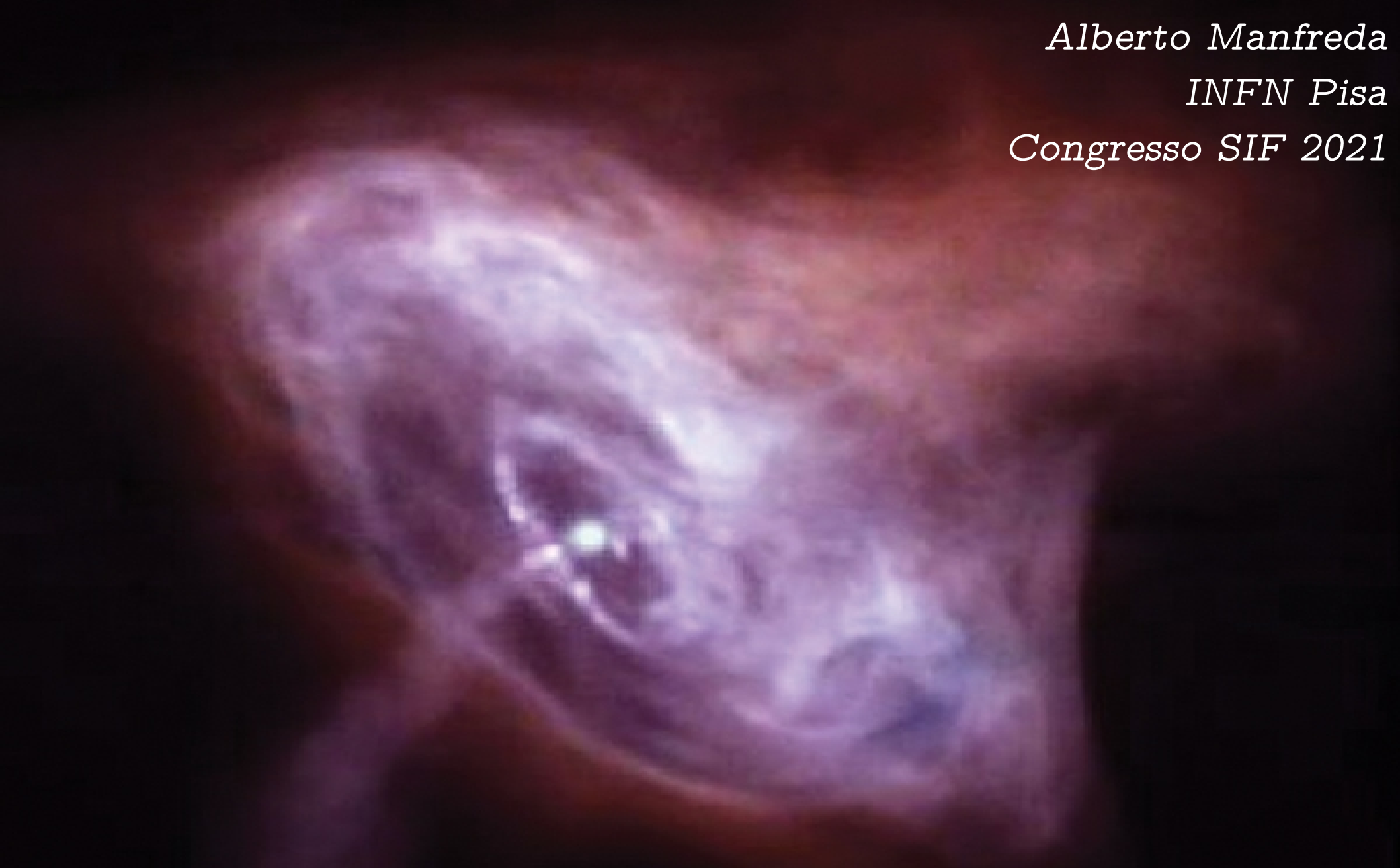
Alberto Manfreda
INFN Pisa
Congresso SIF 2021



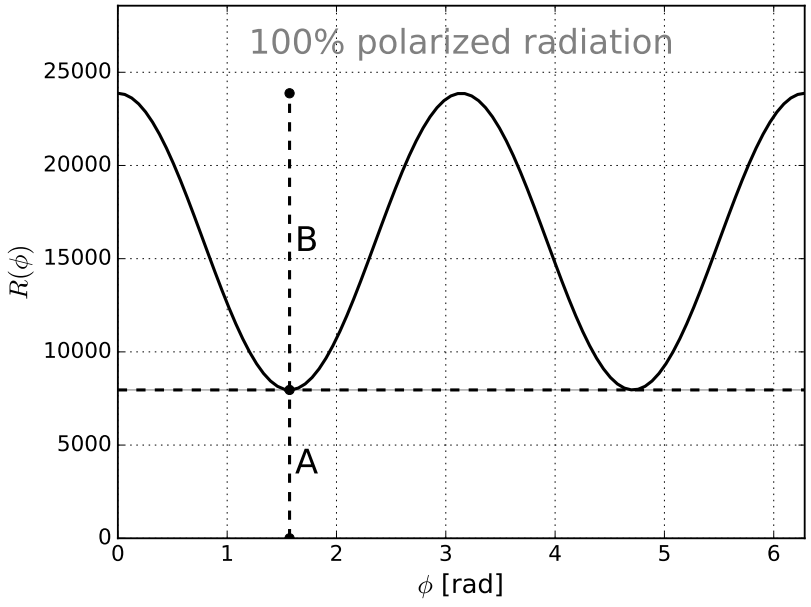
Nuove prospettive per l'astronomia X nello spazio

A new era for X-ray timing and polarimetry

- **Photoelectric-based polarimetry** (Gas Pixel Detectors)
  - Reopen the window for soft X-ray polarimetry after 40 years
  - PolarLight mission (2018)
  - IXPE mission, to be launched in December

- **Large area Silicon Drift Detecors** (SDD)
  - Enable wide surfaces covering with low mass and power budget
  - New detector concept: large effective area, low dead time
  - e-XTP mission proposal, to be launched in late 20's
  - An order of magnitude increase in timing sensitivity

The challenge of X-ray polarimetry



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

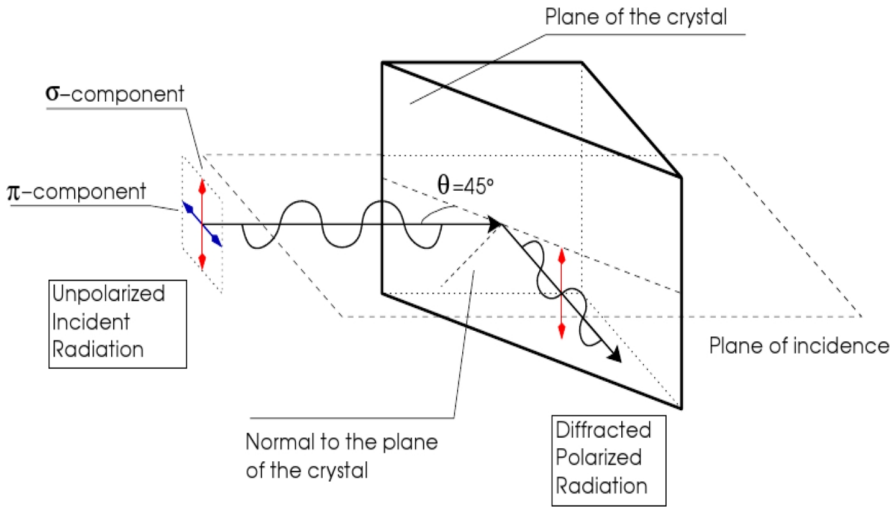
$$\mu = \frac{R_{\max} - R_{\min}}{R_{\max} + R_{\min}} = \frac{B}{B + 2A}$$

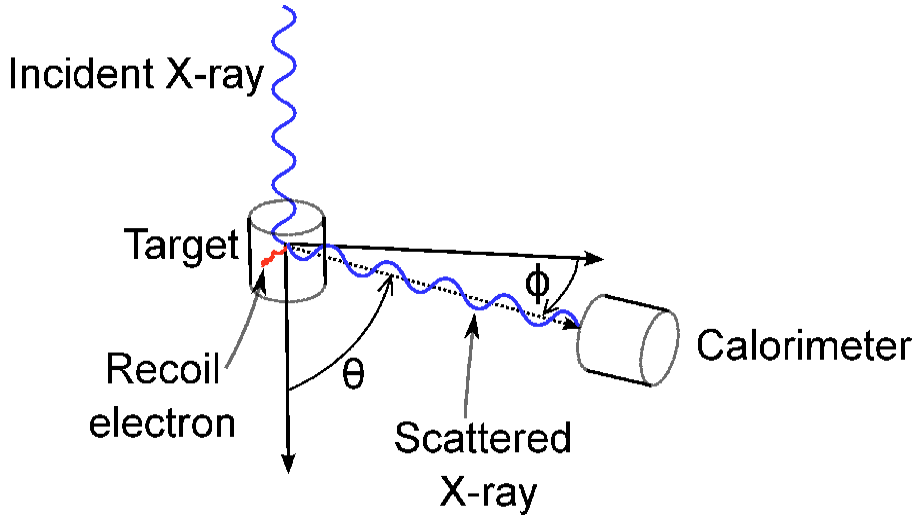
$$MDP_{99\%} = \frac{4.29}{\mu R}\sqrt{\frac{R + B}{T}}$$

- Photon greedy (~100k photons per source)
- Sensitive to detector systematics
- Significantly measured for only 1 source (Crab Nebula):
  - pol. deg. = (19.2 ± 1.0)%
  - pol. ang. = (156.4 ± 1.4)°

Weisskopf et al., ApJ 220, 1978 (L117)

Conventional X-ray polarimetric techniques





Bragg diffraction:

