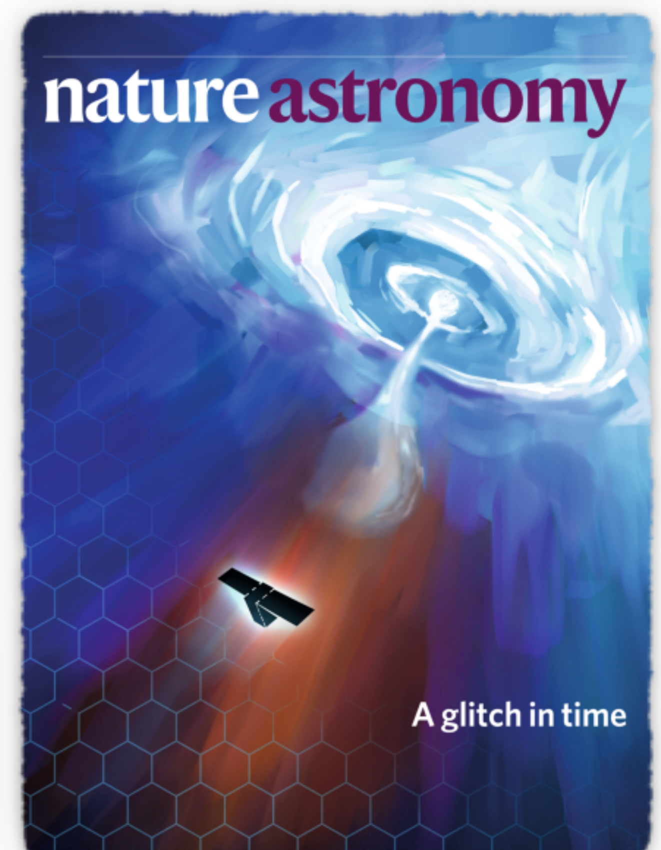
- ***Before 2000:*** X-ray polarimetry was still **undeveloped**
  - Only **1 significant measurement** in 1978:
    20σ measurement of Crab Nebula from a Bragg polarimeter on-board OSO-8 → P = (19.2 ± 1.0)%, phase=(156.4 ± 1.4)° *[Weisskopf et al. 1978]*



- ***Since 2000s:*** **new detector concept** allowed us to improve polarization sensitivity by 2 orders of magnitude wrt OSO-8 polarimeter



***Nature 2001* - TRL 4** (functional verification)



***Nature Astronomy 2020* - TRL 9** (flight proven)

THE X-RAY POLARIMETRY EXPLORER (IXPE) MISSION

IXPE Imaging X-Ray Polarimetry Explorer

- **NASA SMEX** (SMall EXplorer) mission
- **Goal:** X-ray imaging and polarimetry (2–8 keV)
- **Mission characteristics:**
  - Launched on Dec. 9, 2021 on a SpaceX Falcon 9 rocket from NASA's Kennedy Space Center
  - 2-year mission (baseline) + GO phase beyond
  - Equatorial circular orbit at ~600 km altitude

Marshall Space Flight Center	PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving
asi agenzia spaziale italiana	Detector system funding, ground station
Ball	Spacecraft, payload structure, payload, observatory I&T
iaps, INAF Istituto Nazionale di Astrofisica / National Institute for Astrophysics, INFN	Polarization-sensitive imaging detector systems
LASP	Mission operations
Roma Tre Università degli Studi, Stanford University	Scientific theory
McGill	Science Working Group Co-Chair
MIT Massachusetts Institute of Technology	Co-Investigator

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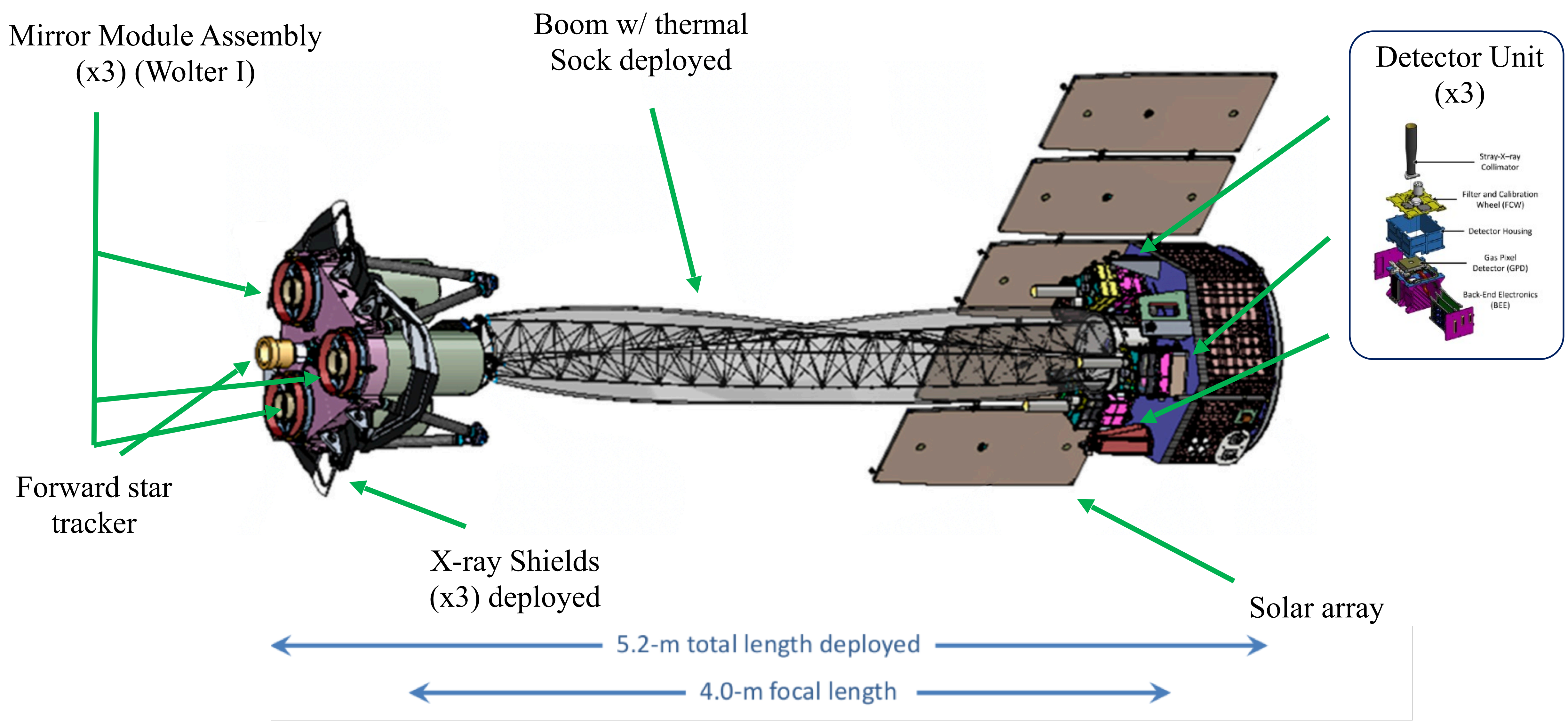
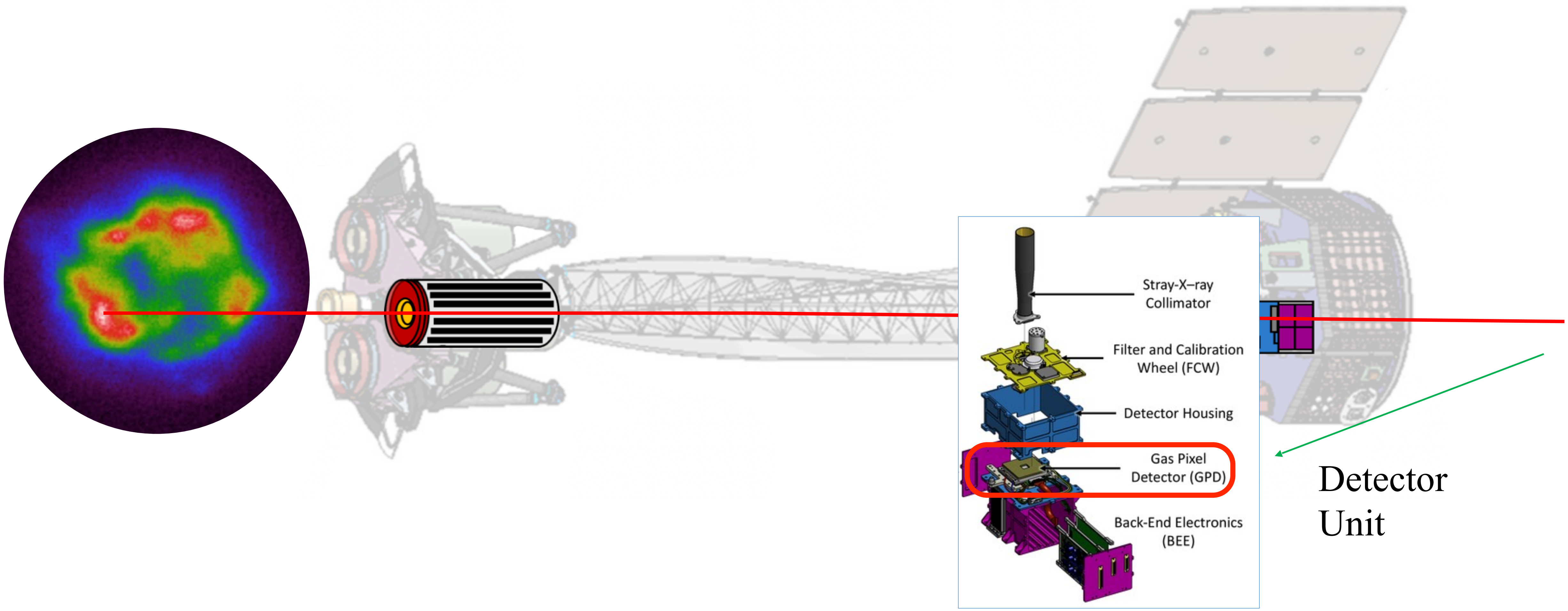
THE IXPE SATELLITE



- **3 identical telescopes** → redundancy, mitigation of systematics, larger acceptance
- Conventional Wolter Type I grazing–incidence optics
- **Extensible boom** to save space during launch
- New imaging and polarization-sensitive detector: **Gas Pixel Detector**

