Marshall Space Flight Center

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IXPE
Imaging
X-Ray
Polarimetry
Explorer

Picking the right direction
Xipe
esa

Synergies between (I)X(I)PE and eASTROGAM

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INAF-IAPS
on the behalf of the
IXPE and XIPE teams

IXPE
NASA Explorer
mission approved

Weisskopf
et al. 2016,
SPIE

Soffitta et al.
2016, SPIE

XIPE
ESA M4 still in
competition

OUTLINE

- Two space mission with the same heart : the Gas Pixel Detector photoelectric polarimeter
- XIPE and IXPE differences and similarities
- XIPE and IXPE synergies with the e-Astrogam science case
- XIPE and IXPE synergies with the e-Astrogam observatory science

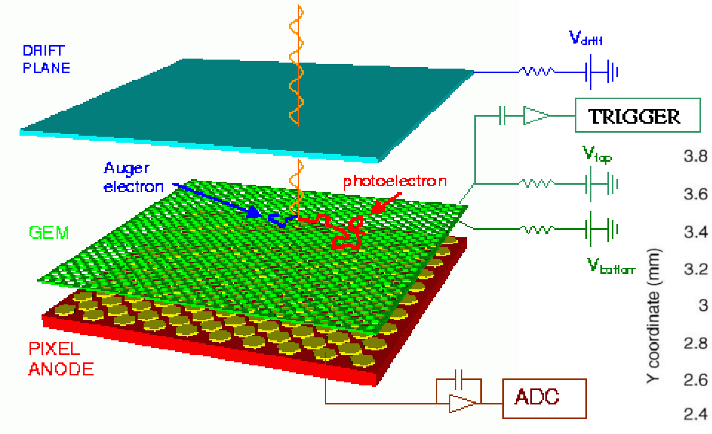
XIPE and IXPE:

→ **both based on the Gas Pixel Detector (GPD) design that provides imaging X-ray Polarimetry, plus timing and spectroscopy**

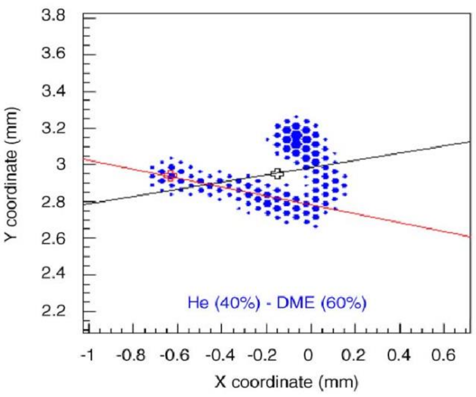
→ **an array of GPDs at the focus of classical grazing-incidence X-ray optics**

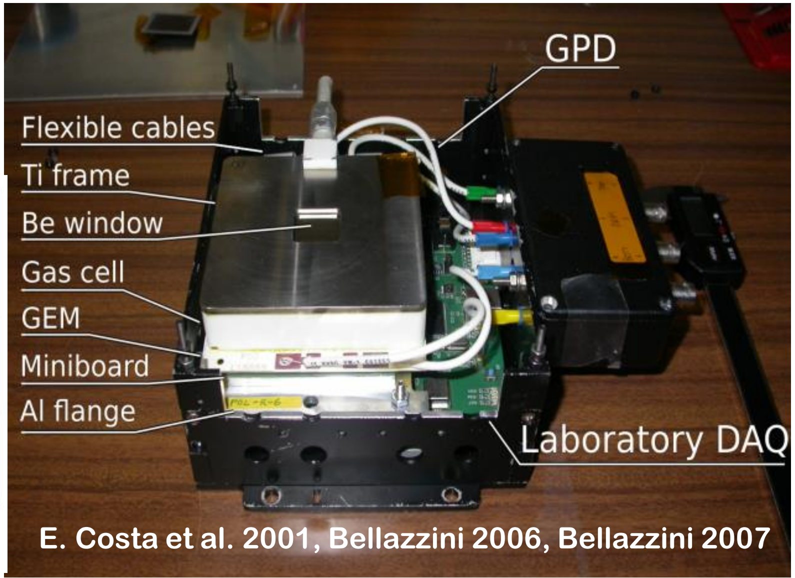
→ **energy band 2-10 keV**

→ **sensitivity orders of magnitudes higher than the polarimeters already flown in the '70**



$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2}\frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$





E. Costa et al. 2001, Bellazzini 2006, Bellazzini 2007

Gas Pixel Detector Parameter	Value
Sensitive area	15 mm × 15 mm
Fill gas and composition	He/DME (20/80) @ 1 atm
Detector window	50-μm thick beryllium
Absorption and drift region depth	10 mm
GEM (gas electron multiplier)	copper-plated 50-μm liquid-crystal polymer
GEM hole pitch	50 μm triangular lattice
Number ASIC readout pixels	300 × 352
ASIC pixelated anode	Hexagonal @ 50-μm pitch
Spatial resolution (FWHM)	$\leq$ 123 μm (6.4 arcsec) @ 2 keV
Energy resolution (FWHM)	16% keV @ 5.9 keV ($\propto \sqrt{E}$)

	IXPE	XIPE
Polarimetric sensitivity (100 ks, 2×10^{-11} cgs)	9.8% (Current Best Estimate)	6.4% (CBE)
Number of telescopes	3	3
Total mirrors area at 3 keV	854 cm^2 (CBE)	1530 cm^2 (CBE)
Focal plane detector	GPD (He-DME filled)	GPD (He-DME filled)
Energy range	2-8 keV (Requirement) 1.5-9 keV (GOAL)	2-8 keV (R) 1.5-12 keV (GOAL)
Angular resolution (including pointing errors)	≤30’’ (R) 28 (CBE)	≤30’’ (R) <20’’ (GOAL)
FoV	12.8’x12.8’ (CBE)	12.8’x12.8’ (CBE)
Timing accuracy to UTC	<100 μs (CBE)	<8 μs
Background	$<5\times10^{-3}$ cts s^{-1} cm^{-2} keV^{-1} det^{-1}(R) $<1\times10^{-3}$ cts s^{-1} cm^{-2} keV^{-1} det^{-1} (G)	$\leq 8\ 10^{-4}$ cts s^{-1} cm^{-2} keV^{-1} det^{-1} (R)
Operational life time	2 years + 1 month commissioning (R) 3 years (G)	3 years (R) + 2 years (G)
Orbit life-time	2 years + 1 month commissioning (R) 4.3 year (CBE; in the range 2.3 – 12 years)	NA
Orbit	540 km circular, 0° inclination	550 km circular, ≤6° inclination (TBD) 10 km corridor
ToO	<72 h (CBE) 48 h from request to MOC (R)	< 12 h (R) 6 h (Best Case)
ToO frequency	1 per month (CBE)	1 per month (CBE)
Launch	On or later 20 Nov. 2020	< 2026