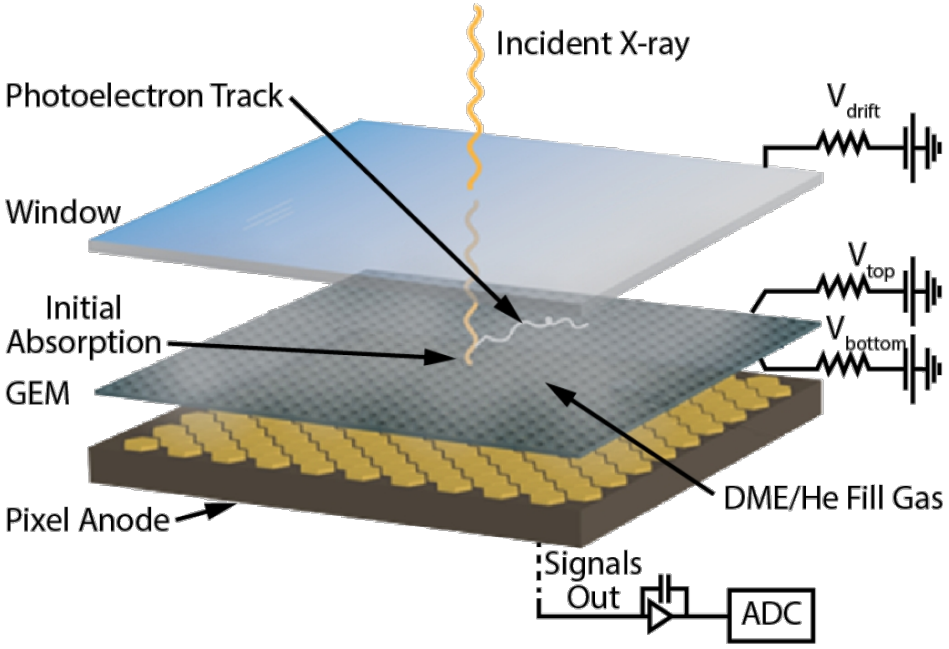
- ✔ Excellent modulation factor
- ✗ Low efficiency
- ✗ Narrow energy band
- ✗ Requires detector rotation

Thompson/Compton scattering

- ✔ Decent efficiency
- ✔ Spectroscopy
- ✗ Compton scattering not 100% modulated
- ✗ Background rejection challenging
- ✗ Detector rotation for syst. reduction

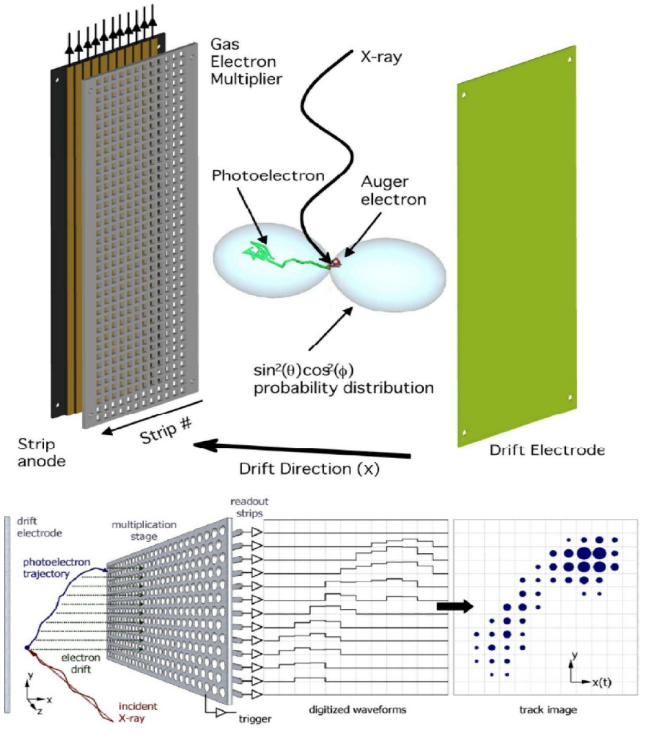
Photo-electric polarimeters

- K-shell emission 100% modulated
- Different designs proposed:



Gas Pixel Detector:

- Imaging
- No detector rotation required
- ✗ Trade-off efficiency/modulation factor



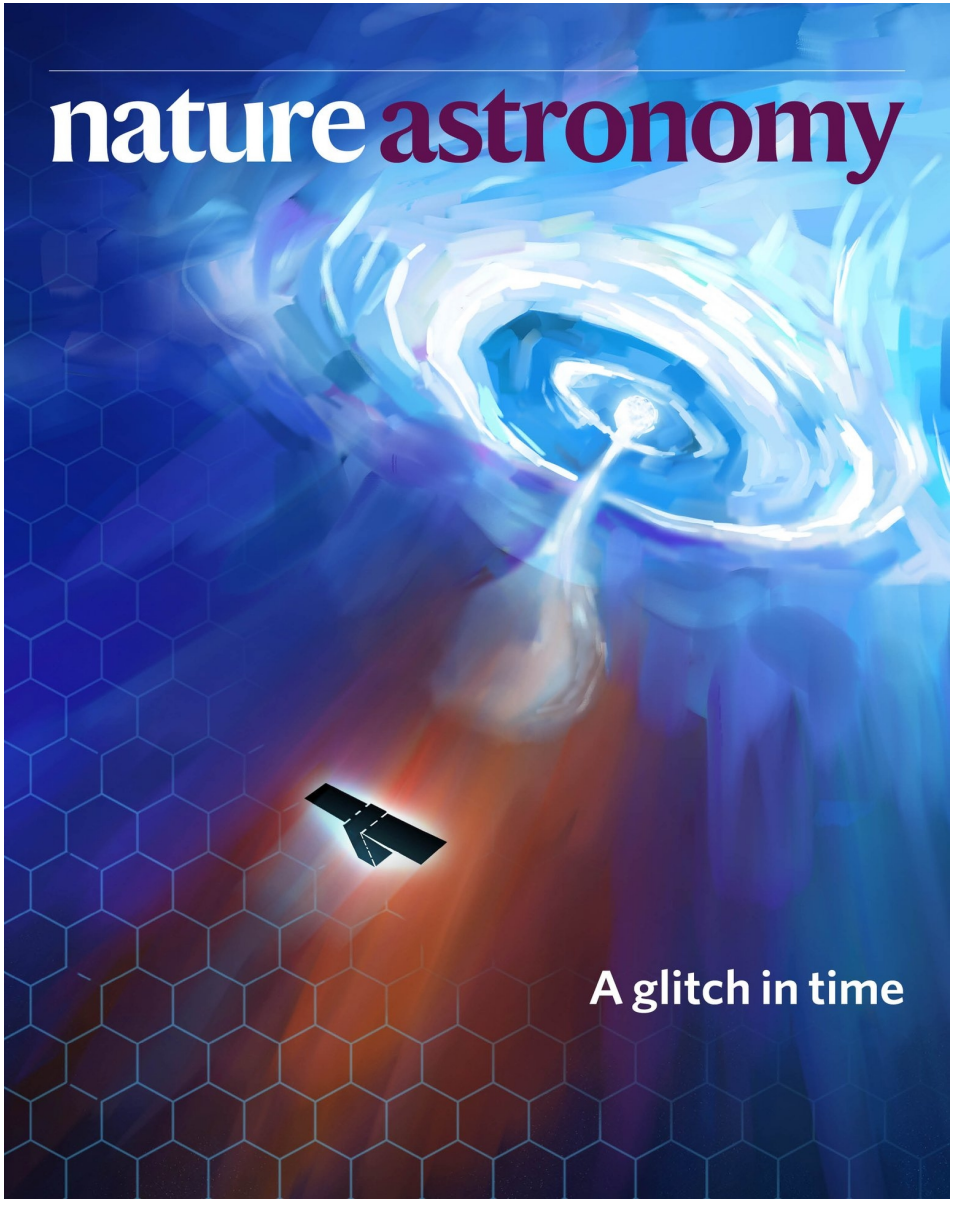
Time Projection Chamber:

- Efficiency decoupled from modulation factor
- ✗ No imaging
- ✗ Requires rotation