THE IXPE SATELLITE



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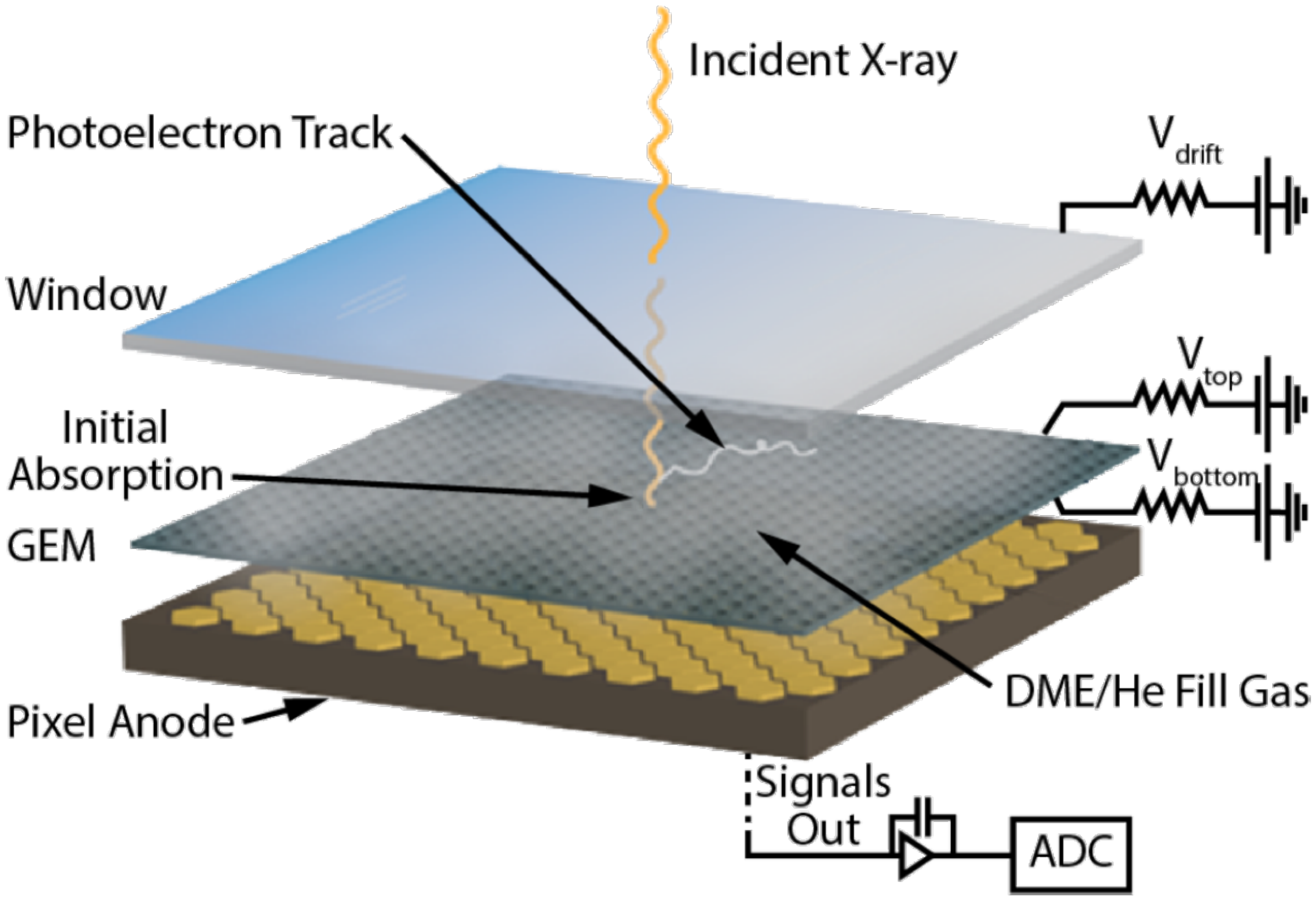
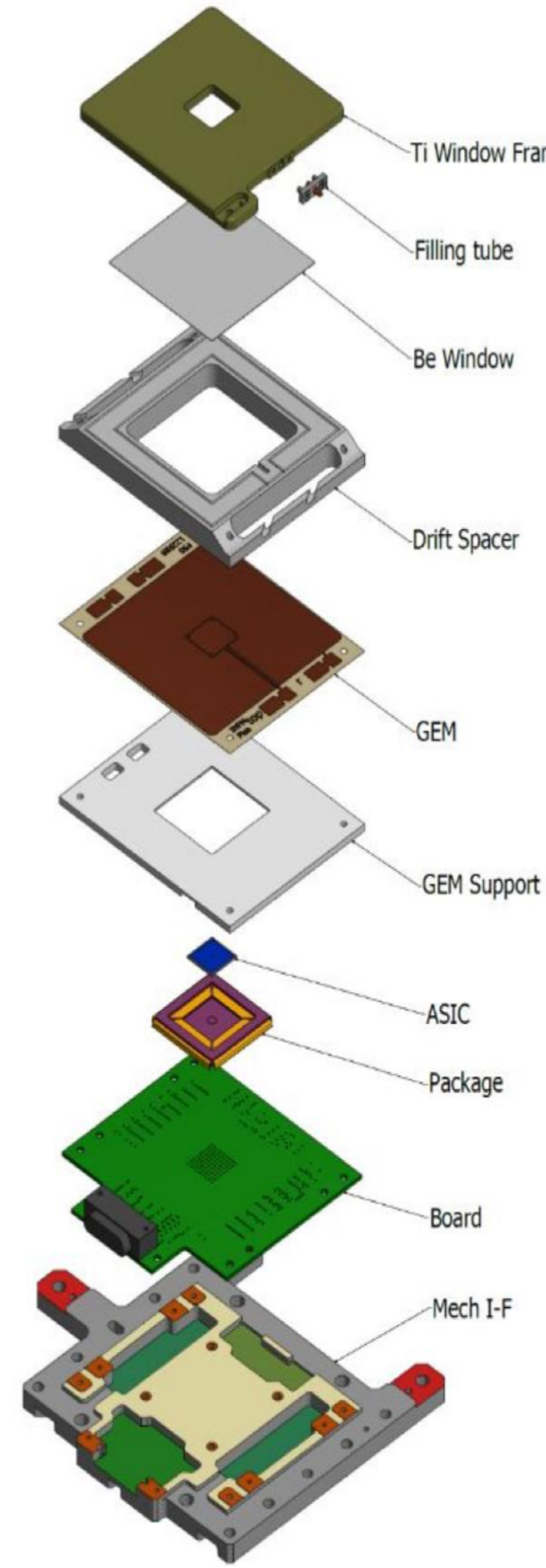
GAS PIXEL DETECTOR (GPD)



- Exploits **photo-electric effect**
  - X-ray absorption in a gas gap + photoelectron emission
- Signal amplification via a **Gas Electron Multiplier** (GEM)
- Finely pixelized **ASIC** as readout anode
- Full two-dimensional imaging and spectroscopy



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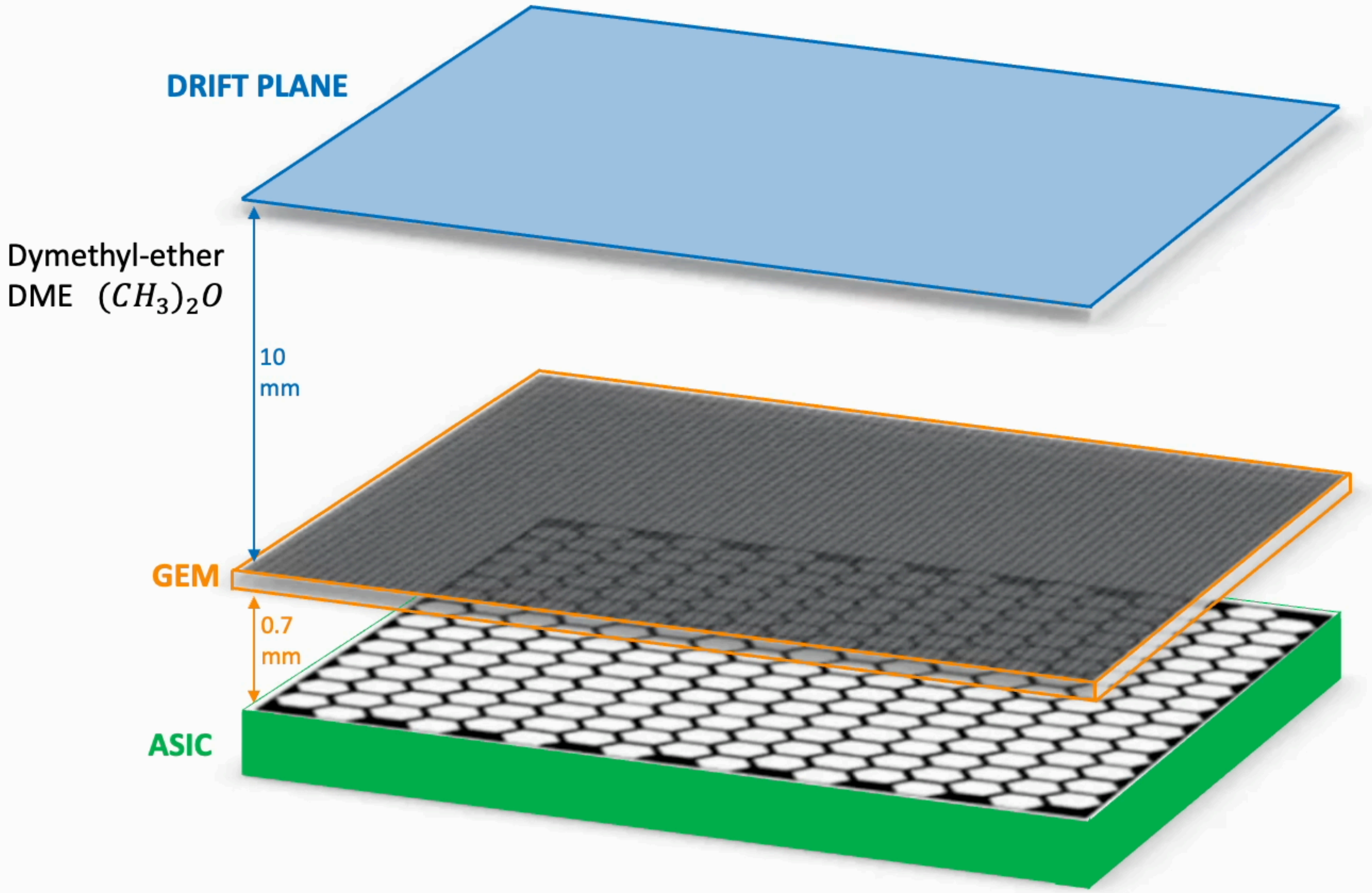
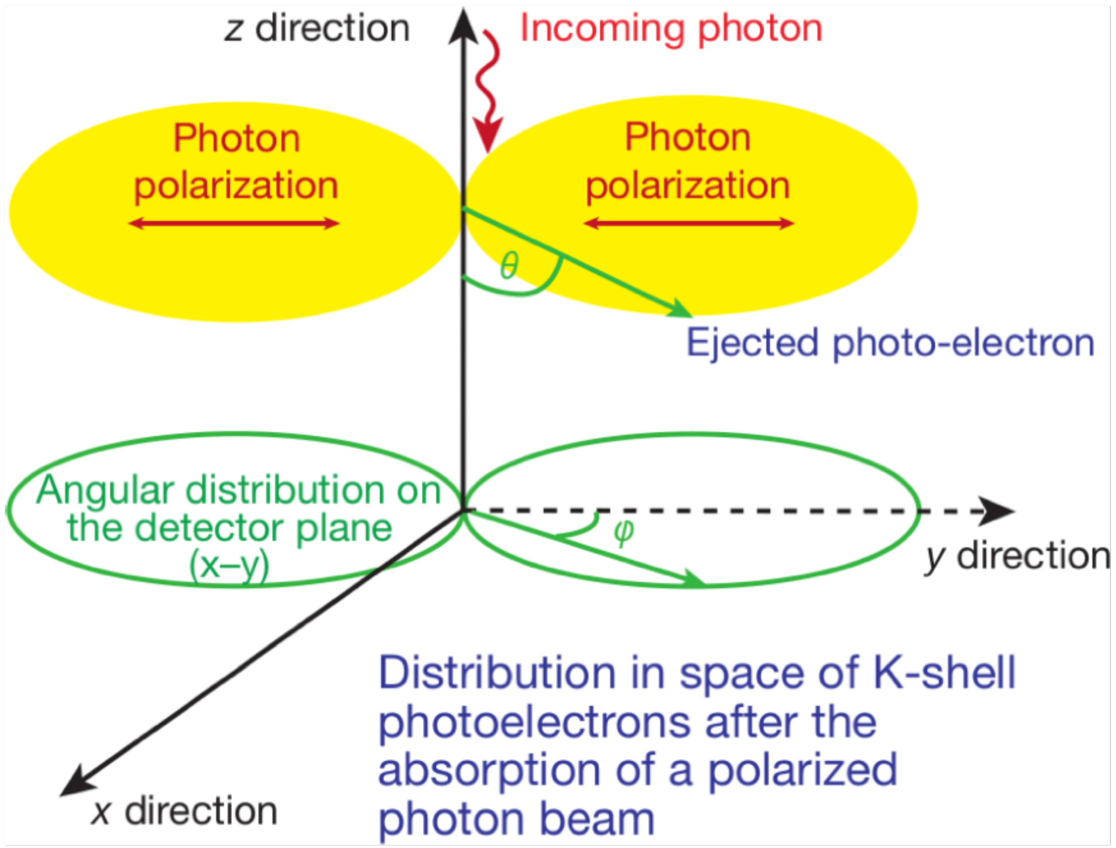


MEASUREMENT PRINCIPLE



- The **photo-electron** (phe) is ejected in a direction, which preferably lies on the oscillation plane of the X-ray electric field (i.e. the polarization direction).
- Polarization recovered on a **statistical basis**, from azimuthal distrib. of phe emission directions
- Distribution of the emission directions of a K-shell phe 100% linearly polarized radiation:

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

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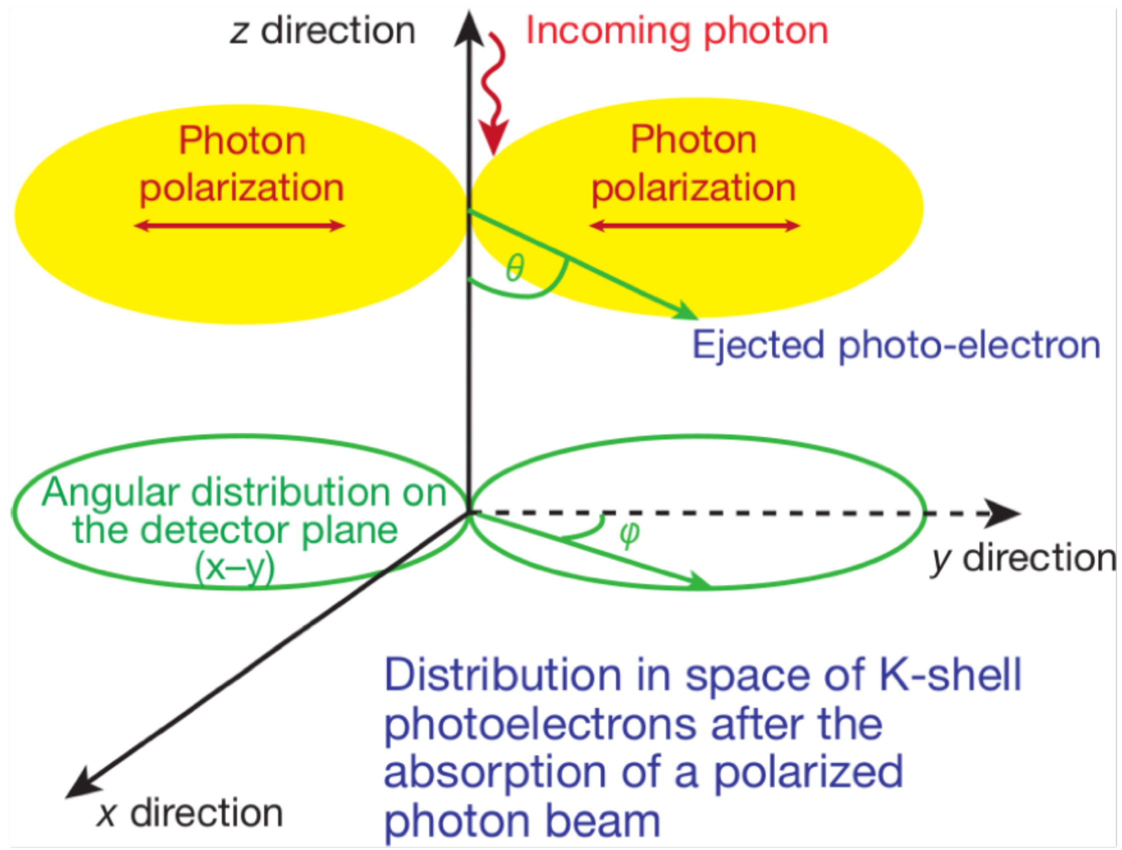