Astrophysics

Acceleration phenomena
- Pulsar wind nebulae
- SNRs
- Jets

Emission in strong magnetic fields
- Magnetic cataclysmic variables
- Accreting millisecond pulsars
- Accreting X-ray pulsars
- Magnetar

Scattering in aspherical situations
- X-ray binaries
- Radio-quiet AGN
- X-ray reflection nebulae

Fundamental Physics

Matter in Extreme Magnetic Fields: QED effects

Matter in Extreme Gravitational Fields: GR effects
- Galactic black hole system & AGNs

Quantum Gravity

Search for axion-like particles

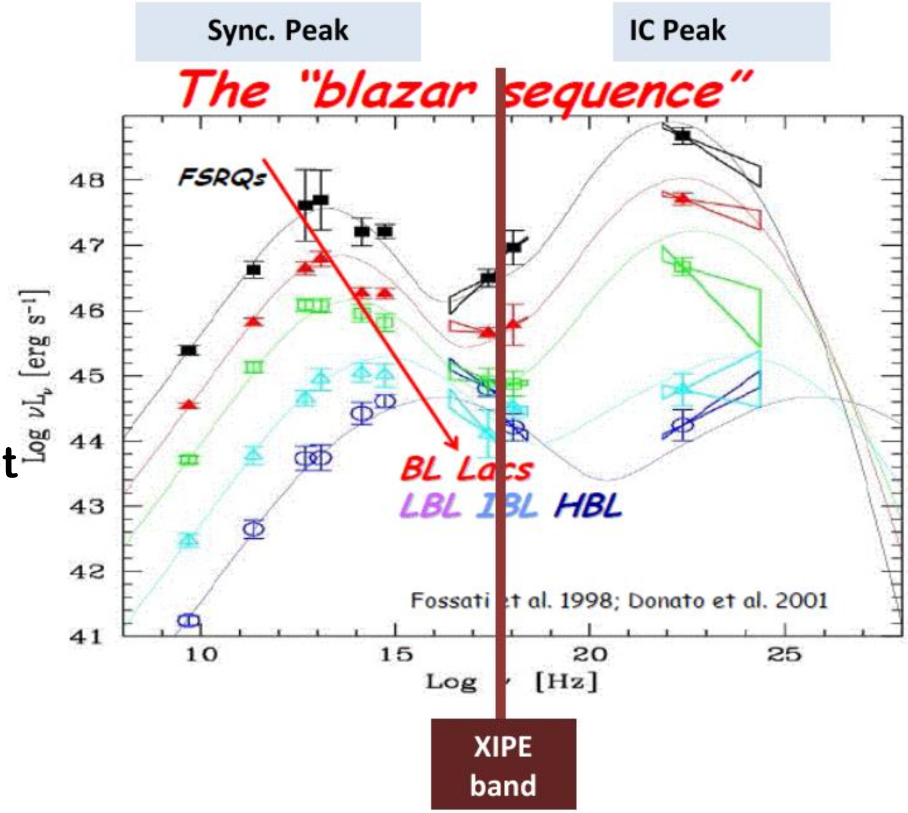
Synergies with e-Astrogam science case

Synergies with e-Astrogam observatory science

XIPE and IXPE synergies with the e-Astrogam science case

e-Astrogam science case: Acceleration phenomena – unresolved Jets

- **Blazars are those radio-loud AGN whose Jets are directed towards us**
- **Jets emission dominates over other emission components due to relativistic aberration**
- **High brightness and high polarization degree**
- **Investigate the role of magnetic fields in jet launching and collimation**
- **Investigate the jet composition and high energy emission mechanism (leptonic, e-e+, hadro-leptonic, e-p+, simply hadronic)**
- **Investigate the dominant mode of particle acceleration**



e-Astrogam science case: Acceleration phenomena – unresolved Jets

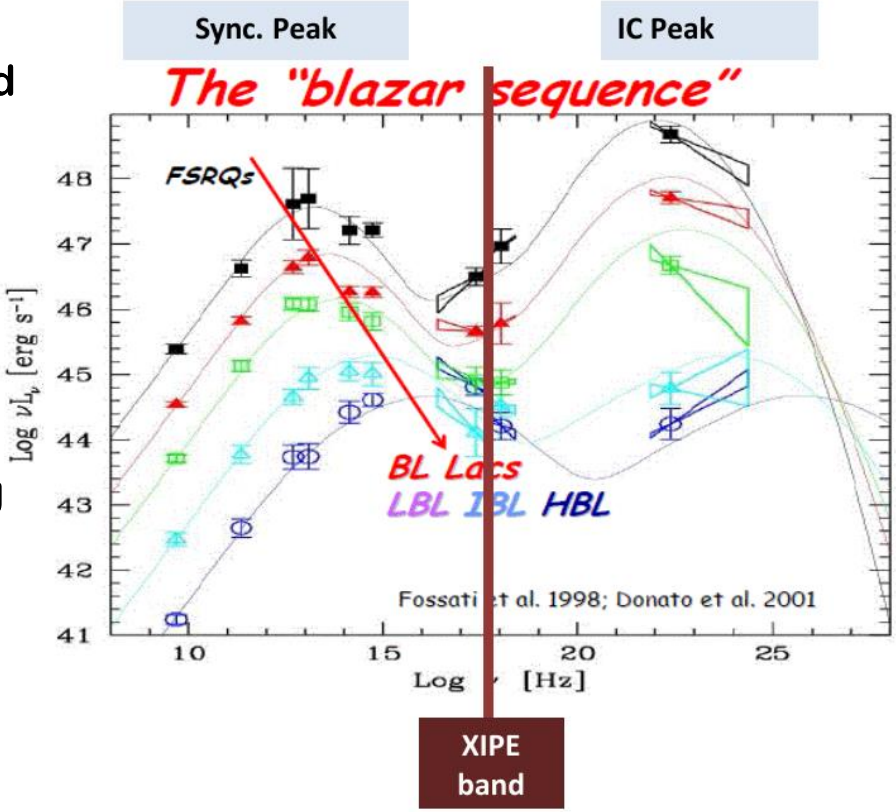
- **In the case of a leptonic emission mechanism, for inverse Compton dominated Blazars, an observation can determine the origin of the seed photons:**

- Synchrotron-Self Compton (SSC) ?