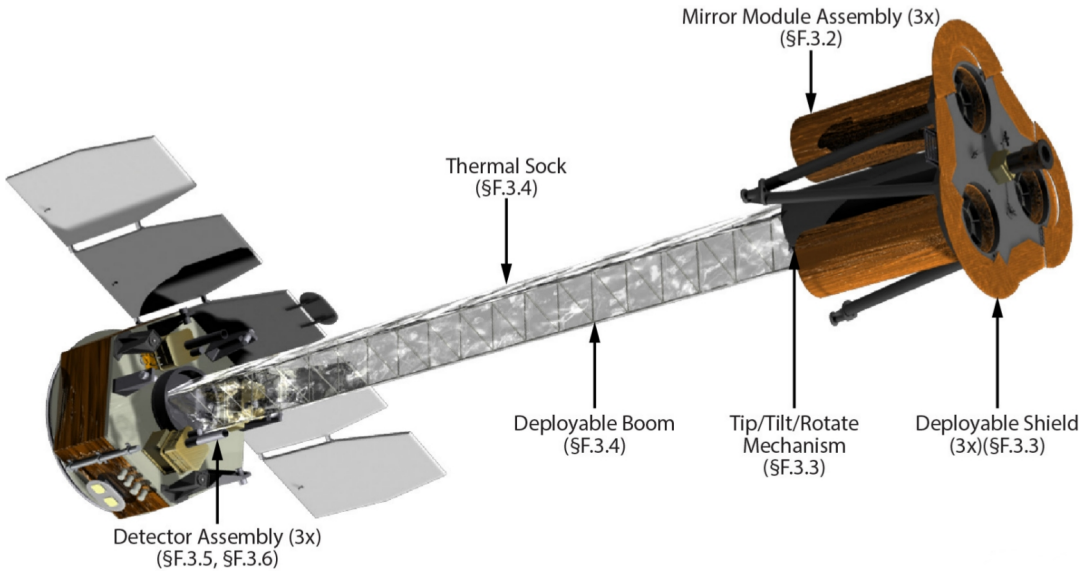
PolarLight

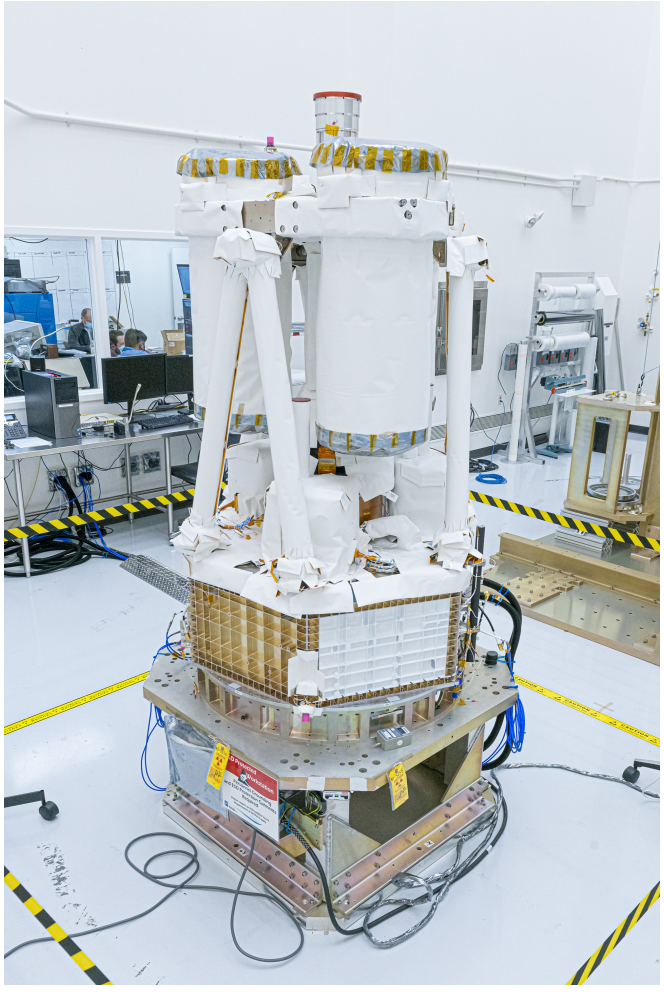
- A Gas Pixel Detector on a CubeSat, launched in October 2018
- First soft X-ray polarimeter to fly in space since 1970s
- A new measurement of the Crab polarization (consistent with OSO-8)
- Detected a polarization drop after a glitch of the Crab in July 2019

Feng, H. et al. Nat Astron 4, 511–516 (2020)



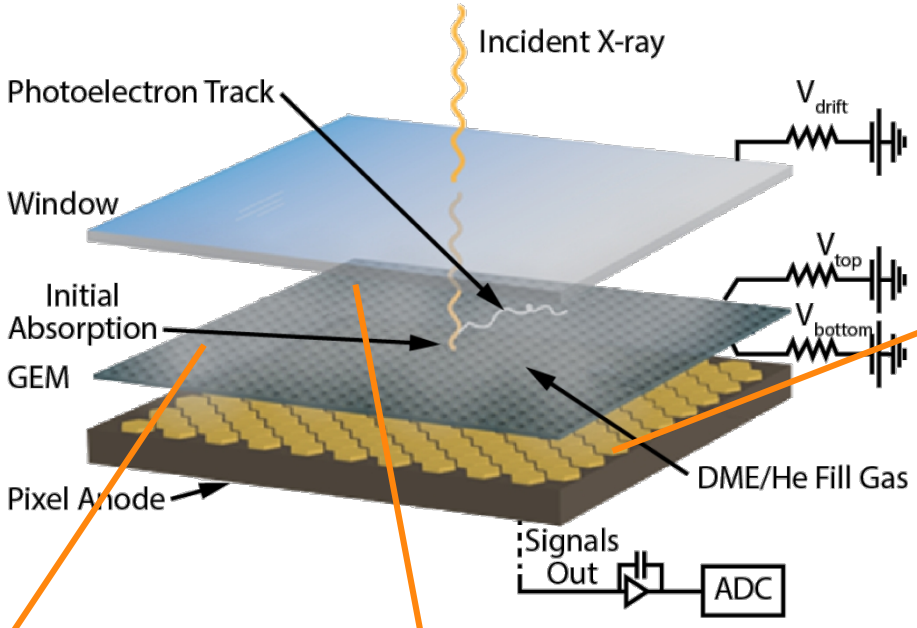
The Imaging X-ray Polarimetry Explorer (IXPE) mission





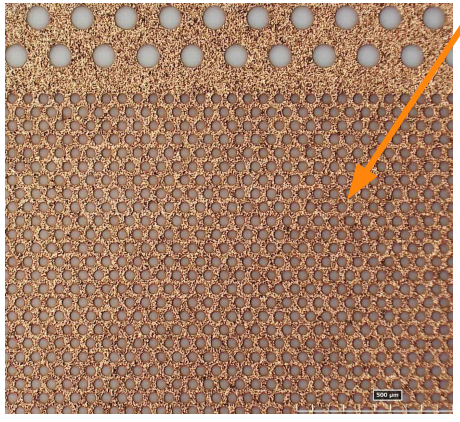
- NASA/ASI mission, to be launched in December 2021 (3 years operation)
- 3 identical telescopes: Wolter I mirror + GPD in the focal plane
- Simultaneous polarimetry, imaging, spectroscopy and timing for >100 sources between [2-8] keV

IXPE GPDs



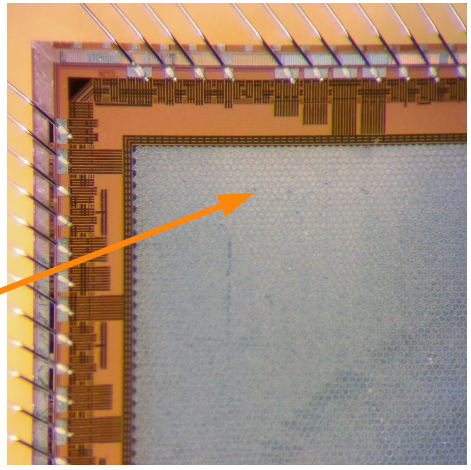
Gas Electron Multiplier (GEM)

- 50 um pitch
- 30 um holes diameter



Gas cell

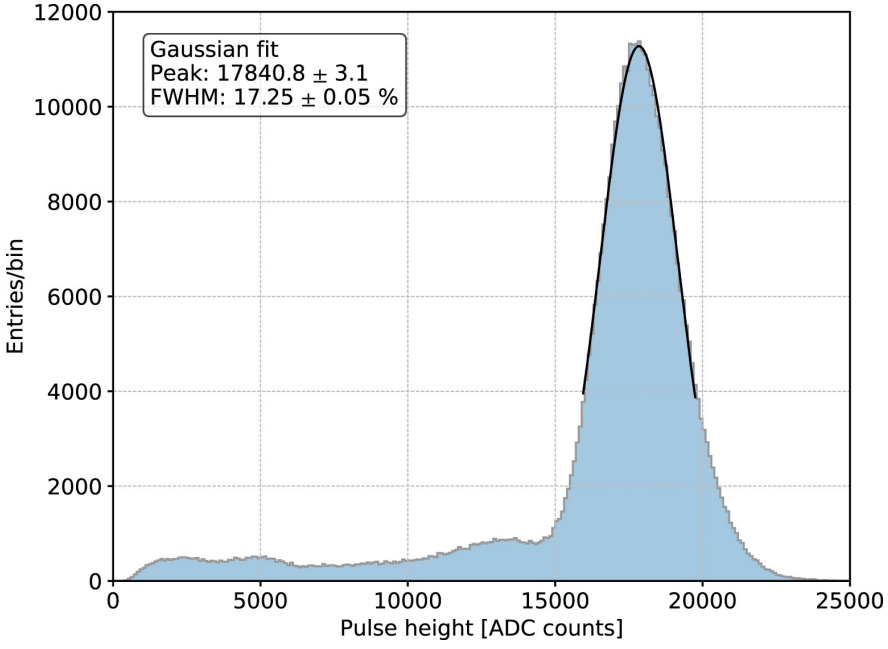
- 1~cm thick
- Titanium frame + Be entrance window
- DME @800 mbar
- Sealed (no gas system)