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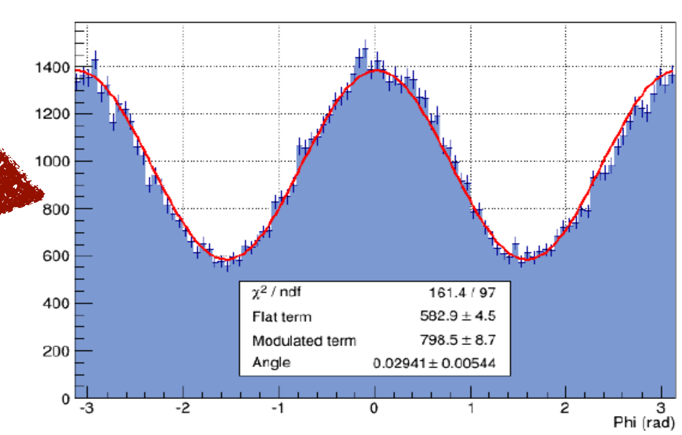

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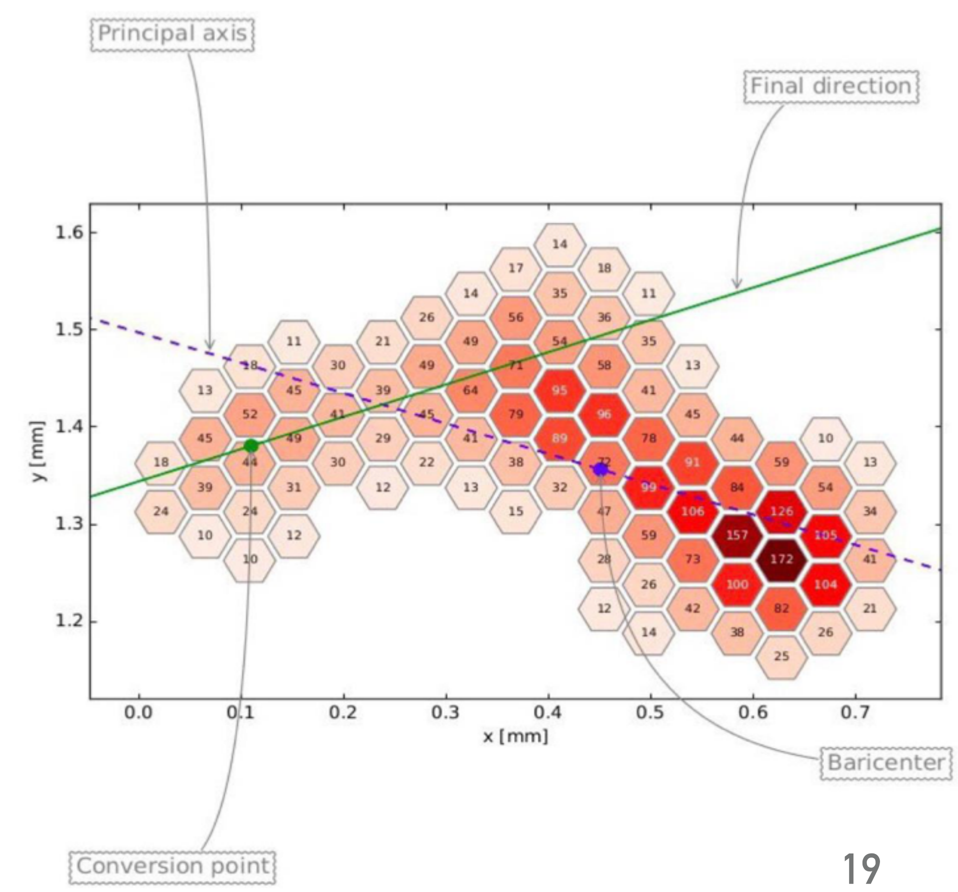
TRACK RECONSTRUCTION

- ***GOAL:*** **accurately reconstruct the direction of emission of the phe**

- Accurate sampling of the phe track requires adequate **detector granularity**; typical track lengths at keV energy are:
  - a few μm in a solid
  - a few hundreds μm in a gas → ***gas is preferred***

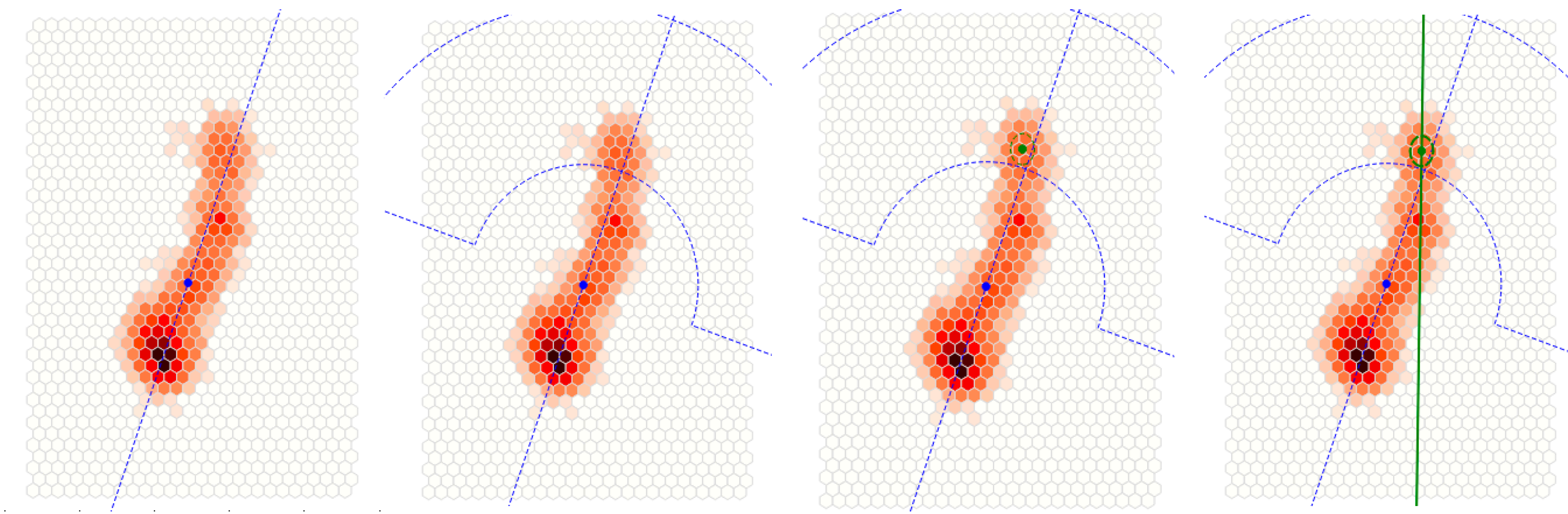
- Challenging reconstruction because of:
  - **Electron scattering** at large angle can smear out the emission direction information
  - Highest ionization density at the end of the track (*Bragg peak*) → feature used in track reconstruction



ANALYTIC ALGORITHM

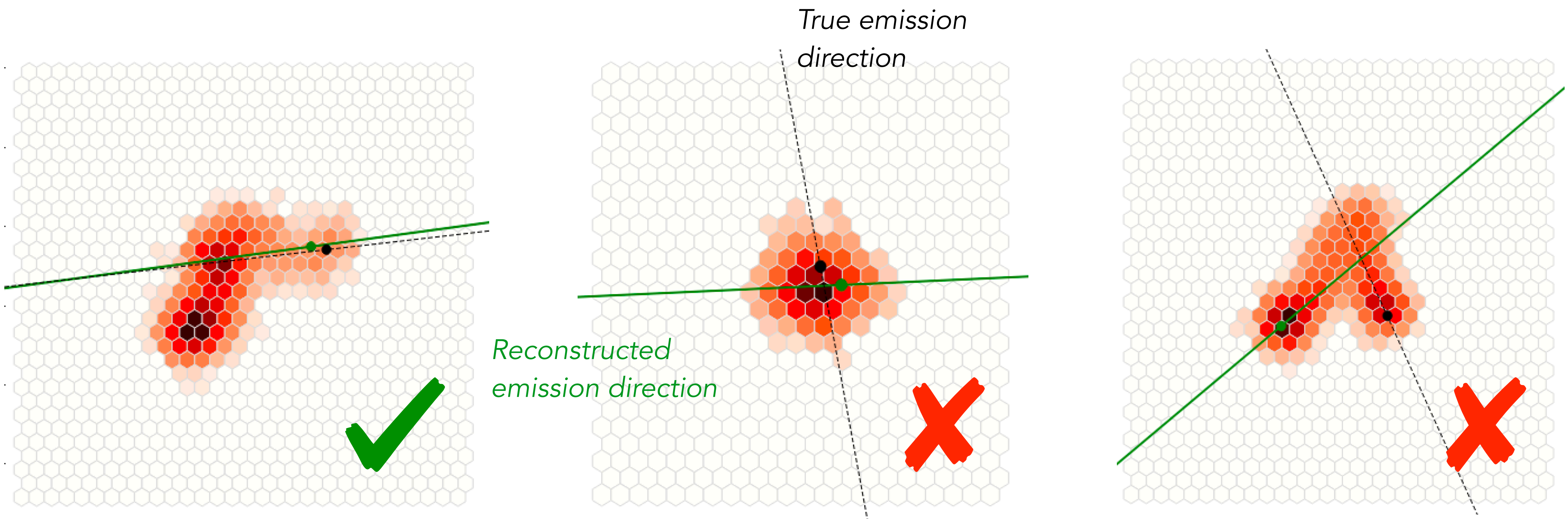
- Current algorithm used for **track reconstruction** is **analytic**:
  - it is based on the calculation of the momenta of the charge distribution.
  - first it detects the impact point, then the emission angle

1. Barycenter and second moment of the charge distribution
2. Identification of the initial part of the track
3. Reconstruction of the impact point
4. Reconstruction of the emission direction



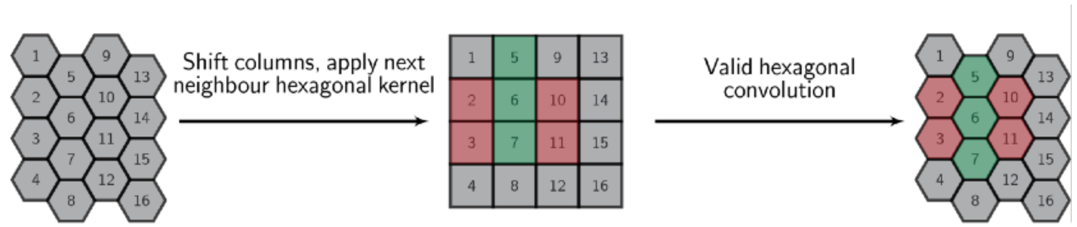
FROM AN ANALYTIC TO A MACHINE-LEARNING APPROACH

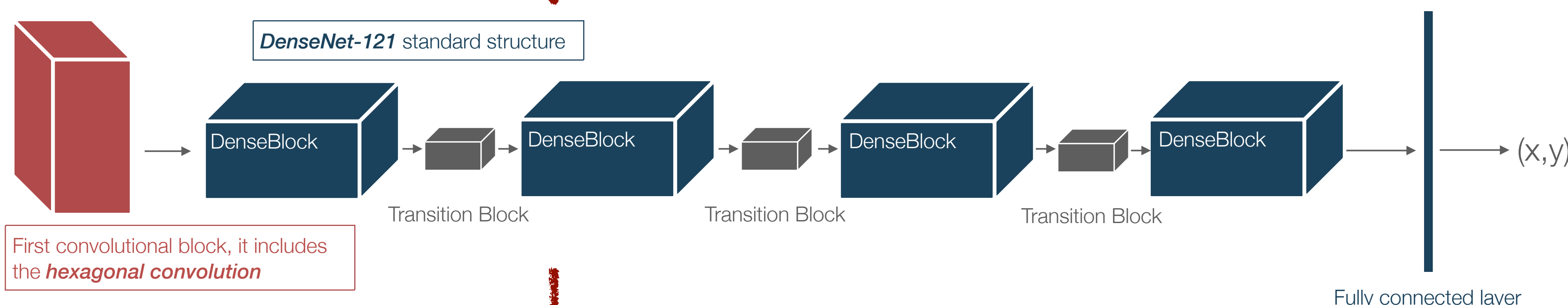
- The reconstruction of the emission angle depends on the **quality of the impact point reconstruction**