  - ➢ **The polarization angle is the same as for the synchrotron peak**
  - ➢ **About 1/2 of the seed polarization degree (optical synchrotron), yielding a maximum of ~15%**

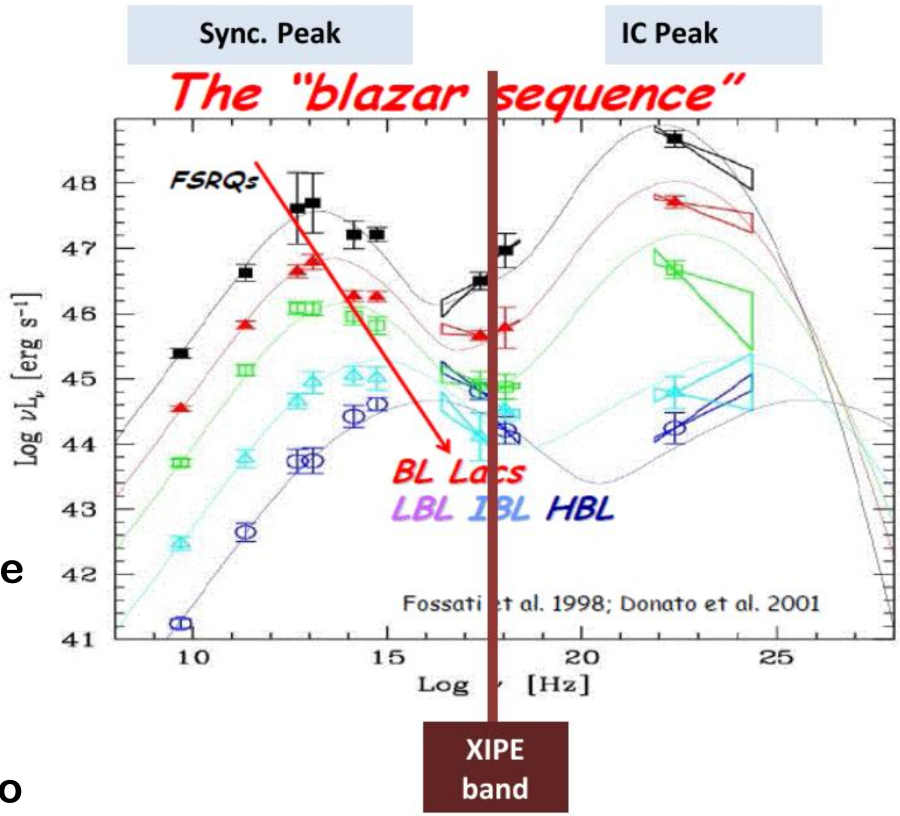
- External Compton (EC)?

The polarization angle may be different



e-Astrogam science case: Acceleration phenomena – unresolved Jets

- In synchrotron-dominated X-ray Blazars, multi-λ polarimetry probes the structure of the magnetic field along the jet.
- Models predict a larger and more variable polarisation in X-rays than in the optical.
- Coordinated multi-wavelength campaigns are crucial for blazars.
- Such campaigns (including polarimetry) are routinely organised and it will be easy for XIPE and IXPE to join them.
- eAstrogam will provide polarimetric data too

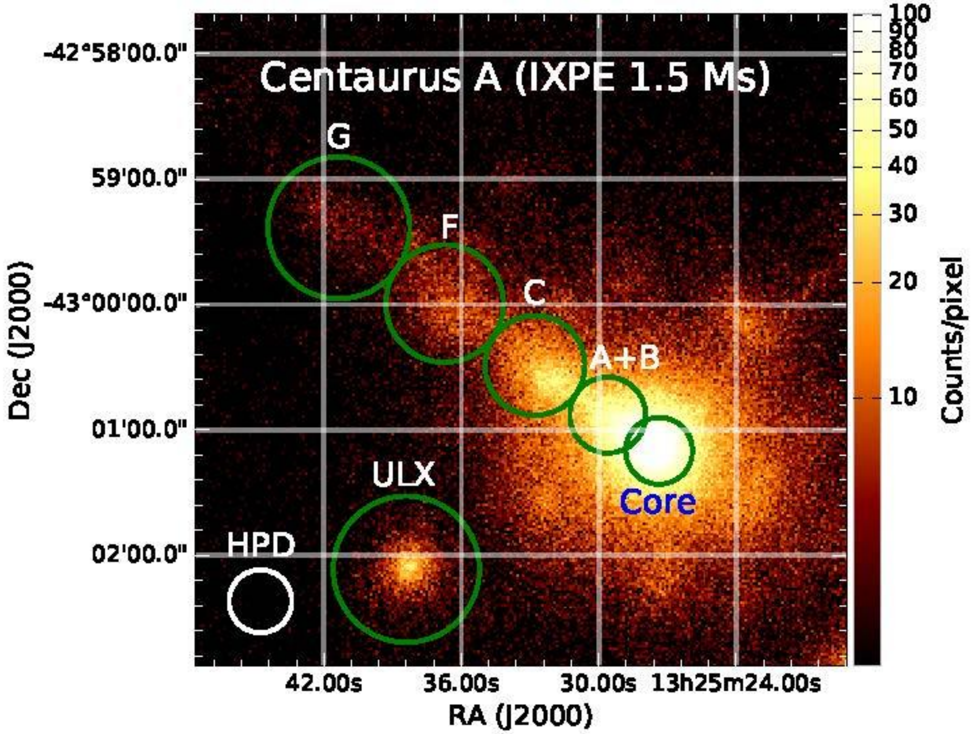


e-Astrogam science case: Acceleration phenomena – resolved Jets in XIPE and IXPE

- **In non-blazar radio-loud AGN the jet is directed away from the line-of-sight and can be, for the closest and brightest candidates, directly imaged in X-rays on arcmin scales.**

- **IXPE 1.5 Ms observation of Cen A**

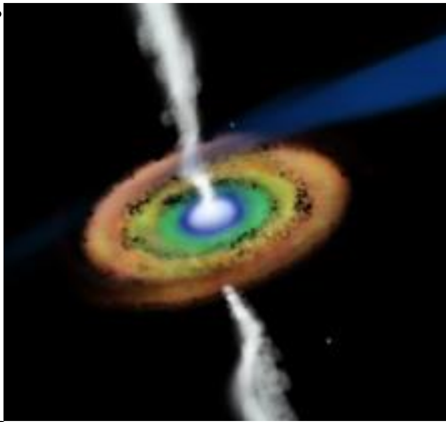
Region	**MDP$_{99}$**
Core	**<7.0%**
Jet	**10.9%**
Knot A+B	**17.6%**
Knot C	**16.5%**
Knot F	**23.5%**
Knot G	**30.9%**
ULX	**14.8%**



- **XIPE MDP for the jet is 5% in 1 Ms of observation in 5 regions**

e-Astrogam core science: Acceleration phenomena – μ-quasars

- Micro-quasars and radio-loud AGNs share the same physics with space-time scales normalized to the BH mass.