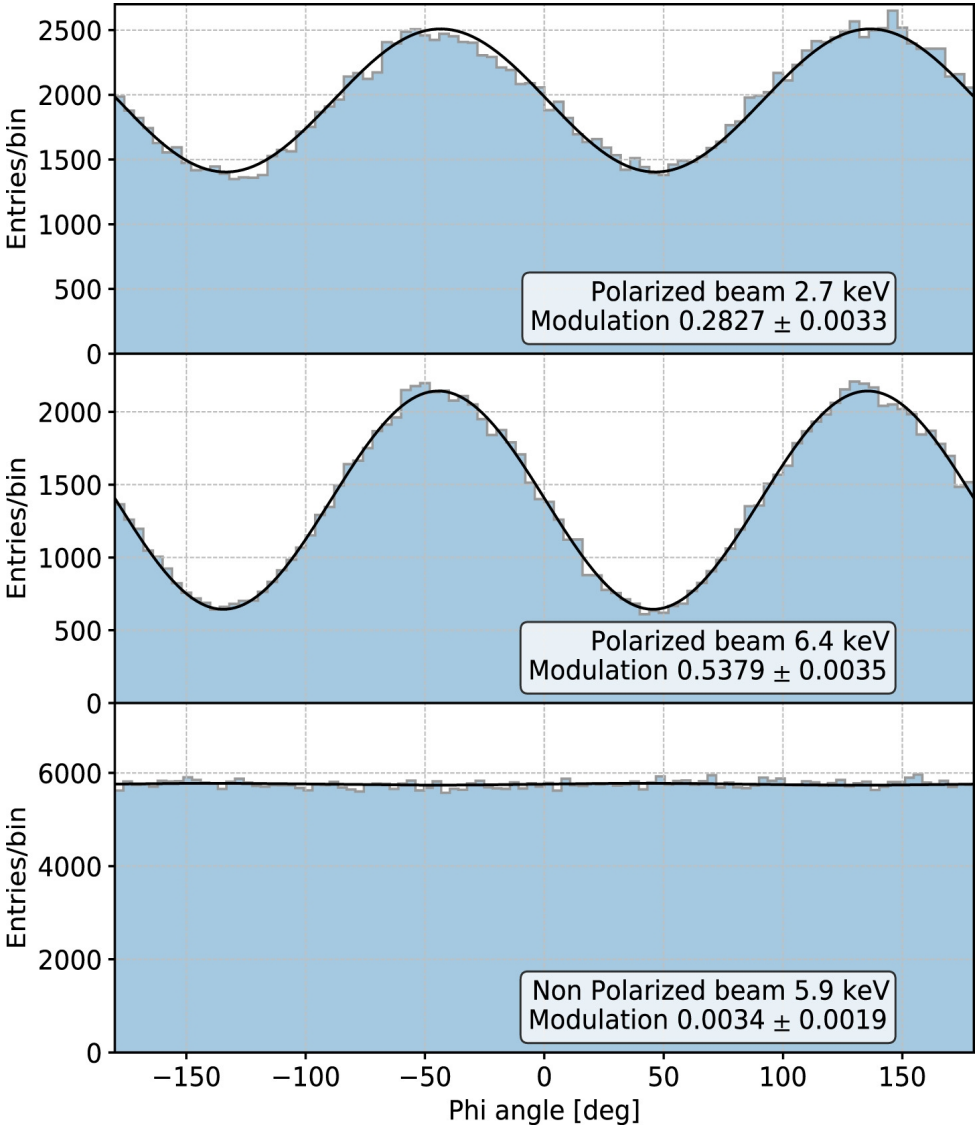
Readout ASIC

- 105k pixels
- Hex grid, 50 um pitch
- Self-triggering
- 1.5mm x 1.5mm active area

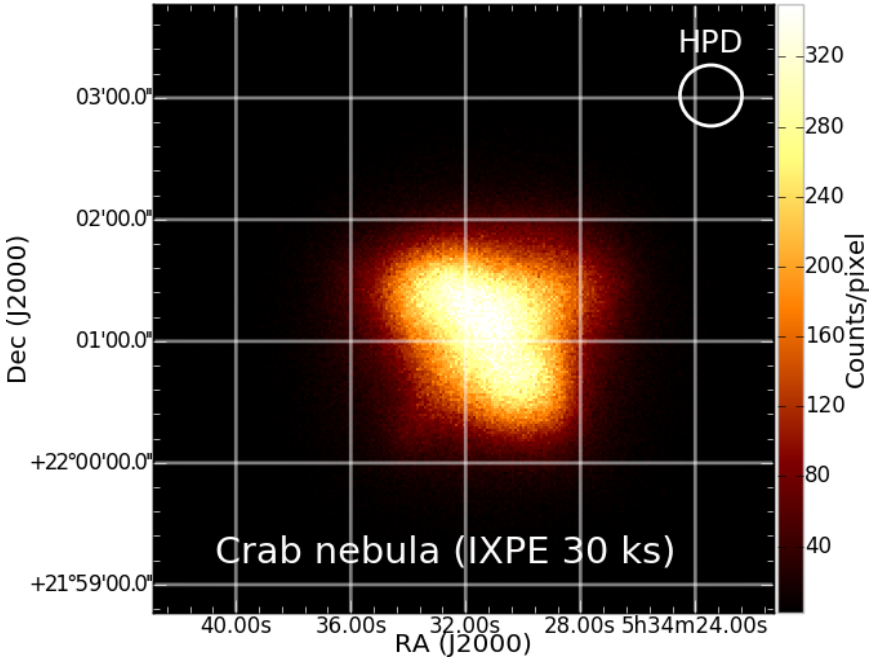
IXPE GPDs performance

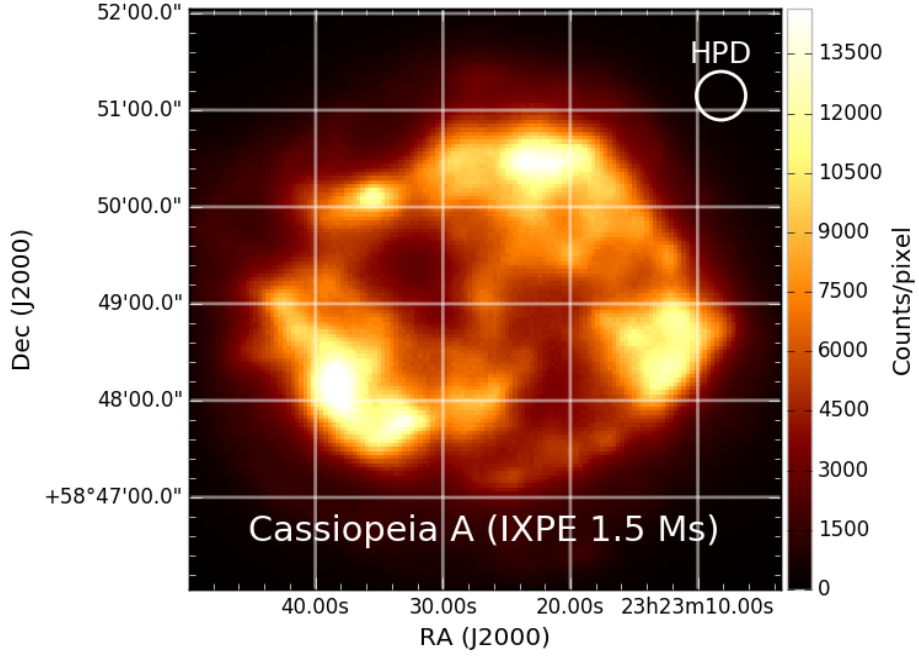


- 17% FWHM @5.9 keV
- μ = 0.54 @6.4 keV
  0.28 @2.7 keV
- ε > 20% @2.0 keV
- ~1 ms dead time



Space and phase resolved polarimetry

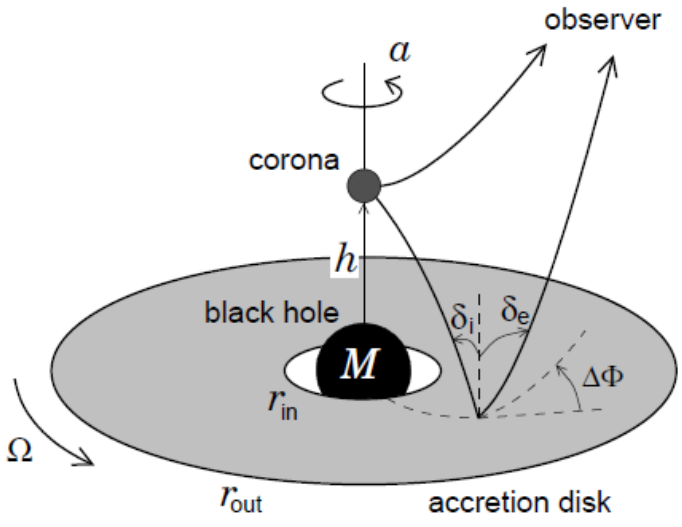




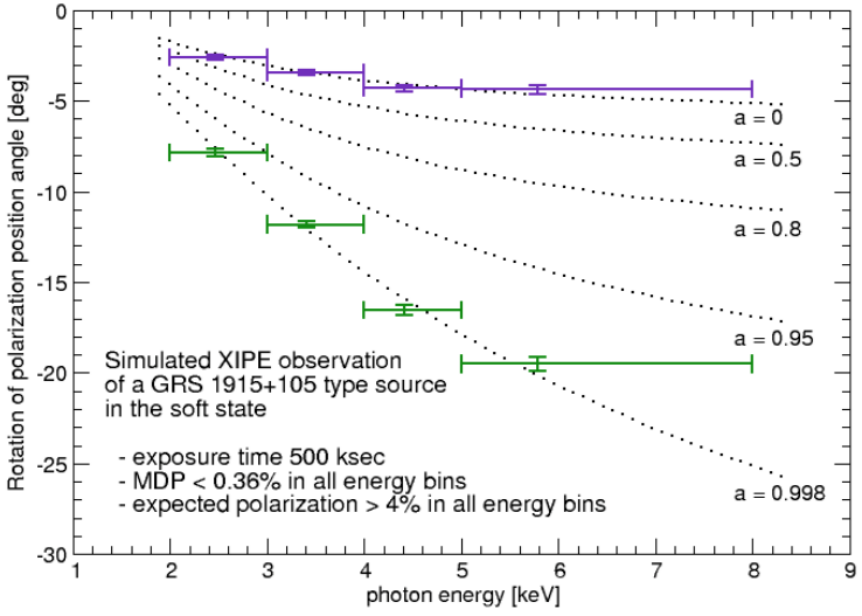
- **Crab Nebula**: separate the torus from the jet; study the polarization pattern of the pulsar as a function of the phase.
- **CasA**: measure the magnetic field direction and uniformity in the regions near the shock fronts where electrons are accelerated