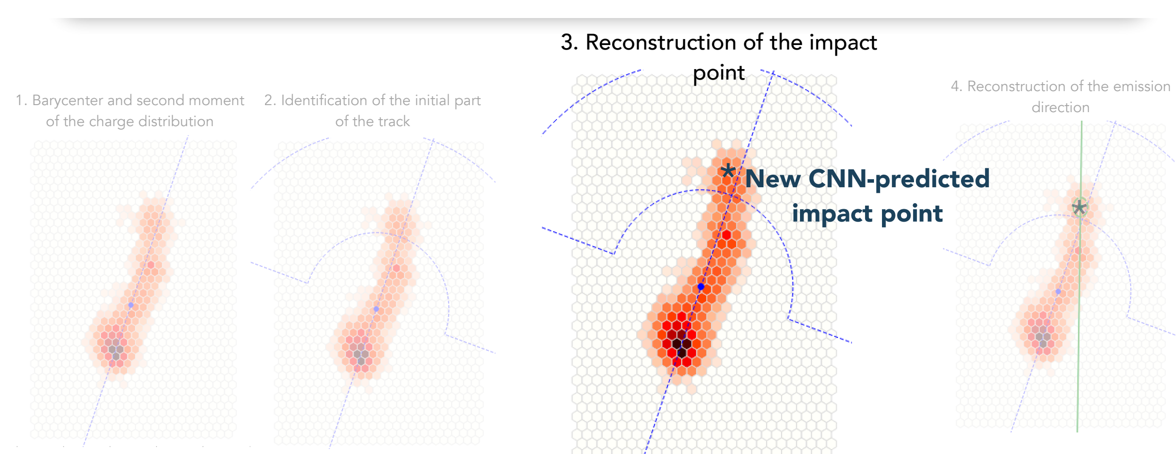


- The analytic method works but with some limitations → the potential of **ML techniques**, in particular Convolutional Neural Networks ***CNN***, has been explored (*Kitaguchi et al. 2019, Moriakov et al. 2020, Peirson et al. 2021*)

HYBRID ALGORITHM







N. Cibrario et al., A&A 674, A107 (2023)

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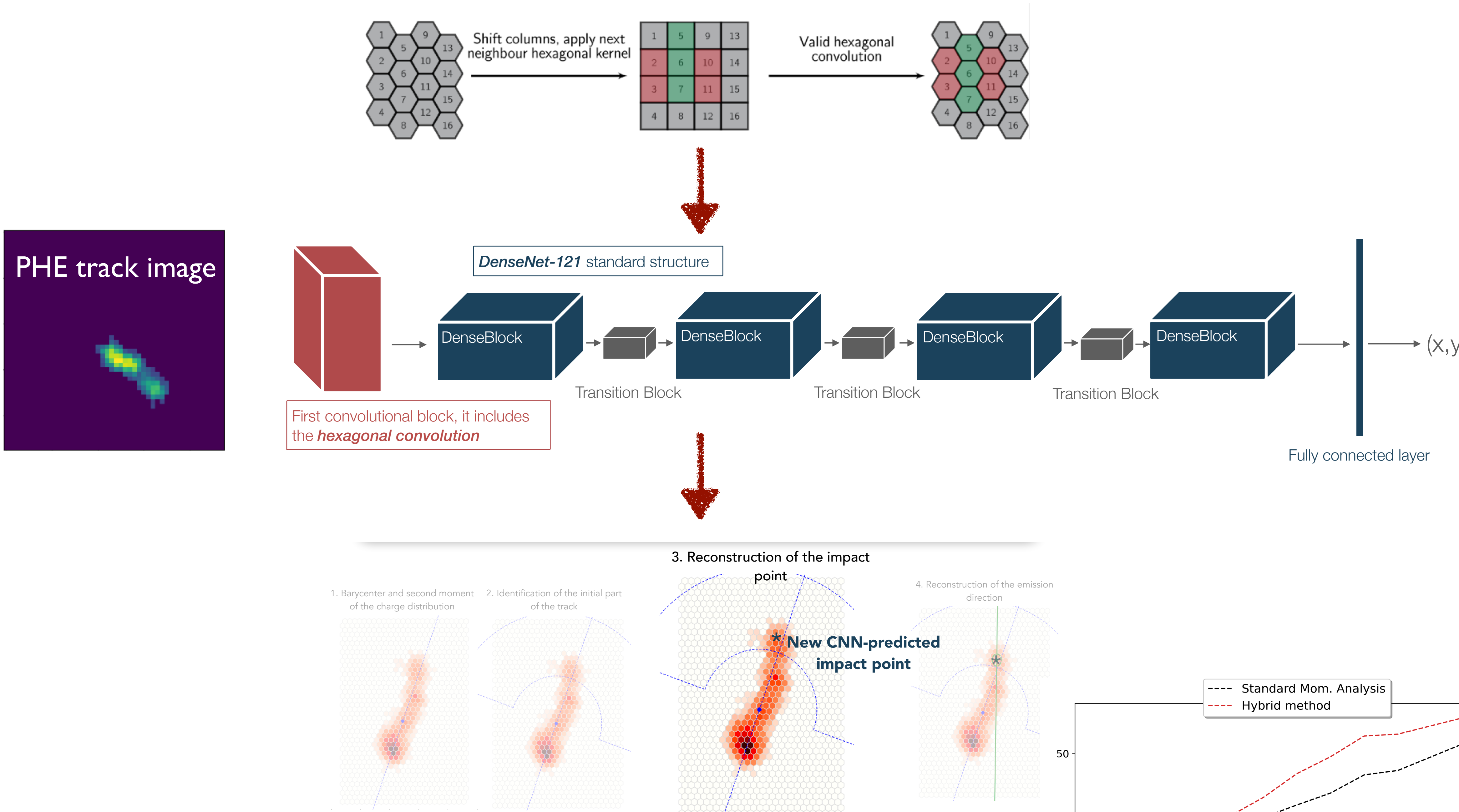

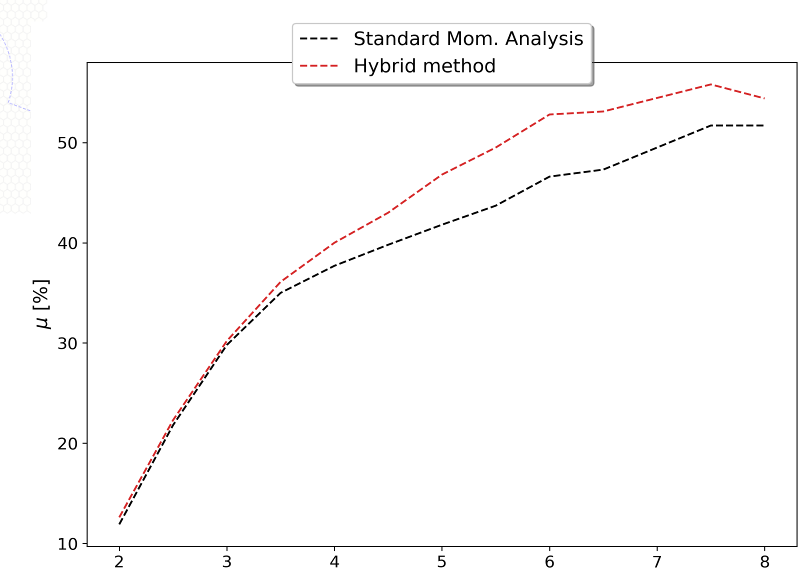

- ***MODULATION FACTOR:*** the response to a 100% polarized source, i.e. the **fraction of modulation recovered** by the algorithm

N. Cibrario et al., A&A 674, A107 (2023)

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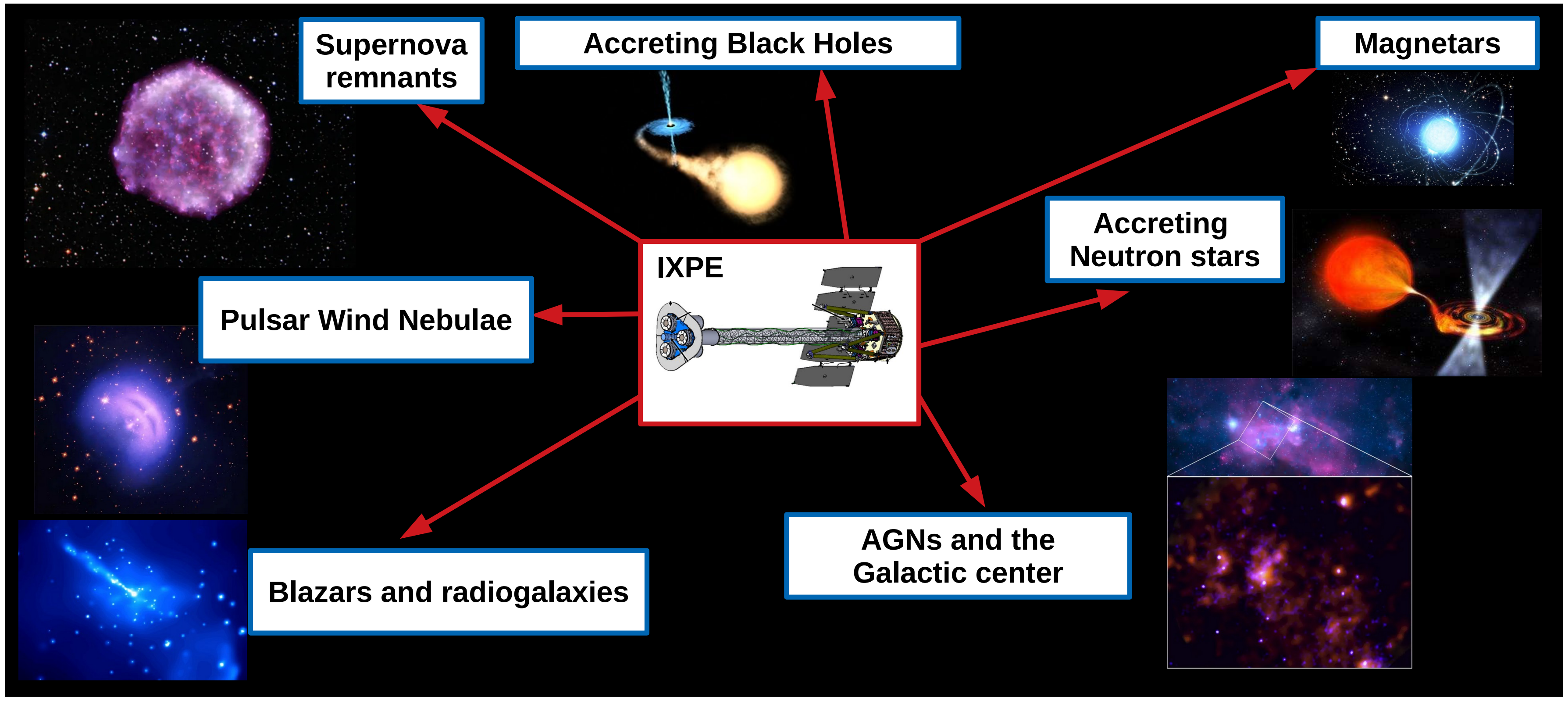
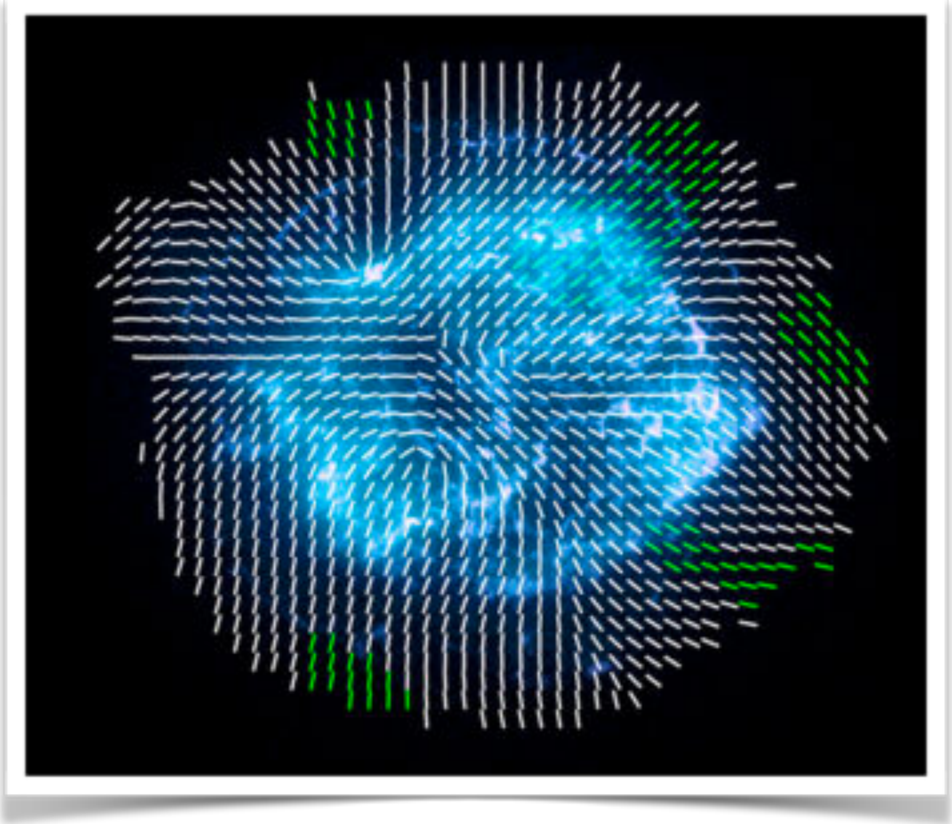
IXPE CAPABILITIES