- Solve the puzzle about the physical nature of their hard X-ray emission:
    - Comptonization of thermal/quasi-thermal disc photons within a hot electron-positron corona. Polarization fractions up to a few per cent at most
    - Synchrotron models of a relativistic jet. Synchrotron emission from the base of a magnetized jet, which in turn can “subsume” the role of the corona (Markoff et al. 2005) are expected to yield polarization fractions well exceeding 10 per cent (e.g., Celotti & Matt 1994; McNamara et al. 2009; see Figure 2.9).
- For different spectral states of the object, XIPE and IXPE will indicate where and how X rays are produced.
- The interplay between accretion processes and jet emission can be studied by eAstrogam in the MeV region, where disk Comptonization is expected to fade and other non-thermal components can originate from jet particles

e-Astrogam core science: Acceleration phenomena – SNR

- **What are the CR energy distributions produced inside SNRs and injected into the surrounding ISM?**

- **The performance of e-ASTROGAM will open the way for spectral imaging of SNRs**

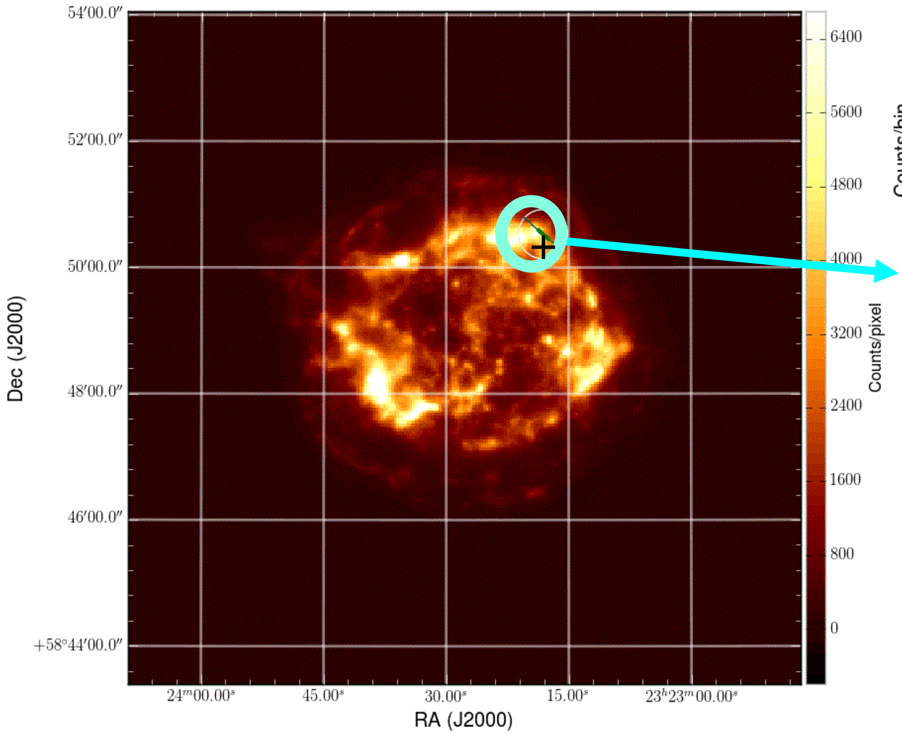
- **e-ASTROGAM bremsstrahlung emitting electrons have energy**
  - **Close to radio synchrotron ones**
  - **Lower than X-ray synchrotron ones**

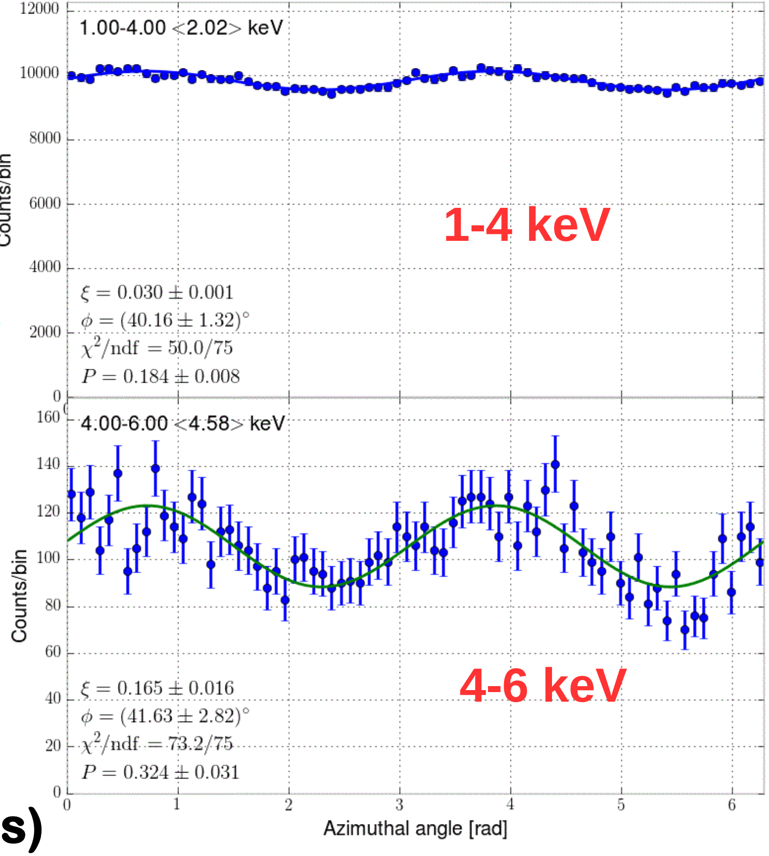
- **Thus allowing for tomographic reconstruction of the magnetic field and electron distributions inside the remnant**

- **Good match with X-ray imaging polarimetry to map magnetic fields in SNR !**

e-Astrogam core science: Acceleration phenomena – SNR

- **Lines and thermal continuum dominate 1-4 keV**
- **Non-thermal emission dominates 4-6 keV, synchrotron in X-rays, bremsstrahlung in γ-rays**