Spectro-polarimetry

M. Dovčiak et al 2011 ApJ 731 75



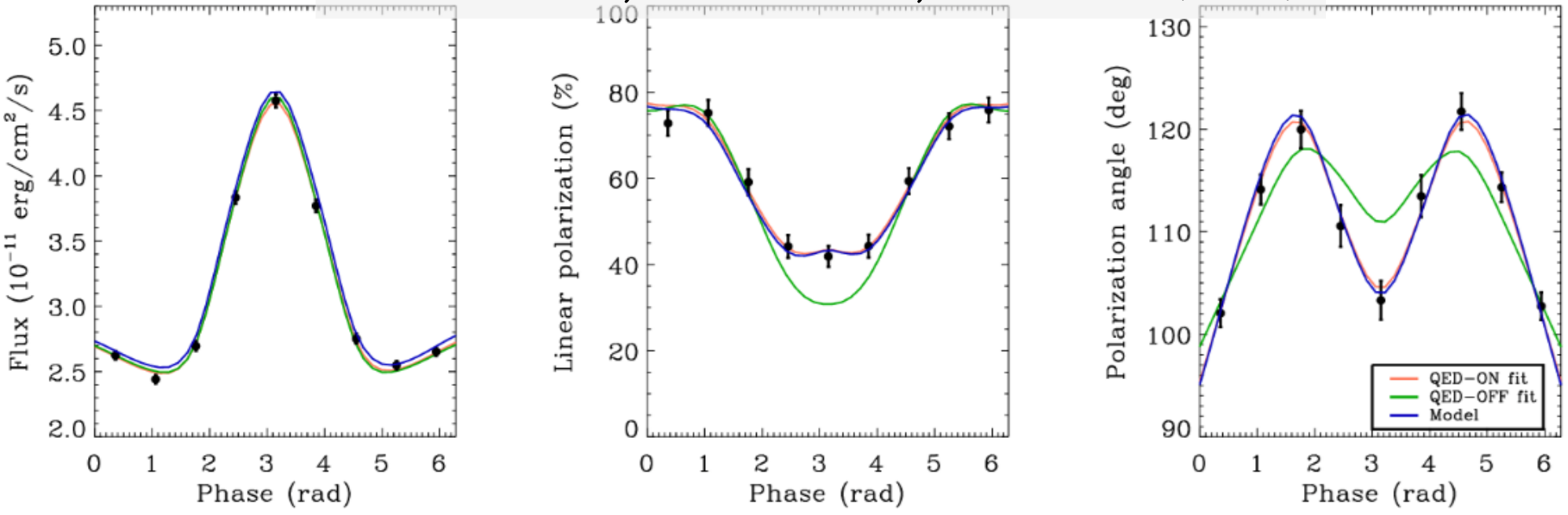
Dovčiak et al., MNRAS 391, 32–38 (2008)



- Thermal emission from the accretion disk of a Black Hole can become polarized by Compton scattering on the Corona
- BH proximity causes a rotation of the polarization angle (increasing with energy)
- An independent technique for measuring the black hole spin

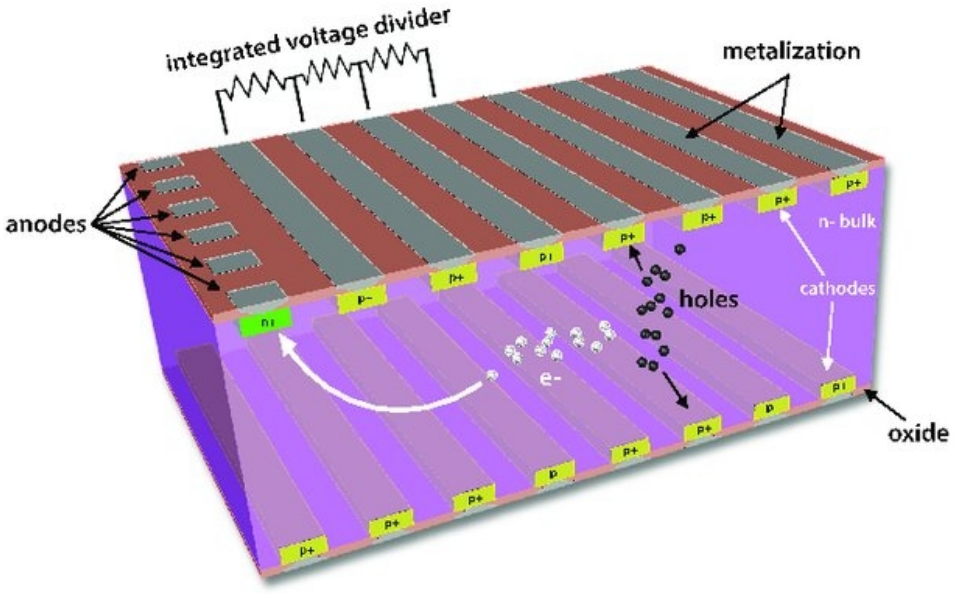
Testing QED effects in strongly magnetized systems

Taverna et al., MNRAS 438, 1686-1697 (2014)

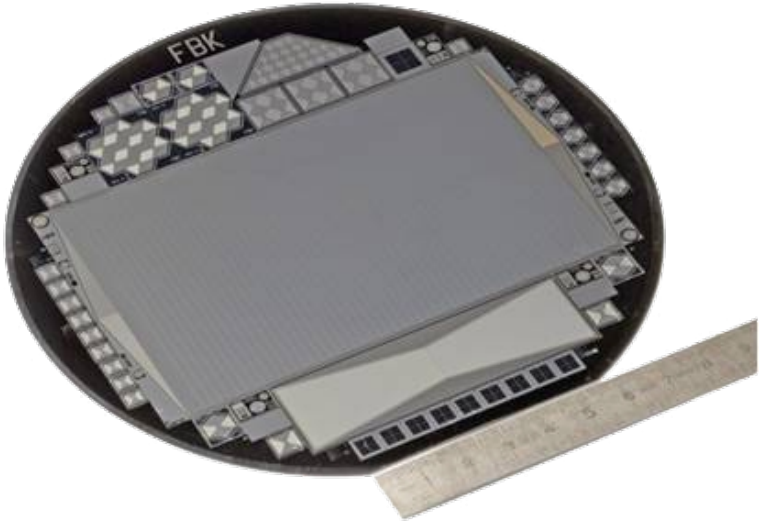


- Vacuum birefringence predicted by Heisenberg and Euler in 1936, but never observed
- The extreme magnetic field of the magnetars (B~ 10^{13} - 10^{15} G) is a natural lab for testing the prediction
- Effect negligible on the flux, visible using polarization variables

Large Area SDDs: a new frontier in X-ray timing



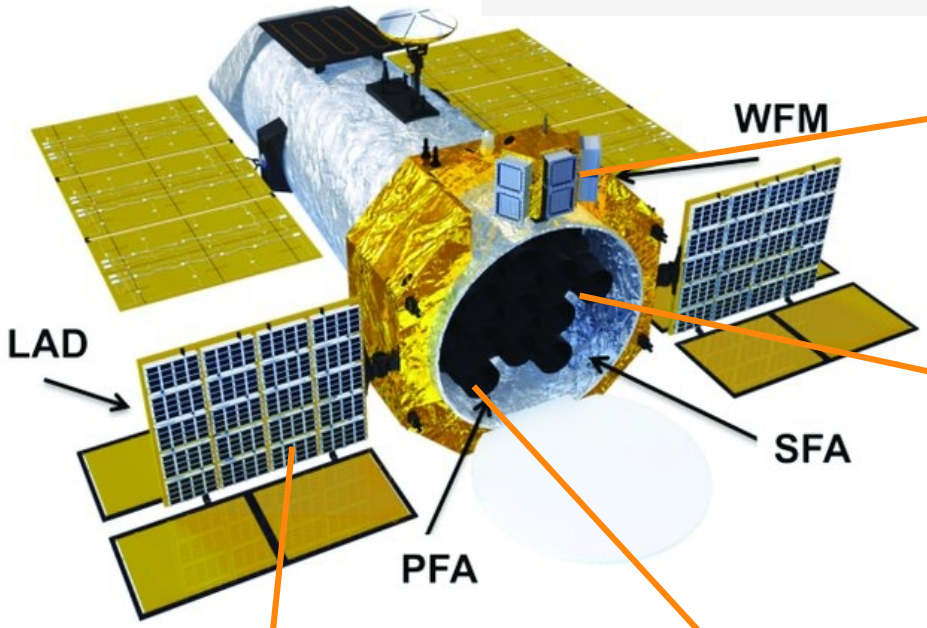
Rachevski et al, JINST 9 P07014 (2014)



- Originally developed for the ALICE detector at LHC
- Design optimized for X-ray astronomy
- Cover wide surfaces with low mass and power budget
- Low noise (low anode capacitance)
- Segmented anode allows for 2D imaging:
  - Drift time inferred from diffusion width $\sigma \propto t^{1/2}$

The enhanced X-ray Timing and Polarimetry mission - eXTP

Zhang et al. Sci. China-Phys. Mech. Astron. 62 (2019)