Sensitivity to polarization *(Minimum Detectable Polarization)*	$MDP_{99\%}$< 5.5%, 0.5 mCrab, 10 days
Angular resolution	< 30"
Field of view (FOV)	12.8' x 12.8'
Energy resolution	≈ 17% @ 5.9 keV
Timing accuracy	≈ 20 µs

- **Unique and powerful X-ray polarization capabilities** → crucial insights into our understanding of X-ray production and the geometry of multiple classes of objects



FIRST IXPE SCIENCE TARGET: SNR CASSIOPEIA A

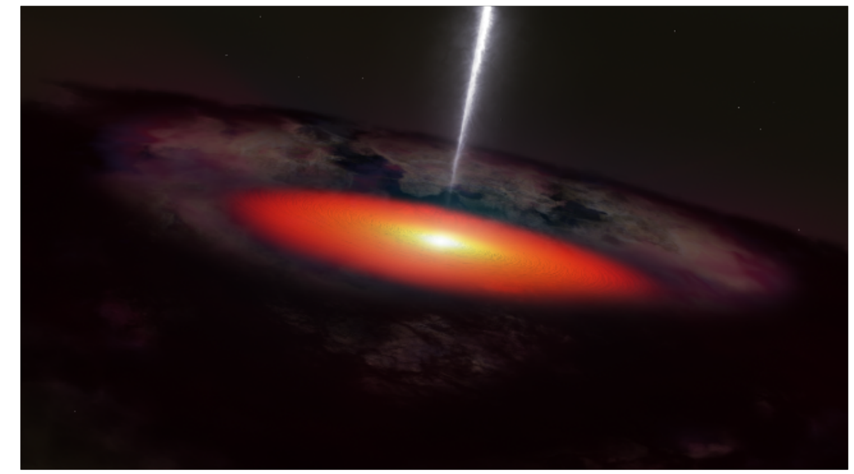


- Overall polarization degree (**PD**) = **1.8±0.3% (5σ)** in the 3-6 keV energy range, by summing over a large region and assuming circular symmetry for polarization vectors
  - *polarization angle* corresponds to a radially-oriented magnetic field, similarly to radio obs. results;
  - *polarization degree* is lower than in the radio band (~ 5%).
- The polarization vectors suggest an **overall radial magnetic-field orientation**

Vink et al. 2022 ApJ

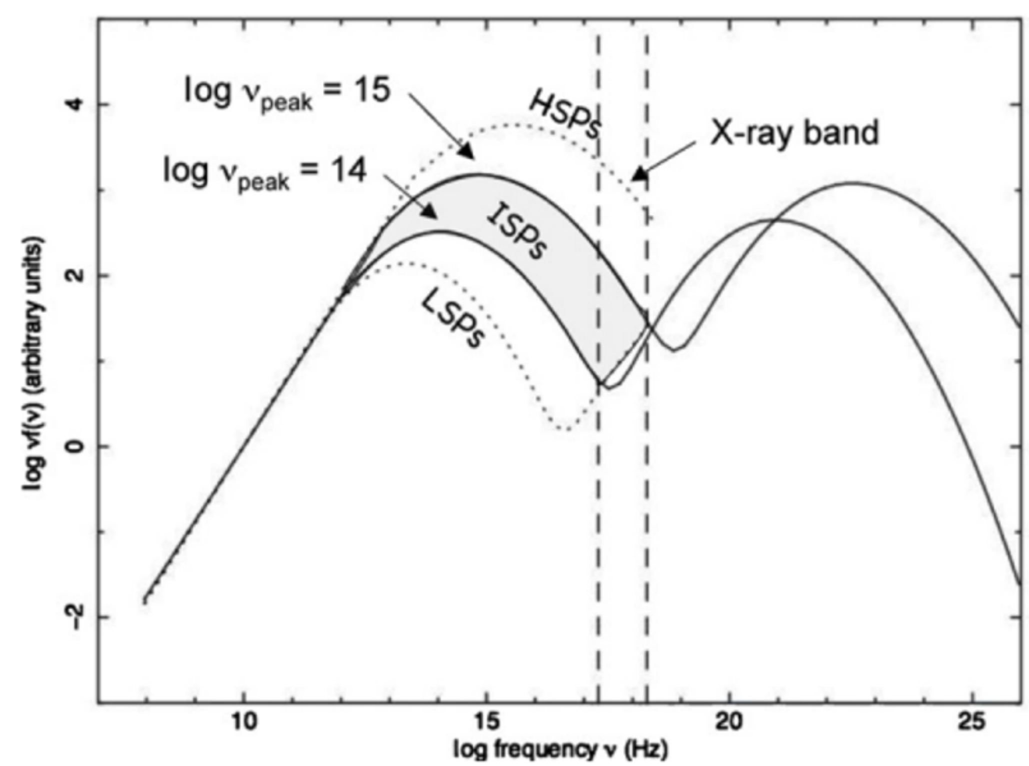
BLAZARS AND RADIO GALAXIES

- **Unique insights into particle acceleration in AGN jets** → when combined with MWL observations, we can break degeneracies - impossible without polarization data



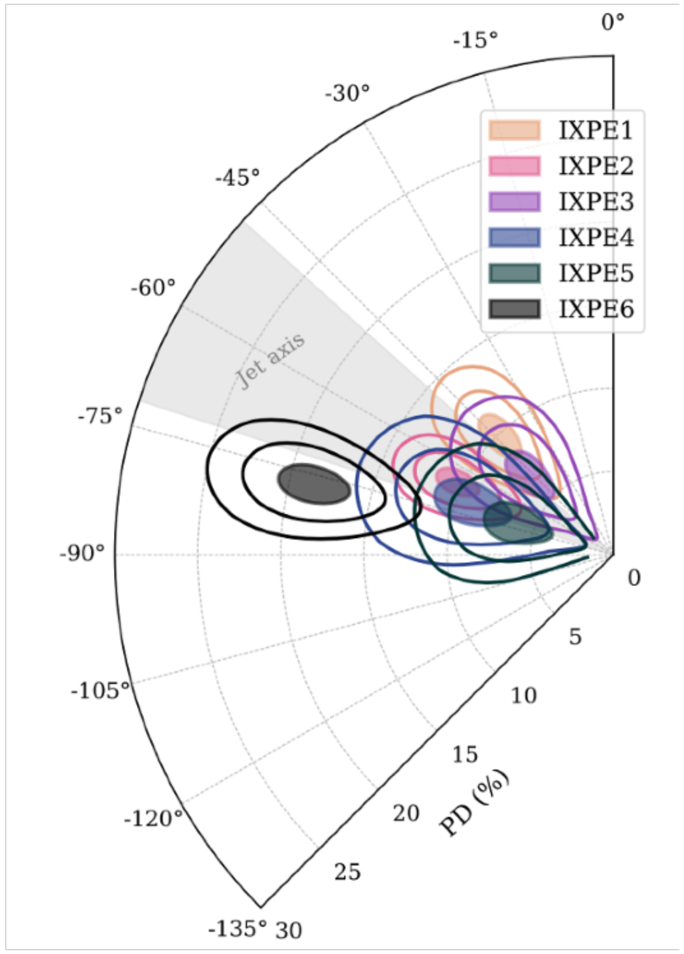
- ~ 20 blazars and radio galaxies observed with IXPE

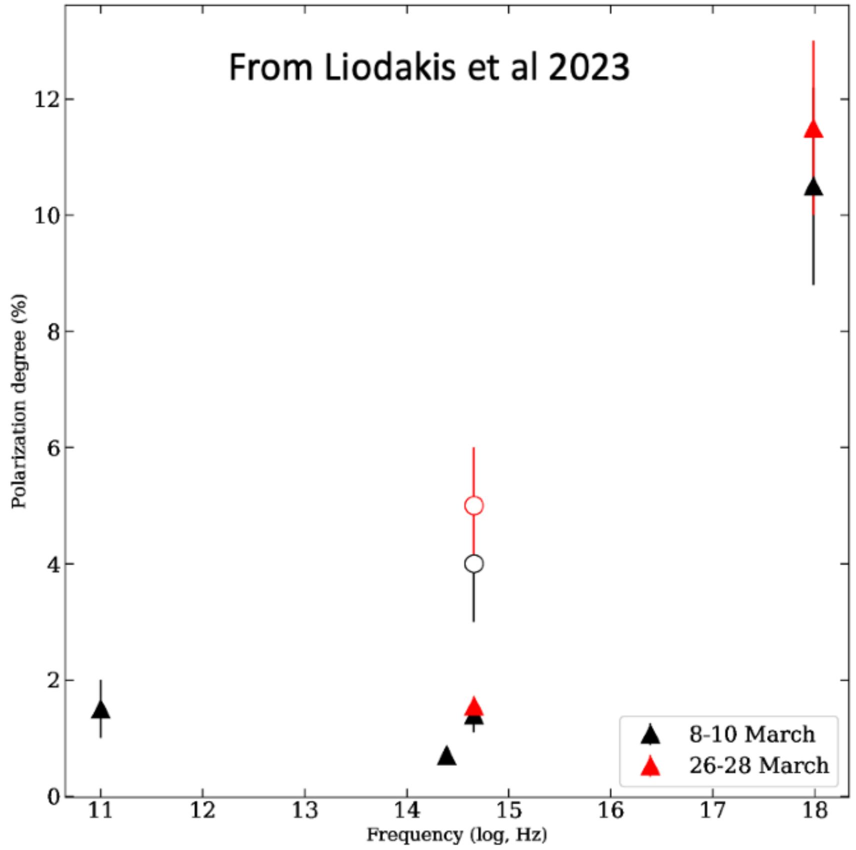
Name	Type	Obs #	Total Exposure (ks)	Polarization Detected?
Mrk 501	HSP	6	595	Y
Cen A	Radio Gal	1	100	N
Mrk 421	HSP	8	893	Y
BL Lac	HSP	4	1222	Y*
3C 273	LSP	1	95	N
3C 279	LSP	1	265	N
3C 454.3	LSP	2	99	N
S5 0716+714	LSP	1	359	N
1ES 0229+200	HSP	2	401	Y
PG 1553+113	HSP	2	130	Y
1ES 1959+650	HSP	2	254	Y
PKS 2155-304	HSP	1	476	Y
S4 0954+65	LSP	1	505	N



FIRST BLAZAR RESULT PUBLISHED: MRK 501

- 1st observation: PD of 10% and PA in line with the radio jet axis (*Liodakis et al 2022, Nature*)
- Mostly **steady behavior** from subsequent observations, except for a PD of 17% in the 6th observation (*Chen et al 2024*).