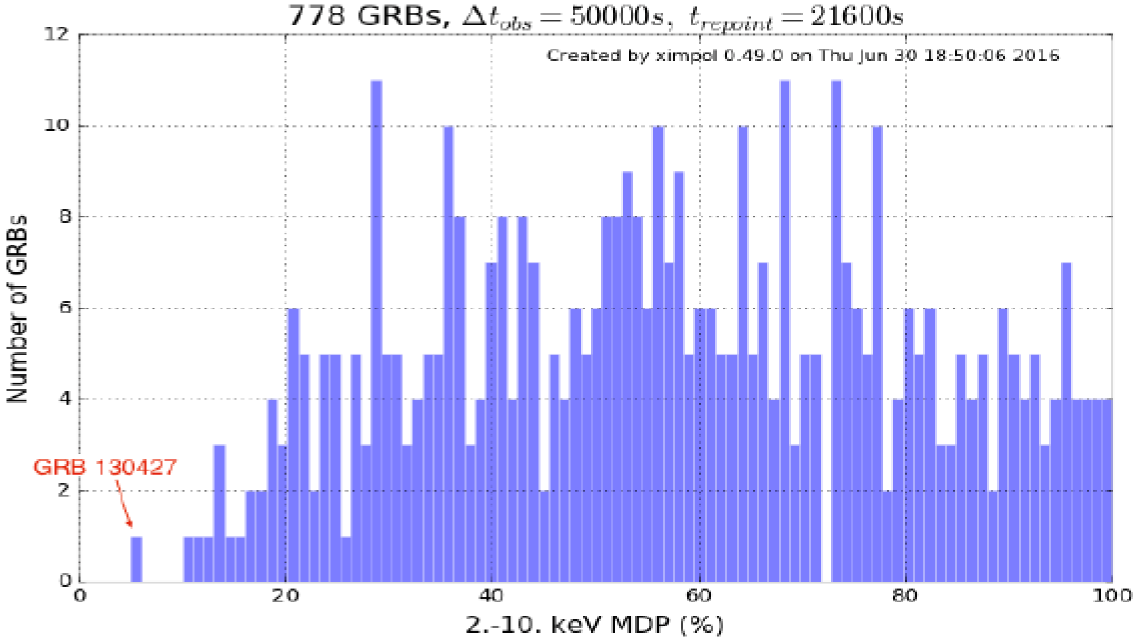


Cas A image at IXPE PSF resolution (1.5 Ms)

e-Astrogam core science: GRB

- Detection of prompt γ-ray flares with polarization degrees as high as 80% (Covino & Götz 2016 and references therein)
- Early optical afterglows with reverse shock polarizations up to 30% have been claimed.
- XIPE repointing after external trigger (< 12 h, best case 6 h)
- Possible direct XIPE detections of ordered magnetic fields in GRB jets (Mundell et al. 2013).

- Histogram MDP for 50-ksec XIPE exposure starting 6 hours post burst from all Swift GRBs observed for 6 hours or more post burst



- MDP<5% for bright GRBs like 130427A
- MDP<20% for 20
- MDP<40% for 100

e-Astrogam core science: GRB

- **For a substantial number of bright GRBs e-ASTROGAM will be able to detect polarization in the MeV range.**

- **42 GRBs/year with a detectable polarization fraction of 20%**

- **16 GRBs/year with detectable polarization fraction of 10%**

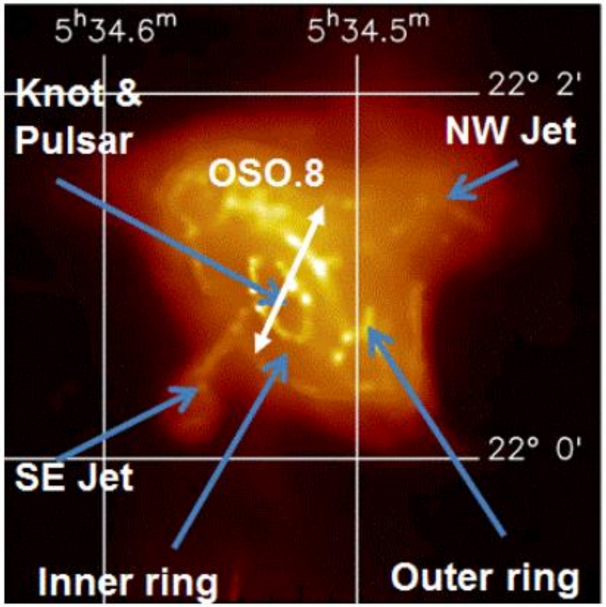
e-Astrogam + XIPE : γ-ray prompt polarimetry + X-ray afterglow polarimetry

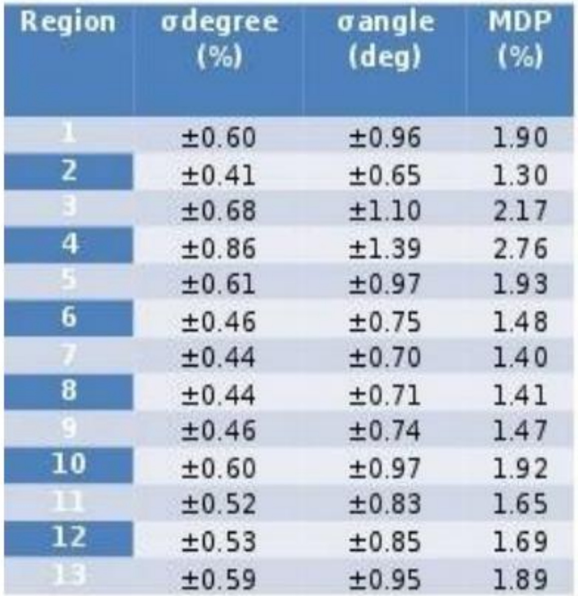
- **Unique diagnostic opportunity to address the role of magnetic fields in the radiative output and dynamics of the most relativistic outflows in our Universe**

XIPE and IXPE synergies with the e-Astrogam observatory science

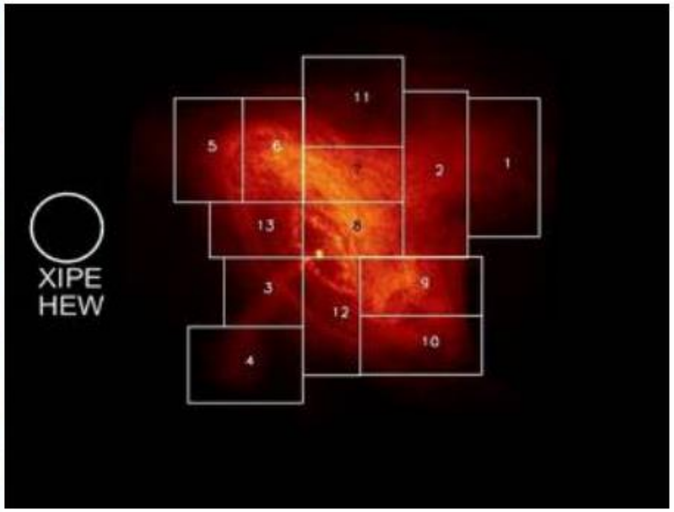
e-Astrogam observatory science: PWNs

- Synchrotron X rays from an ultrarelativistic pulsar wind shocked in the ambient medium. X-rays are produced in the regions close to where the electrons are accelerated and therefore provide a much cleaner view of the inner regions than optical.
- X-ray polarimetric imaging probes the magnetic-field topology





Region	σdegree (%)	σangle (deg)	MDP (%)
1	±0.60	±0.96	1.90
2	±0.41	±0.65	1.30
3	±0.68	±1.10	2.17
4	±0.86	±1.39	2.76
5	±0.61	±0.97	1.93
6	±0.46	±0.75	1.48
7	±0.44	±0.70	1.40
8	±0.44	±0.71	1.41
9	±0.46	±0.74	1.47
10	±0.60	±0.97	1.92
11	±0.52	±0.83	1.65
12	±0.53	±0.85	1.69
13	±0.59	±0.95	1.89