Wide Field Monitor

- Transient monitoring
- Source discovery
- 4 sr FOV
- [2-50] keV

Spectroscopic Focusing Array

- Spectroscopy
- Timing
- [0.5-10] keV

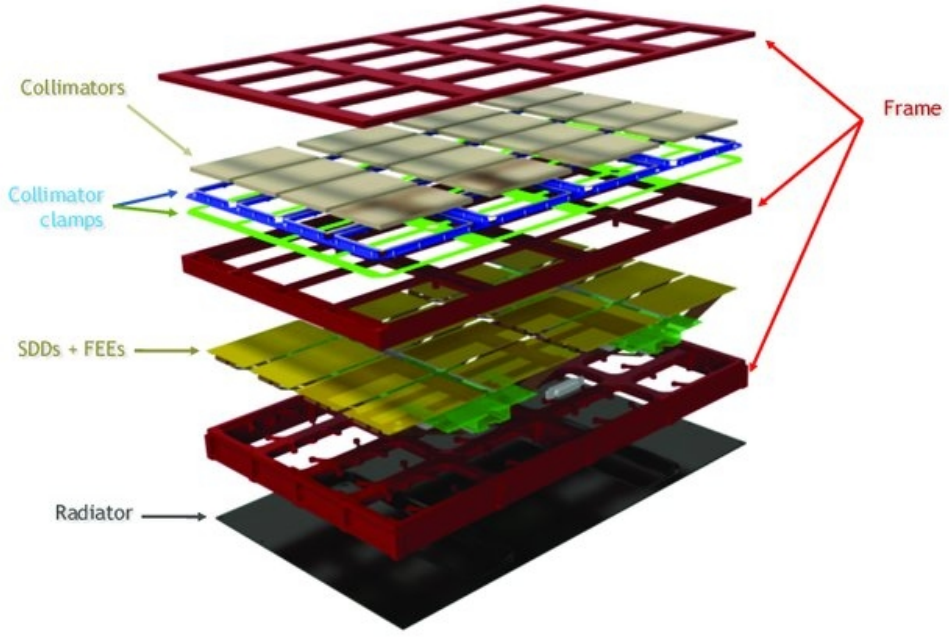
Large Area Detector

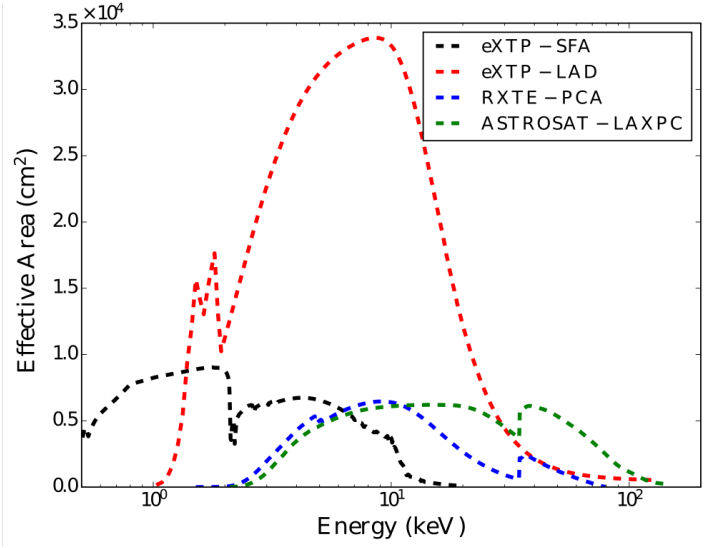
- Timing
- Spectroscopy
- [2 - 30] keV

Polarimetry Focusing Array

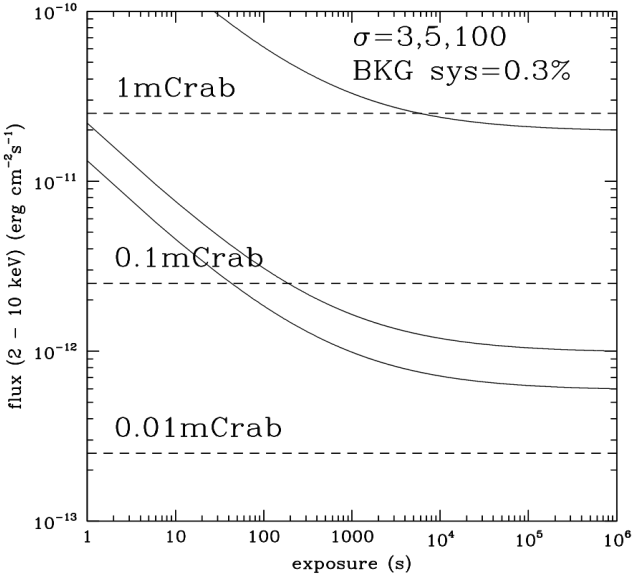
- Polarimetry (2-3 x IXPE Effective Area)
- Imaging
- [2-8] keV

Large Area Detector (LAD)



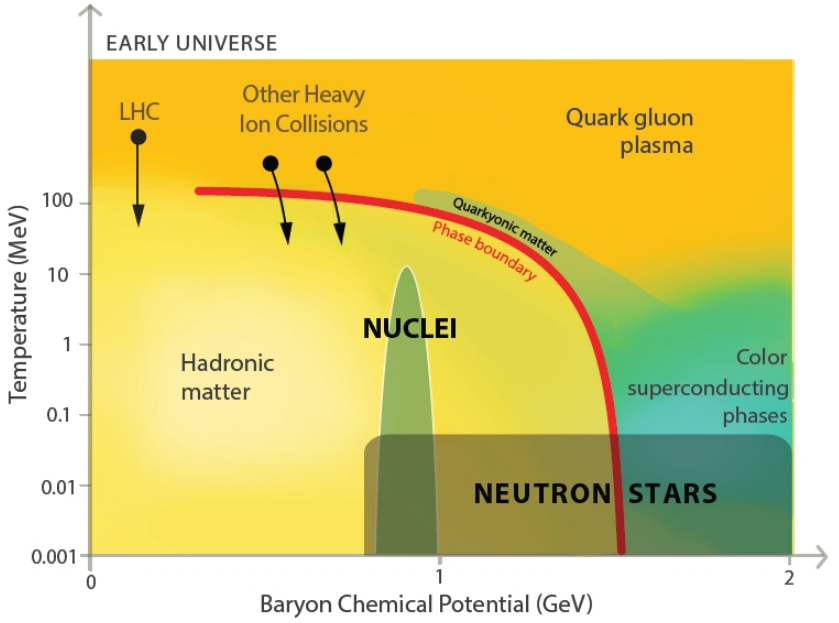


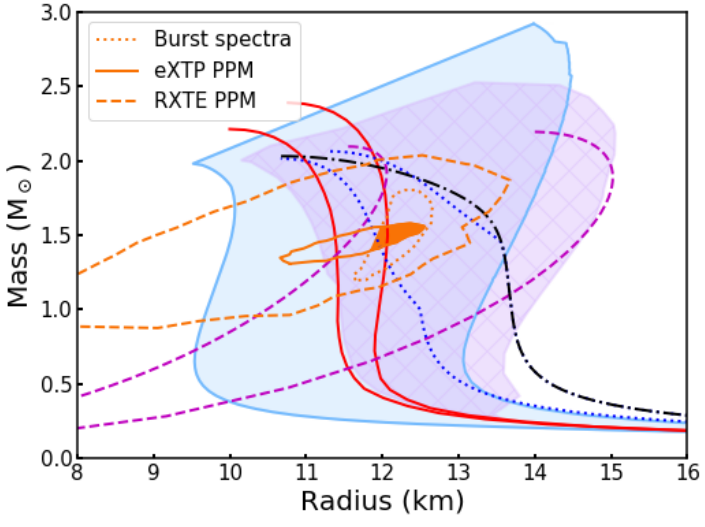
- 640 SDDs
  - 11 × 7 cm², 450 μm Si thickness
- Focusing based on capillary plates
  - FOV < 0.95° (FWHM)
- **Peak Effective Area of 3.4 m²**
- Dead Time (at 1 Crab) < 0.5%



Dense matter with eXTP

- NS density > 10 x nuclear density: probe the physics of **strong interactions**
- Low T environment: complementary to Heavy Collider search
- Possibly revealing "exotic" states and phases of matters
- Constrain the **EOS** by measuring M and R
  - Pulse profile modeling
  - Spin measurements
- Polarimetry can remove geometrical degeneracy

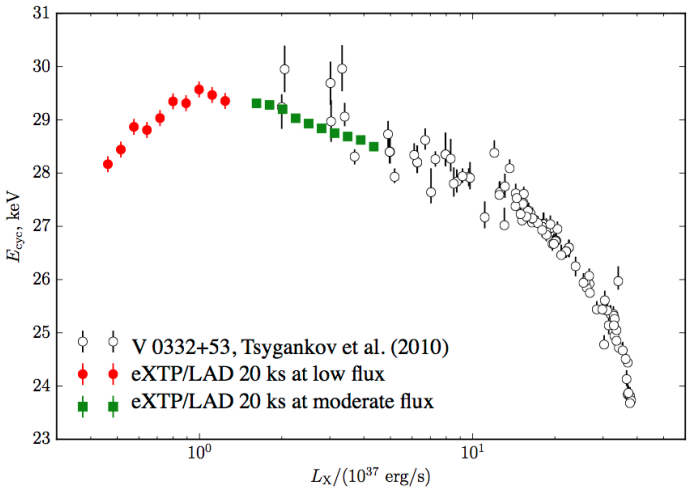




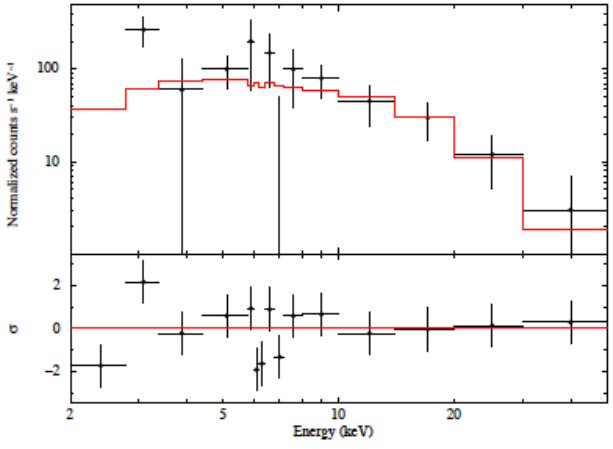
Watts et al, Sci. China-Phys. Mech. Astron. 60 (2017)