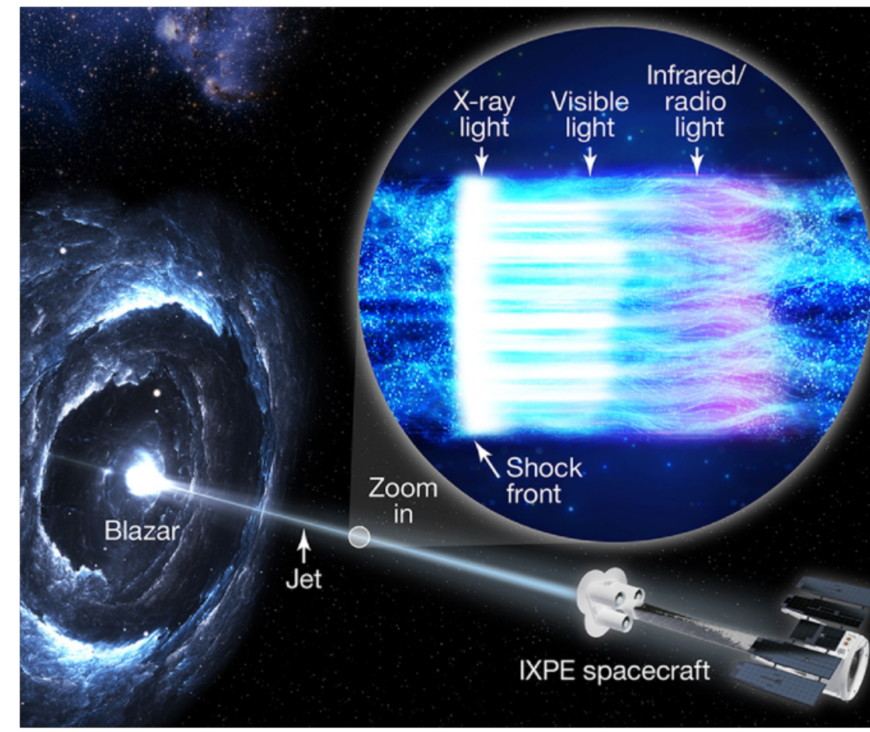


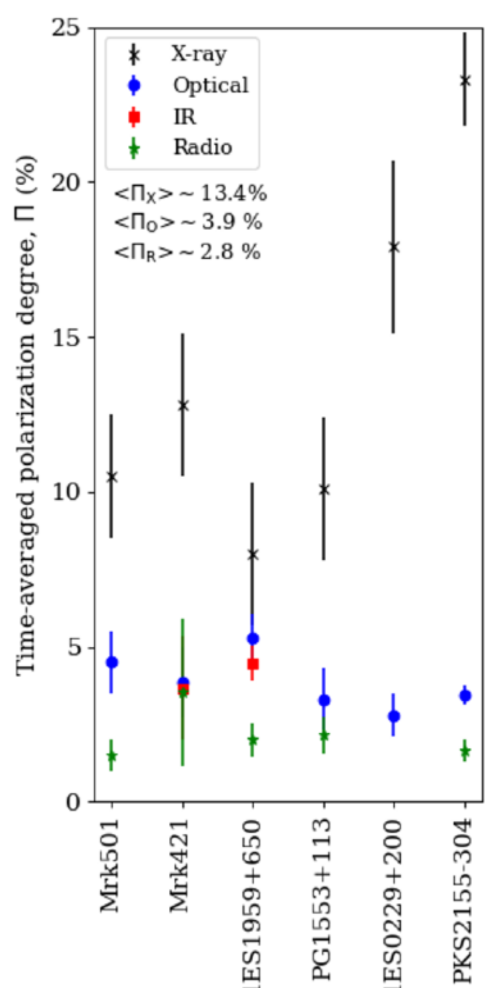


- **PD higher in X-ray than in optical and radio**

FIRST BLAZAR RESULT PUBLISHED: MRK 501

- **MWL simultaneous observations**:
  - pol. degree higher in X-ray than in optical and radio
  - consistent with **energy-stratified emission model:**
    - X-rays are produced by electrons accelerated in *ordered B fields* just after the shock,
    - optical and radio ph are generated further downstream in regions with *more turbulent B fields*.

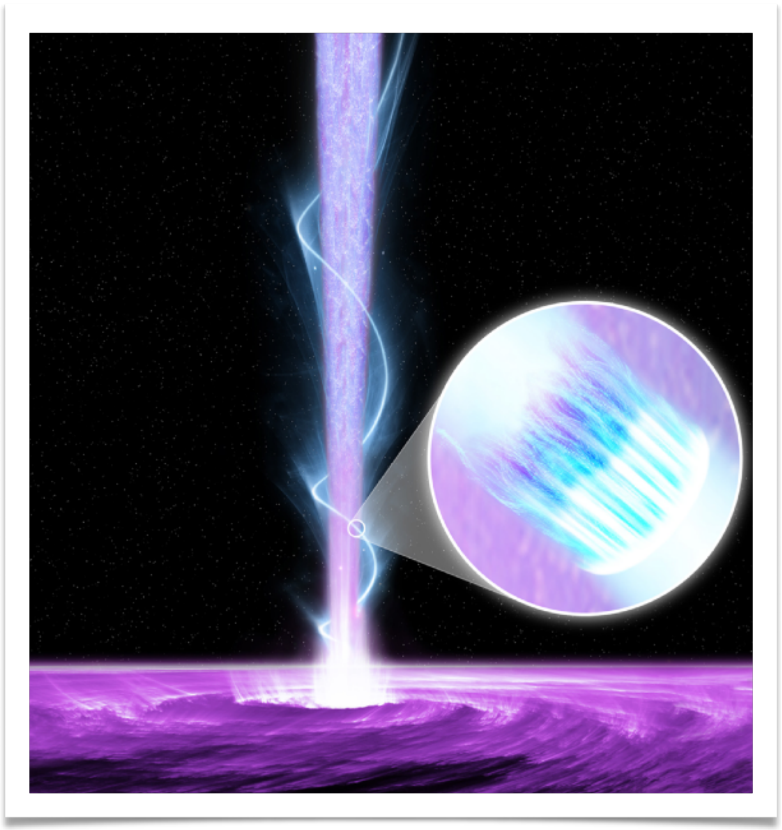


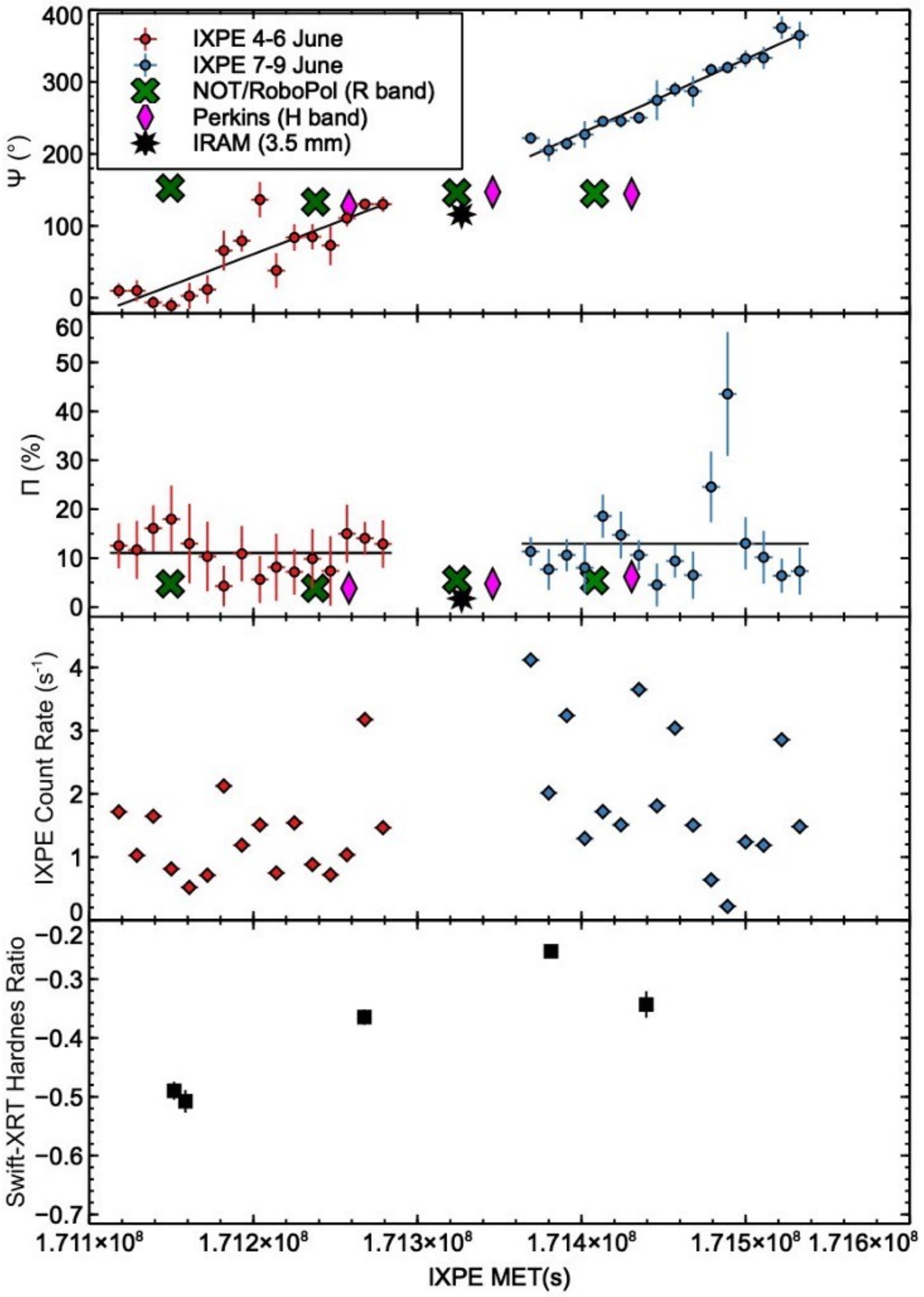


- **Similar behavior for the majority of HSP's**

BLAZARS MRK 421

- PD ~ 10%
- Discovery of **PA rotating at rate 80°/day**
  - No similar rotation at longer λ → X-ray emitting site not completely overlapped wrt radio, IR and optical one
  - Explained with a **helical magnetic structure in jet**, illuminated by shock propagating along the helix.

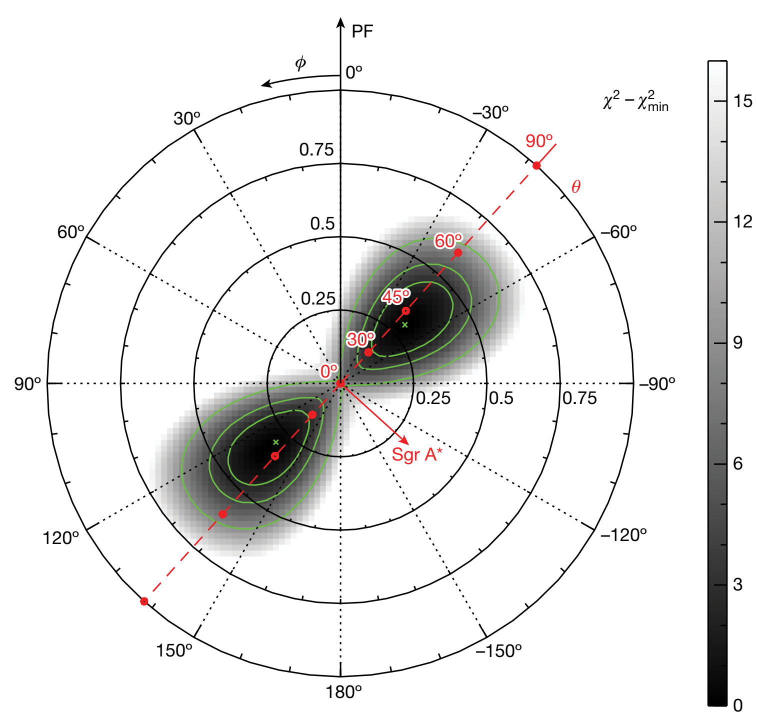


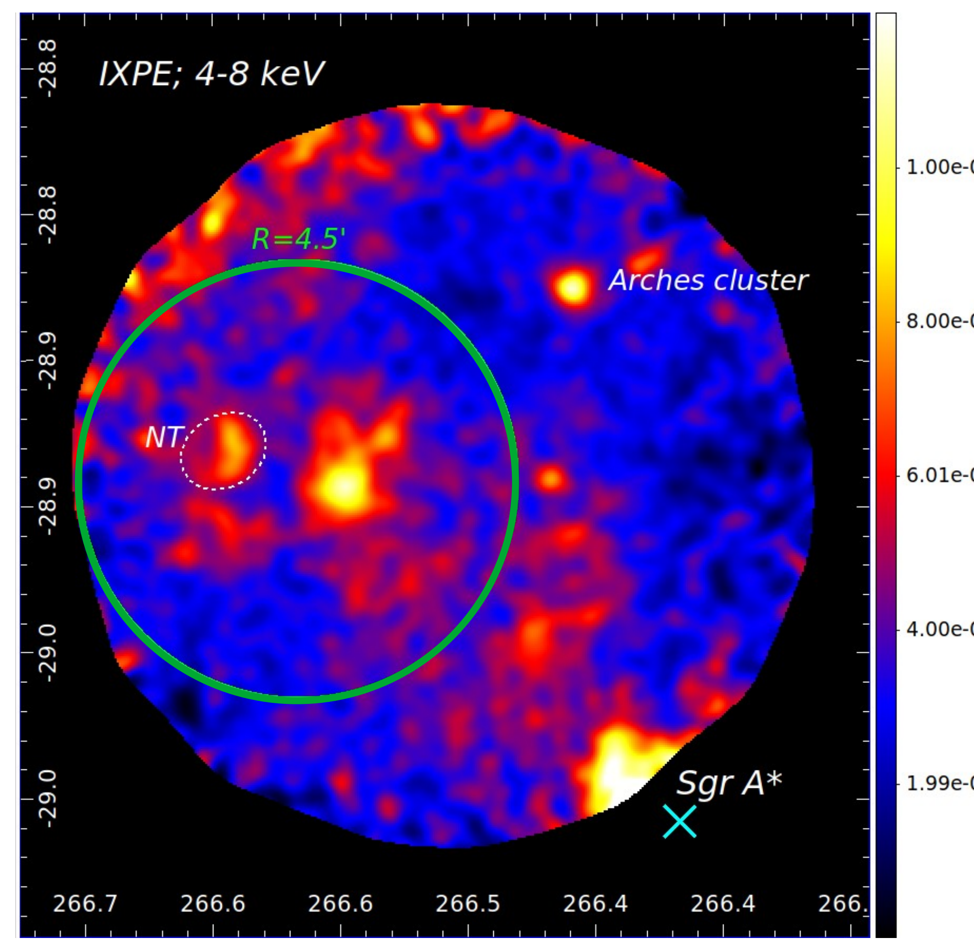


Di Gesu et al. 2022, ApJL; Di Gesu et al. 2023, Nat. Astr.