20 ks with XIPE

e-Astrogam observatory science: PWNs - pulsars phase resolved polarimetry: the Crab Pulsar

- Probe the emitting regions of pulsars through phase resolved polarimetry: Crab Pulsar

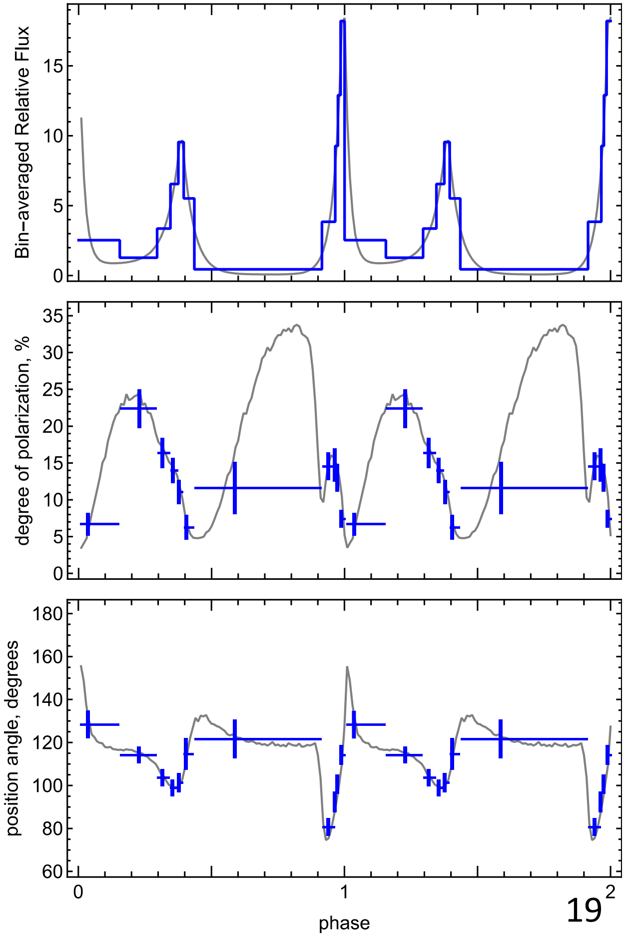
- Competing models predict differing polarization behavior with pulse phase

- X-rays provide cleaner probe of geometry
  - Absorption likely more prevalent in visible band
  - Radiation process entirely different in radio band

  Recently discovered no pulse phase-dependent variation in polarization degree and position angle @ 1.4 GHz

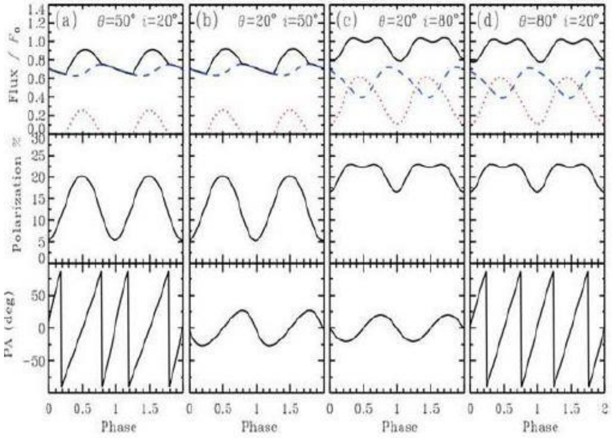
- **IXPE 140-ks observation gives ample statistics to track polarization degree and position angle**

Grey = optical

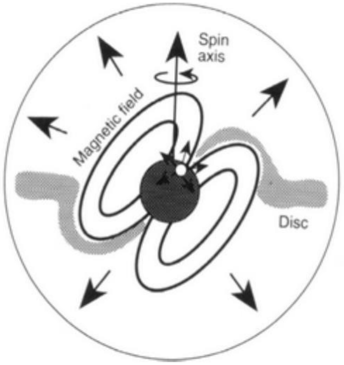


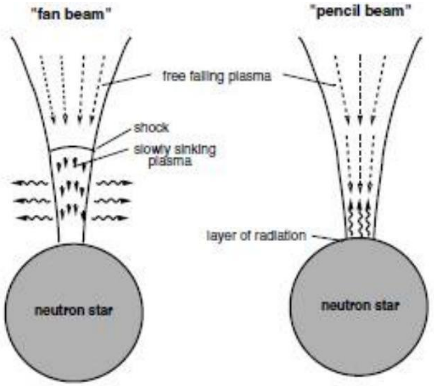
e-Astrogam observatory science: Pulsars and millisecond pulsars isolated and in binaries

- XIPE and IXPE core science includes:
- **Accredting millisecond pulsars** whose emission is due to scattering in hot spots and have a phase-dependent linear polarization
- **Binary X-ray pulsars** whose polarization allows signature is different for fan beam and pencil beam models



Viironen & Poutanen 2004

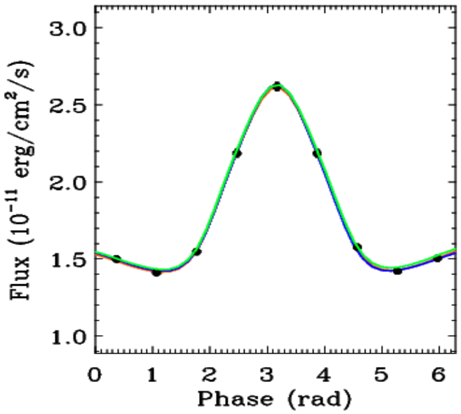




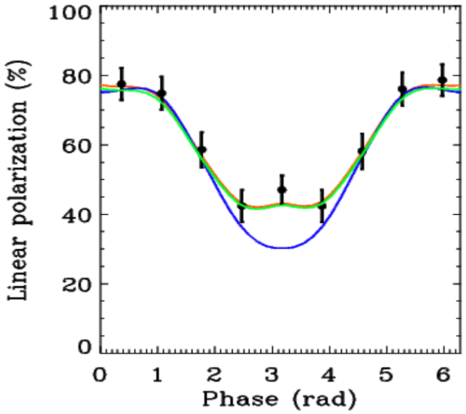
e-Astrogam observatory science: Magnetar – QED effects

- **Magnetar is a neutron star with magnetic field up to 10^{15} Gauss**
  - Non-linear QED predicts magnetized-vacuum birefringence
    - Refractive indices of the two polarization modes differ from 1 and from each other
    - Impacts polarization and position angle as functions of pulse phase, but not the flux
  - IXPE Example is the magnetar 1RXS J170849.0-400910, with an 11-s pulse period
    - Can exclude QED-off at better than 99.9% confidence in 250-ks observation