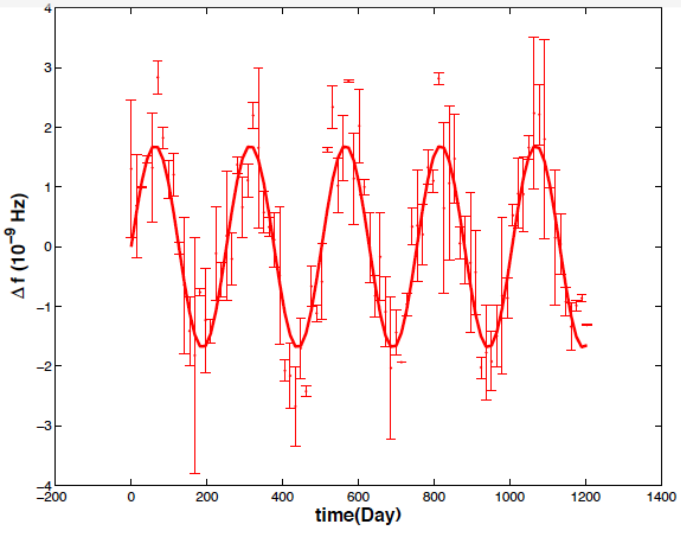
Strong Magnetic fields systems

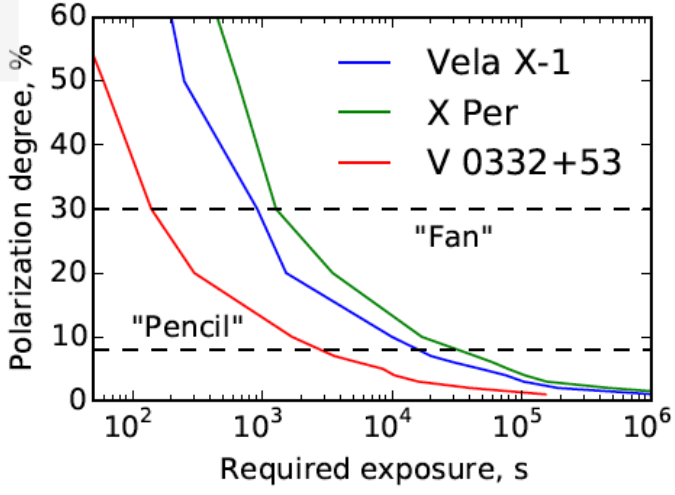
- Discover new magnetar candidates
- Monitor magnetar spin period
- Phase resolved polarimetry of accreting X-ray pulsars
- Study the luminosity dependence of the cyclotron resonance scattering feature (CRSF)



A. Santangelo, et al. Sci. China-Phys. Mech. Astron. 62 (2019)

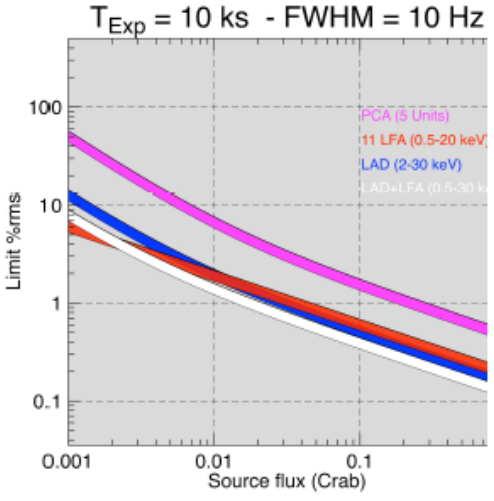


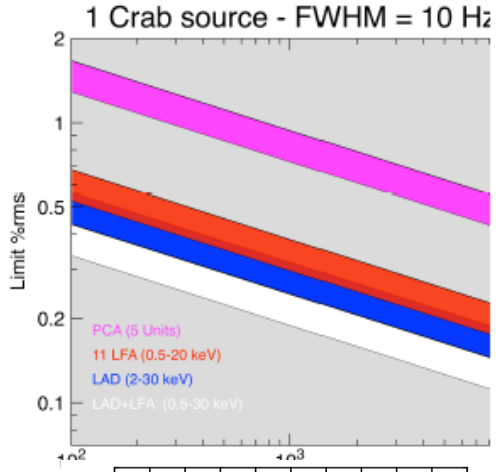


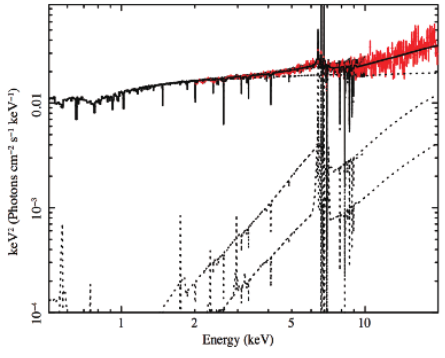


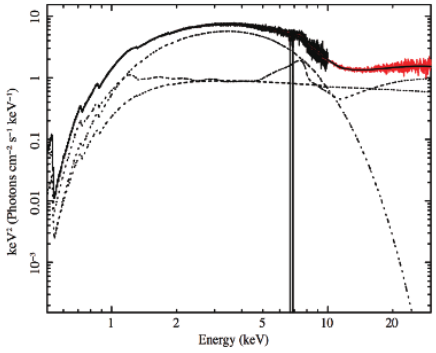
Accretion in strong field gravity

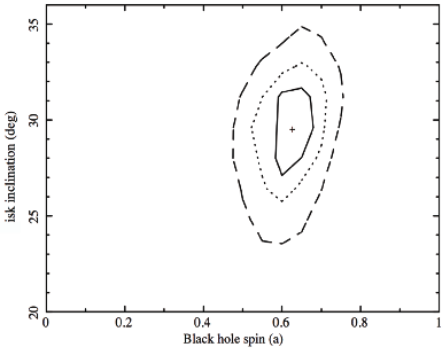
- Relativistically broadened Fe lines
- Quasi-periodic oscillations (QPOs)
  - Phase resolved spectroscopy
  - Phase resolved polarimetry