SGR A*

- GC hosts a BH of ~ 4 10^6 M_{SUN}, quiescent at present, with a luminosity << ordinary AGN:
  - Local sources fail to explain the bright X-ray emission observed in molecular clouds near GC
  - Possible explanation: **reflection of past hard X-ray flares** by dense gas in the GC region → reflected X-ray emission should be highly polarized and the PA should point back to GC
- IXPE observed **polarized X-ray emission** in the direction of molecular clouds in GC:
  - PA = - 48° ± 11° → **consistent with Sgr A***
  - PD = 31% ± 11% → 200 years ago Sgr A* briefly had X-ray luminosity comparable to Seyfert galaxy

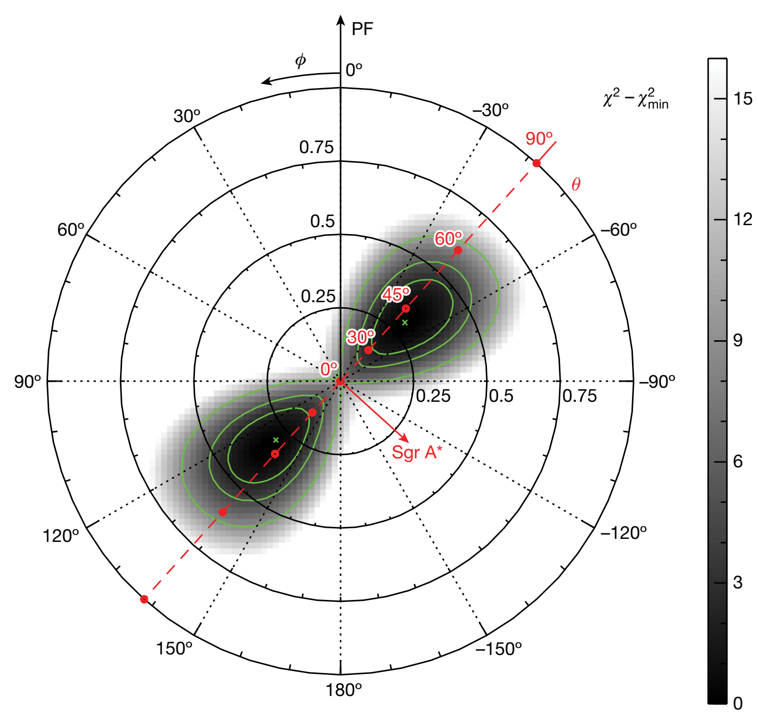


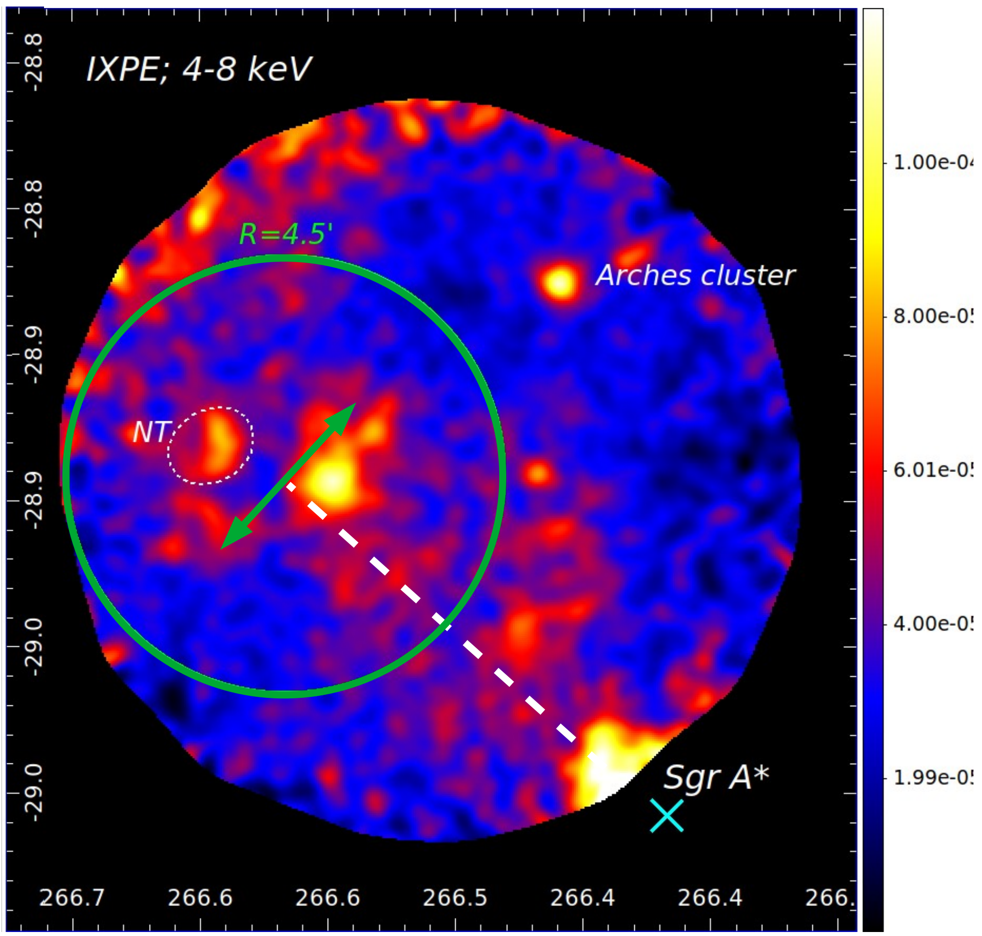


Marin et al. 2023 Nature

SGR A*

- GC hosts a BH of ~ 4 10^6 M_{SUN}, quiescent at present, with a luminosity << ordinary AGN:
  - Local sources fail to explain the bright X-ray emission observed in molecular clouds near GC
  - Possible explanation: **reflection of past hard X-ray flares** by dense gas in the GC region → reflected X-ray emission should be highly polarized and the PA should point back to GC
- IXPE observed **polarized X-ray emission** in the direction of molecular clouds in GC:
  - PA = - 48° ± 11° → **consistent with Sgr A***
  - PD = 31% ± 11% → 200 years ago Sgr A* briefly had X-ray luminosity comparable to Seyfert galaxy





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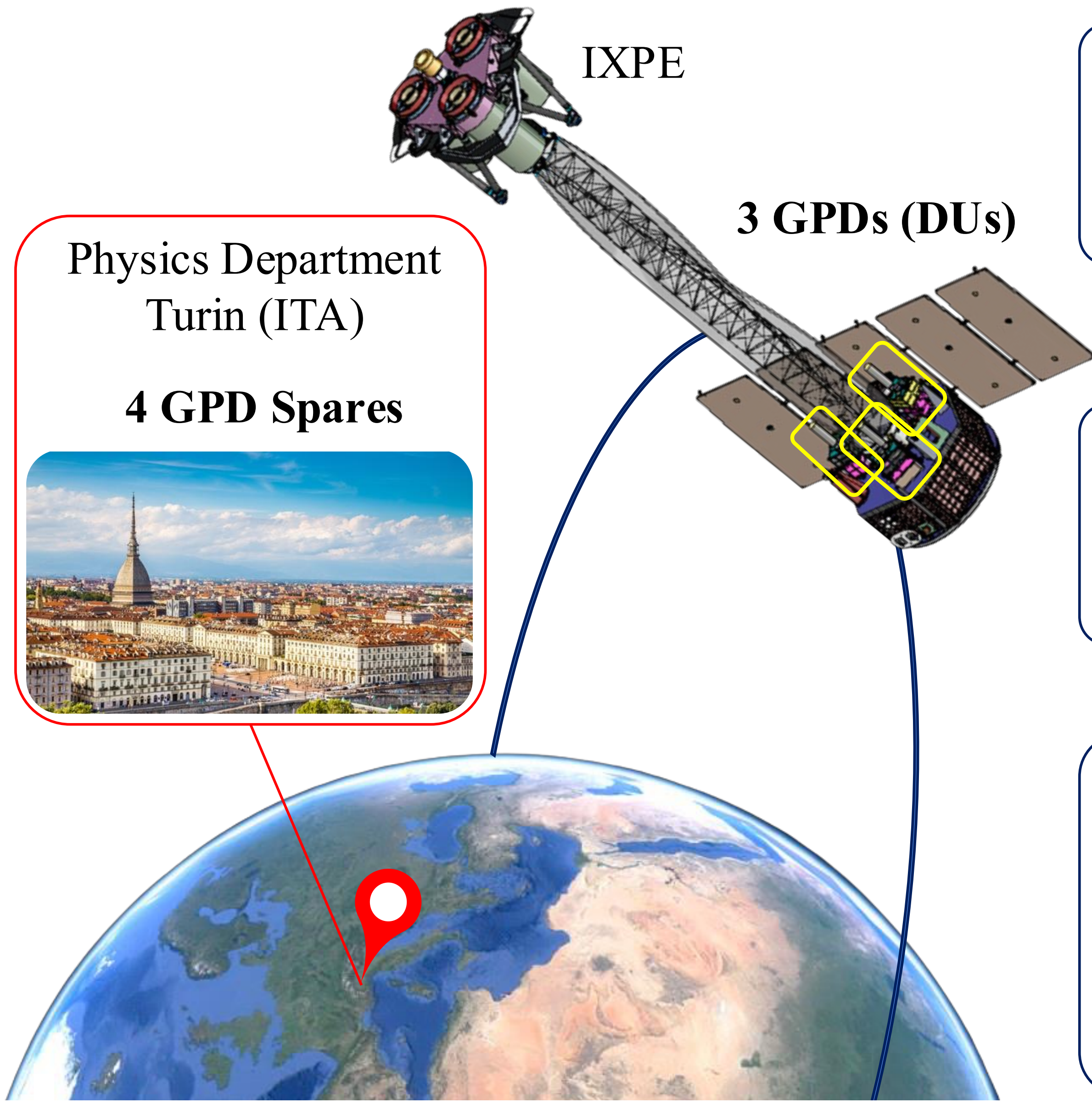
OUTLINE

- **X-ray polarimetry** and **astrophysical context**
- **IXPE**
  - Gas Pixel Detector (GPD)
  - Track reconstruction algorithm
  - Scientific results
- **X-ray Calibration Facility (XCF)** for R&D of future X-ray detectors

X-RAY CALIBRATION FACILITY (XCF) @ UNIV. OF TURIN



Space

GPDs → Only space-qualified detectors currently used for X-ray polarization

Ground

Systematic testing and monitoring on GPD spares → Essential in view of future X-ray polarimeters

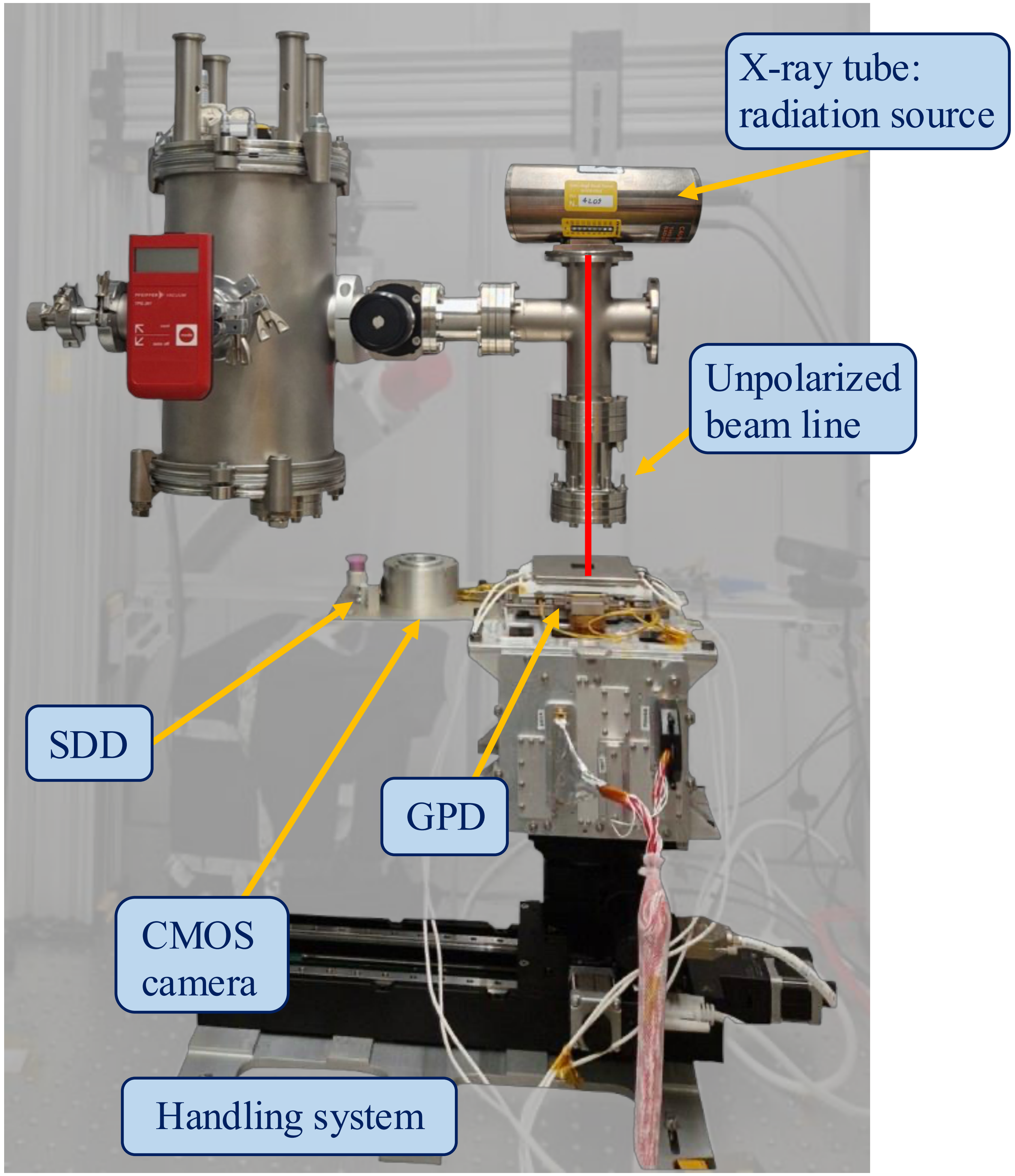
We need a facility that provides photon beams with various spatial and energy configurations and offering both unpolarized and linearly polarized beams