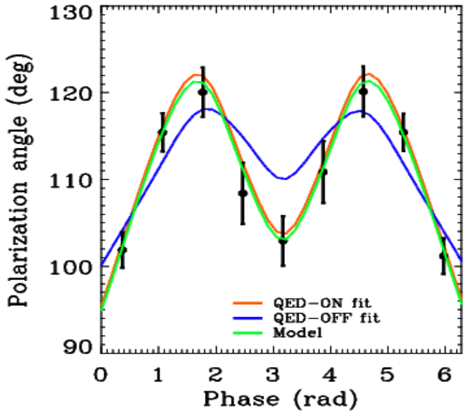
Light Curve



Polarization degree



Polarization Angle



e-Astrogam observatory science: propagation of photons over cosmological distances – ALPs search

- In a magnetic field the mixing between photons and ALPs produces both a photon-ALP conversion and, if a transverse component is present, a change of the photon polarization

- Intergalactic, intracluster and Galactic magnetic fields may significantly affect the polarization of radiation emitted by distant sources

- ALPs signatures should strongly depend on energy and on the projected position of the object on the sky because of the different magnetic field morphology in different directions of observation

- Blazars are natural candidate, but ALP-induced effect can be searched also in the correlation between the polarization of galactic sources and the viewing direction.

- Axion-photon conversion may rotate the polarization plane, of the emission from neutron stars (Perna et al. 2014).

XIPE available sources

Class	Required targets	Goal targets
Accreting millisecond X-ray pulsars	6	10
Blazars	19	31
Cataclysmic Variables	5	8
Galaxy clusters	1	2
Magnetars	5	7
Molecular Clouds	2	3
Pulsar Wind Nebulae & Rotation-powered Pulsars	5	8
Radio galaxies	5	8
Radio-Quiet AGNs	6	10
Supernova Renmants	5	8
X-ray binaries with black hole	7	11
X-ray binaries with neutron star	5	8
X-ray binaries with unknown companion	2	4
X-ray pulsars	8	13
TOT	**81**	**131**

Summary of the number of sources that XIPE will observe during nominal (required targets) and nominal + extended mission duration (goal targets)