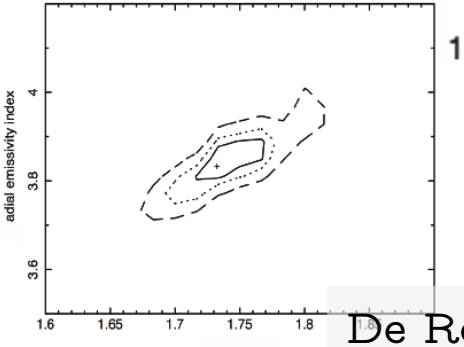


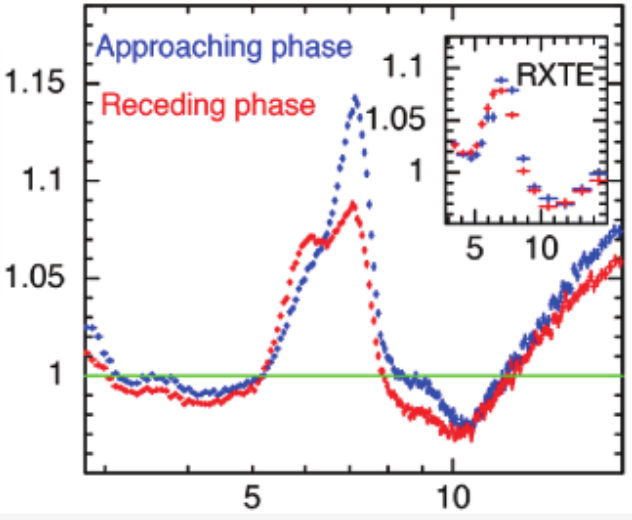


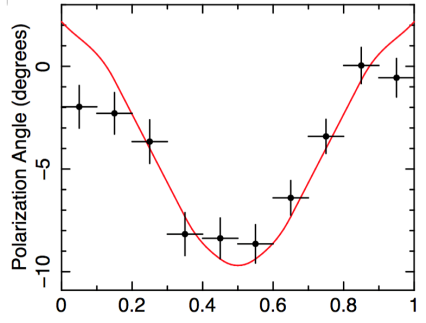


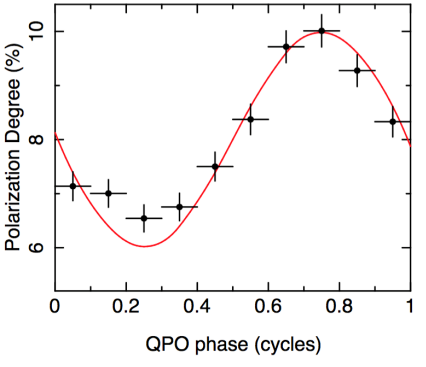






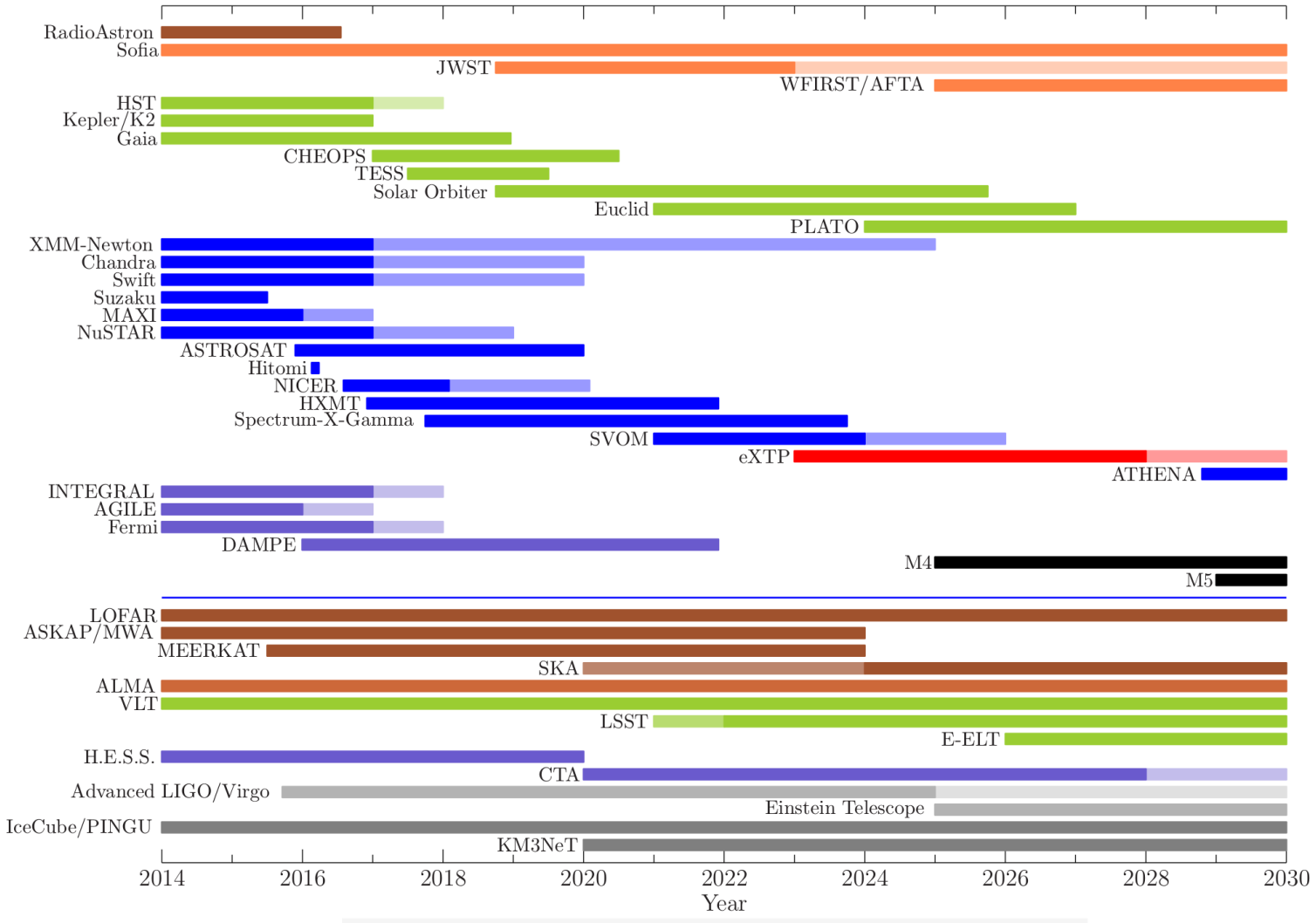






De Rosa, et al. Sci. China-Phys. Mech. Astron. 62 (2019)

Observatory science



J.J.M. in 't Zand, et al. Sci. China-Phys. Mech. Astron. 62 (2019)

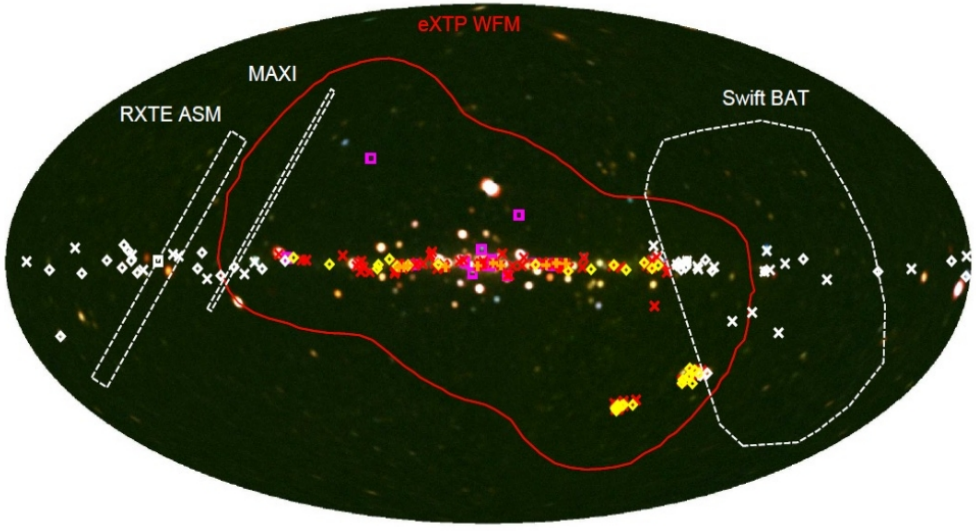
Conclusions

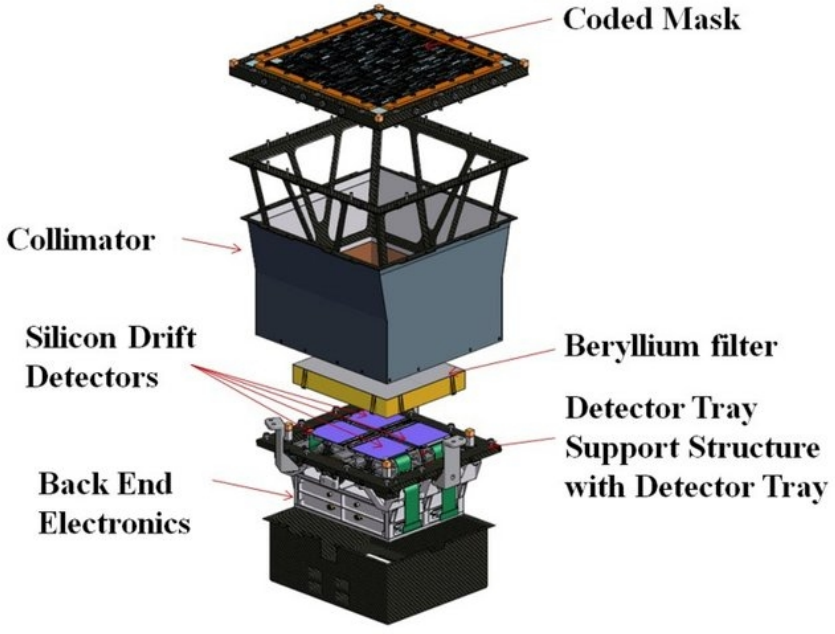
- Advancement in detector technology will open new windows in X-ray astronomy
- Thanks to photoelectric-based polarimeters, the **IXPE** mission (December 2021) will perform for the first time systematic measurements of the polarization of tens of soft X-ray sources
- Innovative large area SDDs will allow timing study with unprecedented sensitivity in future missions like **e-XTP**
- The future missions will improve our understanding of physics in conditions of extreme gravity and magnetic fields

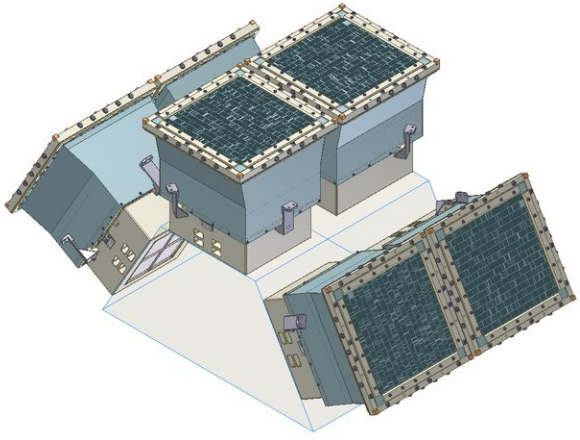
Backup

Wide Field Monitor (WFM)

- 6 coded-mask cameras
- 4 sr FOV
- ang. res. < 4.3 arcmin (FWHM)
- energy res. 300 eV at 6 keV (FWHM)



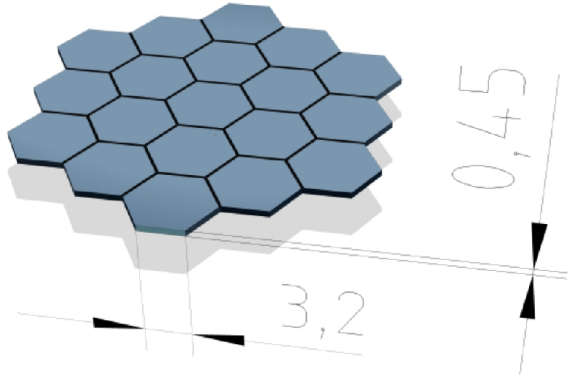


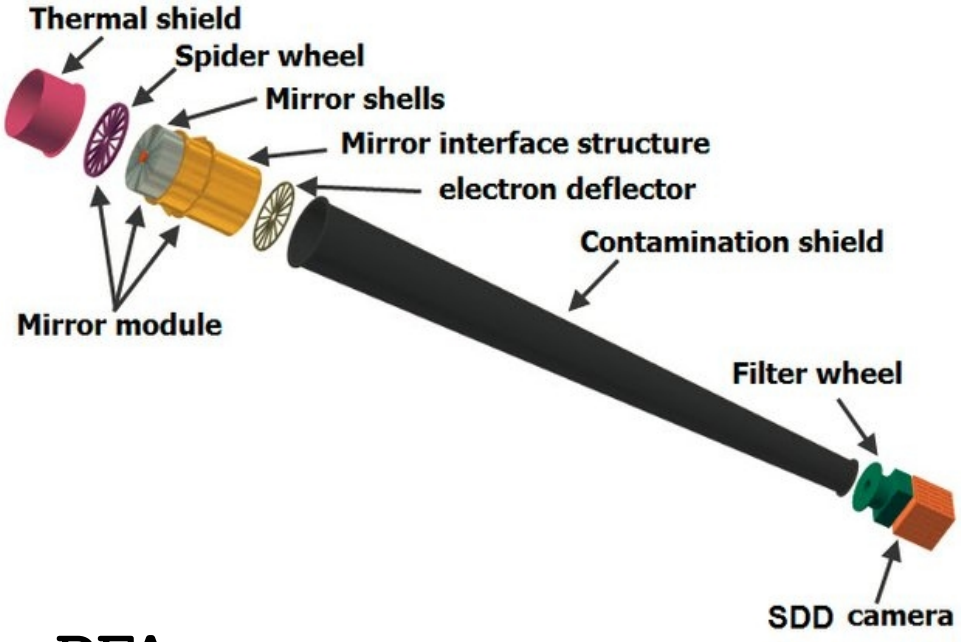


Spectroscopic Focusing Array (SFA)
Polarimetry Focusing Array (PFA)

SFA:

- 9 Wolter 1 optics modules
- SSD camera in the focal plane (19 hex. detector)
- 12 arcmin FOV
- < 1 arcmin ang. res.
- < 5% dead time at 1 Crab





PFA:

- 4 telescopes (SFA optics)
- GPDs in the focal plane
- Concept similar to IXPE
  - Improved design
- < 30 arcsec resolution