↓

XCF

X-RAY CALIBRATION FACILITY (XCF) @ UNIV. OF TURIN

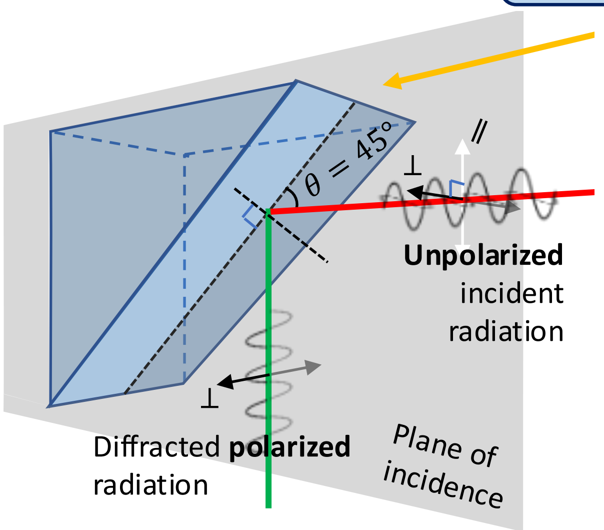
XCF: UNPOLARIZED BEAM LINE

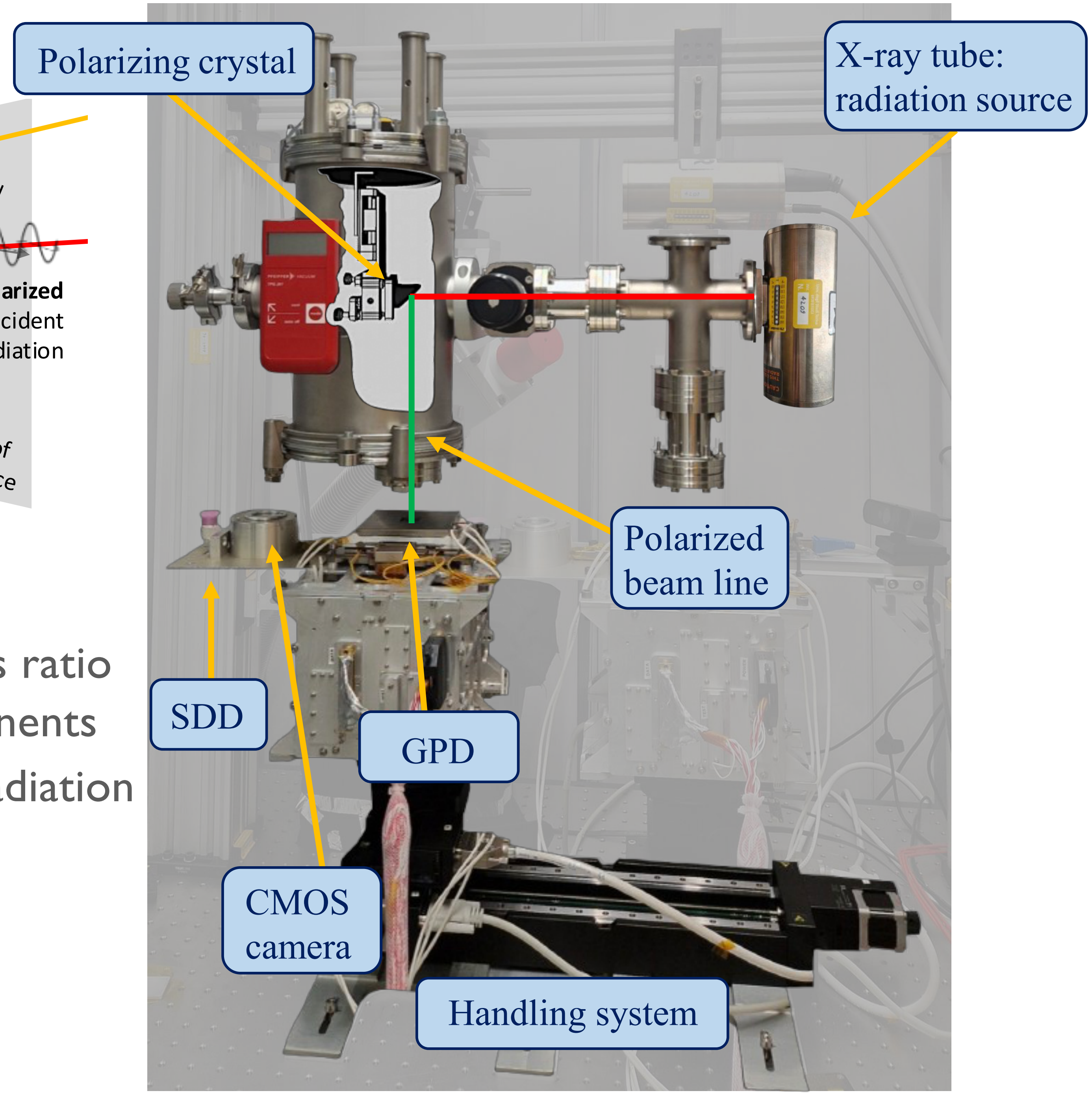


XCF: POLARIZED BEAM LINE

Bragg diffraction:

$$E = \frac{hc}{2d\sin\theta_{Bragg}}$$



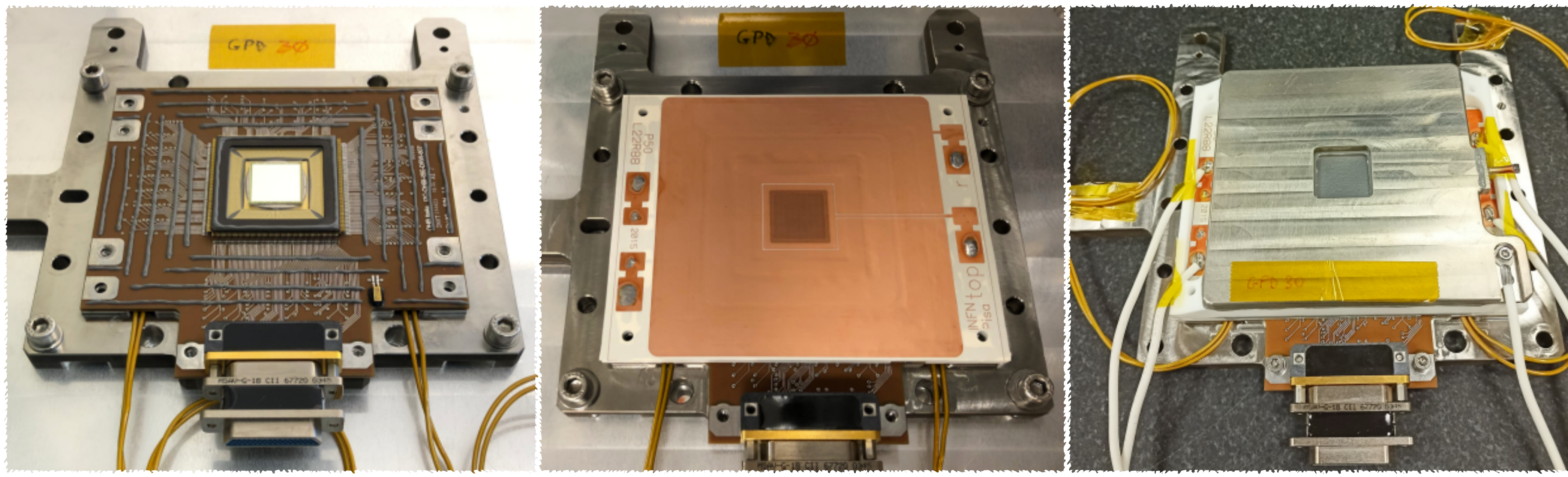


- Polarization degree is: $P = (1-k)/(1+k)$, k is ratio of the integrated reflectivities of the 2 components
- For k = 0, i.e. $\theta = \theta_{Bragg} = 45°$ → 100% pol. radiation

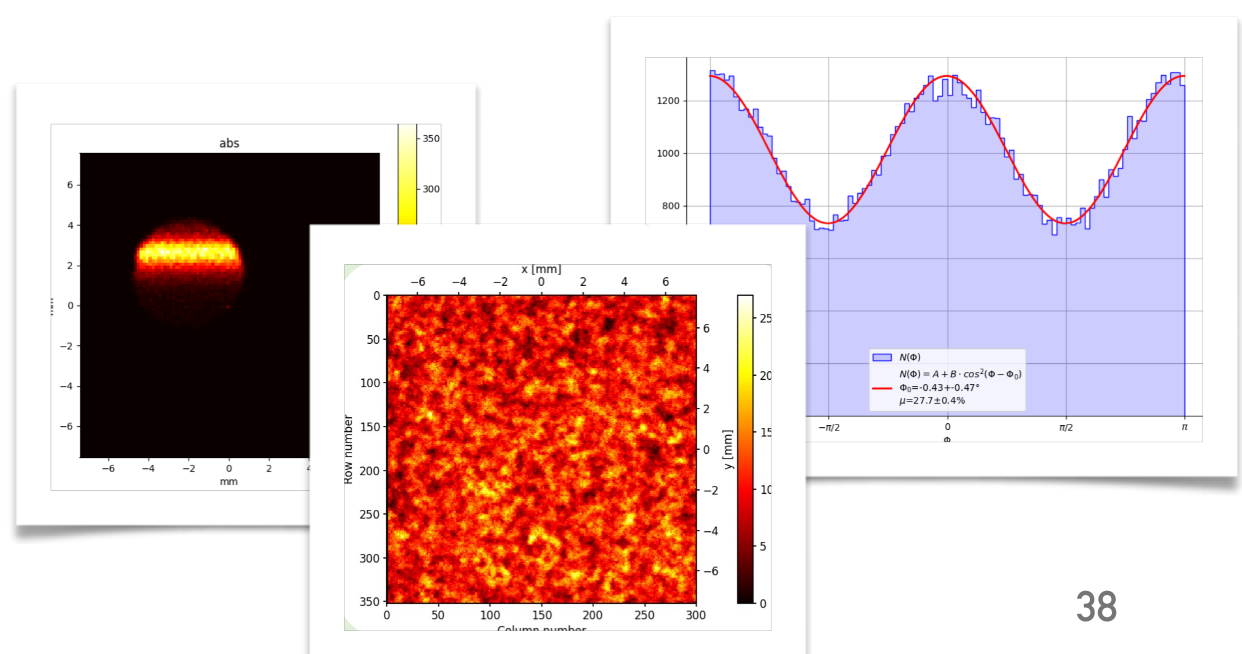
Anode line	E [KeV]	Xtal	2d (A)	θBragg	P
Mo Lα	2.2932	InSb111	7.481	46.28	99.32%
Rh Lα	2.697	Ge111	6.532	44.87	99.28%
Pd Lα	2.839	Si111	6.271	44.12	>95.08%
Ti Kα	4.511	Si 220	3.840	45.71	99.51%
Fe Kα	6.404	Si 400	2.7142	45.5	99.7% ??
Ni kα	7.478	Ge 422	2.31	45.86	99.04%

XCF PRESENT AND FUTURE

- XCF has been conceived to:
  - **qualify Gas Pixel Detectors** developed for astrophysical missions of present (i.e. IXPE) and future generation



  - support **R&D programs of innovative** position-, energy- and polarization-sensitive **X-ray detectors**



CONCLUSIONS

- IXPE has produced (and will continue to produce) **outstanding science**:
  - simultaneous imaging, spectral, timing, and polarization data for 2-8 keV X-rays
  - unique and powerful X-ray polarization capabilities and has been providing crucial insights into our understanding of X-ray production and the geometry of multiple classes of objects.
- Baseline 2-year mission completed, now in **General Observer (GO) program phase**
  - First 2 calls for GO proposals released in summer 2023 and 2024, pre-proposal workshop in preparation for the 3rd cycle
  - General Observer Facility at GSFC to administer IXPE GO Program
  - HEASOFT analysis tools and documentation (including quick start guide) at GSFC GOF
  - IXPE Mission Partners execute and process observations, archive to HEASARC
  - NASA policy: no exclusive-use period (can request 6 months exclusive use)

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- **Istituto Nazionale di Fisica Nucleare**
- **Agenzia Spaziale Italiana**