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Picking the right direction

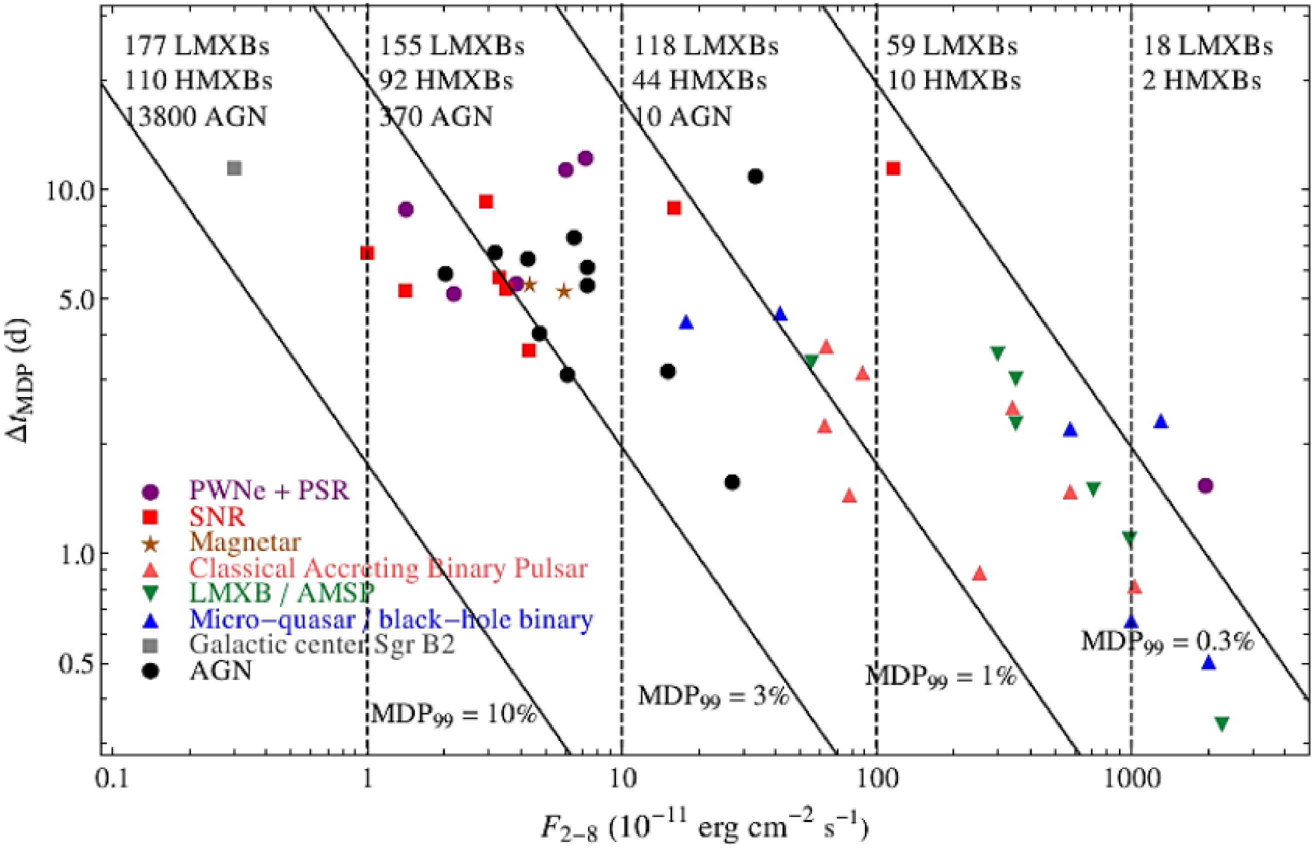
Xipe

esa

XIPE available sources

Object	$F_{2\text{-}8\ keV}$ (10^{-11} cgs)	T_{exp} (ks)	MDP (%) or ΔP/Δφ	CBE	Expected Polarization	Science goal
Crab Nebula **PWN**	1950	20	ΔP<1.3% Δφ <2deg in 13 regions	ΔP<0.8% Δφ <1.3deg in 13 regions	>19% (Weisskopf et al. 1978, Volpi et al. 2008)	Map of the Nebula
Vela PWN **PWN**	6.0	100	MDP=8.9%	MDP=5.7%	>10% (Volpi et al. 2008)	Mean polarization
Cas A **SNR**	116	1000	MDP=4.1%-7.2% in 7 regions	MDP=2.6%-4.6% in 7 regions	>10% in selected regions (Bykov et al. 2009, Fabiani et al. 2014)	Map of the remnant
Cyg X-1 **µQSO**	1000	100	MDP=0.44%	MDP=0.28%	<5%@2.6 keV (Weisskopf et al. 1977)	Jet, corona
Mrk 421 **Blazar**	27	100	MDP=2.7%	MDP=1.7%	>10-20% (Poutanen 1994, Celotti & Matt 1994)	Jet
Cen A (jet) **Radiogalaxy**	4	200	MDP=4.8%	MDP=3.1%	>10-20% (Poutanen 1994, Celotti & Matt 1994)	Jet (spatially resolved)
Am Her **MCV**	10	1000	MDP=4.4% /10 phase bins	MDP=2.8% /10 phase bins	5-10% (Matt 2004)	Accretion column
SAXJ1808 **AMP**	100	100	MDP=4.4% /10 phase bins	MDP=2.8% /10 phase bins	>5-10% (Viironen & Putanen 2004)	Scattering corona
Her X-1 **LMXB Pulsator**	90	100	MDP=4.7% in 10 phase bins	MDP=3.0% in 10 phase bins	>10% (Meszaros et al. 1988)	Fan vs. Pencil beam
1RXS J1708 Magnetar	4	250	MDP=14% in 10 phase bins	MDP=9% in 10 phase bins	>50% (Taverna et al. 2014, Van Adelsberg & Lai 2006)	Vacuum polarization
GX339-4 (outburst) **XRB**	500	100	MDP=0.62%	MDP=0.40%	>a few % (Schnittman & Krolik 2010)	Corona
GX339-4 (quiescence) **XRB**	4	1000	MDP=2.2%	MDP=1.4%	Unknown	Corona
NGC1068 **AGN**	0.5	1000	MDP=6.3%	MDP=4.0%	10% (Goosmann & Matt 2011)	Torus geometry
IC4329A **AGN**	10	100	MDP=4.4%	MDP=2.8%	> a few % (Schnittman & Krolik 2010)	Corona
SGR B complex **Molecular cloud**	0.3	1000	ΔP<6.3% and Δφ<5°	ΔP<4% and Δφ<3°	>20% (Churazov et al. 2002, Marin et al. submitted)	Past activity of SgrA*
GRS1915+105	1300	500	ΔP<0.78% and Δφ <1 deg	ΔP<0.50% and Δφ <1 deg	>5% (Dovciak et al. 2008, Schnittman et al. 2009)	BH spin
MCG-6-30-15 **AGN**	4	1000	MDP=2.2%	MDP=1.4%	5% (Dovciak et al. 2011)	BH spin

IXPE available sources



Exposure time Δt required to reach a specified minimum detectable polarization MDP at 99% of confidence level , as a function of source flux in the band 2-8 keV. The markers identify targets to be observed during the first year of the Baseline Science.

Conclusions

- **XIPE / IXPE share a relevant fraction of their science cases with e-Astrogam science case and observatory science.**

- **The acceleration of particles is for sure the most relevant point of contact**
    - **Jet in galactic sources and AGNs**
    - **SNR**
    - **PWN**
- **This includes the relationship between the jet, the disc and the corona**

- **e-Astrogam: M5 launch foreseen in 2029**

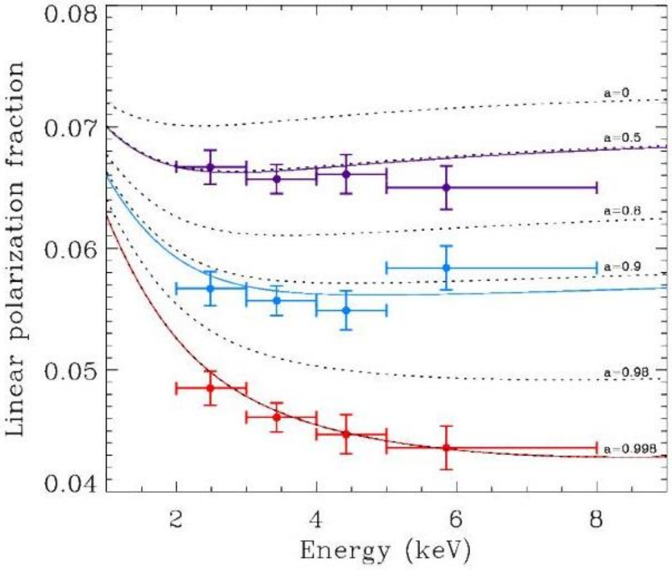
- **IXPE launch scheduled in November 2020 + 2 years of nominal operation**

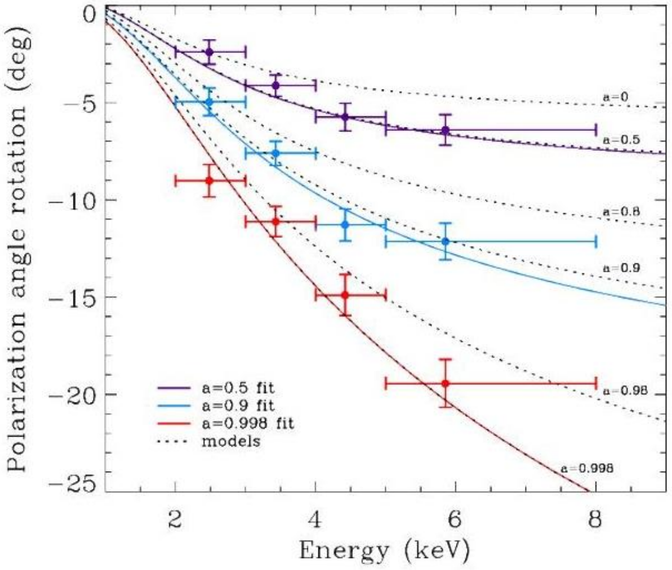
- **XIPE: M4 lauch foreseen in (<)2026 + 3 years of nominal operation (possibly GRB afterglow spectro-polarimetry in synergy with prompt γ-ray spectro polarimetry of e-Astrogam)**

e-Astrogam core science: black hole spin

For a micro-quasar in an accretion-dominated state constrain the BH spin

- **Scattering polarizes the thermal disk emission**
- **Energy dependent rotation of the X-ray polarisation plane due to strong gravitational filed**
- **Polarization rotation is greatest from inner disk (hotter, higher energy)**
- **GRO J1655-40, GX 339-4, Cyg X-1, GRS, 1915+105, XTE J1550-564, ...**
- **Example GRX1915+105 model a = 0.50±0.04; 0.900±0.008; 0.99800±0.00003**





**IXPE
200 ks
observation**

e-Astrogam core science: Acceleration phenomena μ-quasars

- **Microquasar SS443 large-scale, bi-conical jets.**
- **A XIPE 1 Msec exposure would cover ~10 per cent of the jets' precession period (160 days), enabling us to disentangle the polarization signature from the core vs. the jets by measuring phase-dependent changes.**