Transforming our understanding of the X-ray Universe: the Imaging X-ray Polarimetry Explorer (IXPE)

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CNRS

Université de Strasbourg

October 16th, 2018, Lagrange, Nice

INTRODUCTION

Quizz:

Who can tell me the name of a past/current mission dedicated to X-ray astronomy (spectroscopy, timing, polarimetry, imaging ...) ?

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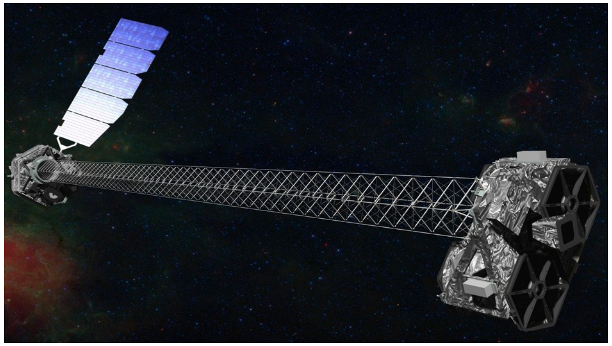
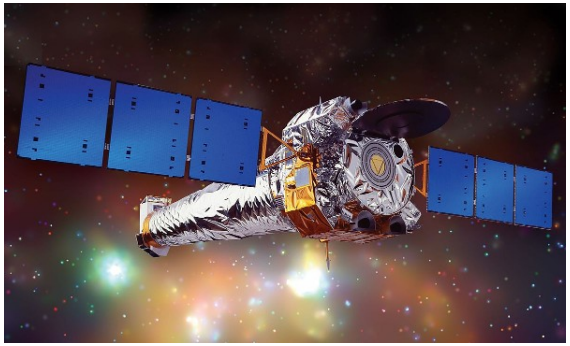


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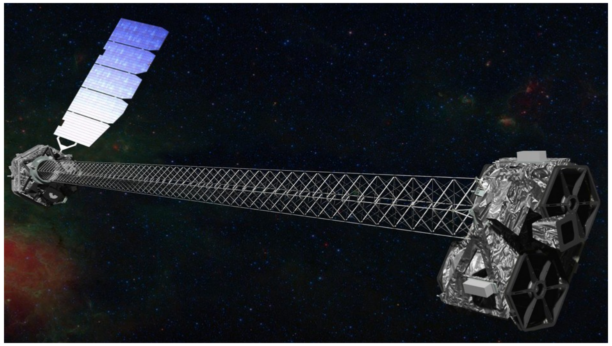

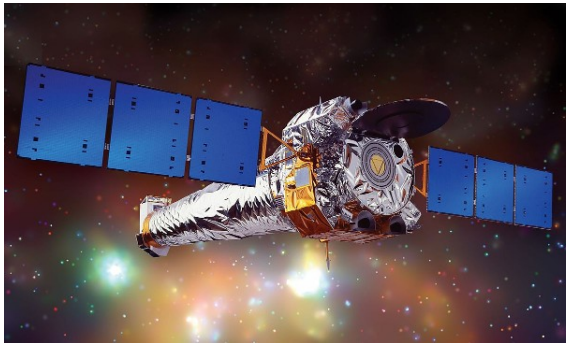

Who can tell me the name of a ***past mission dedicated to X-ray polarimetry*** *?*

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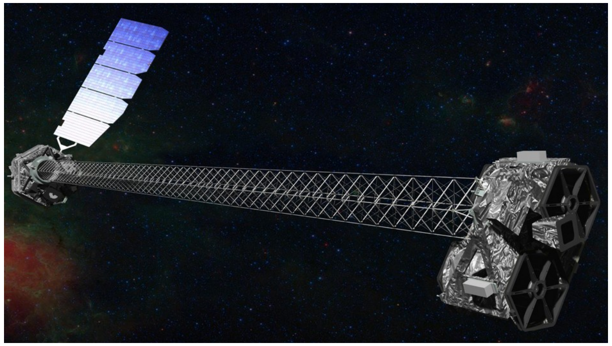

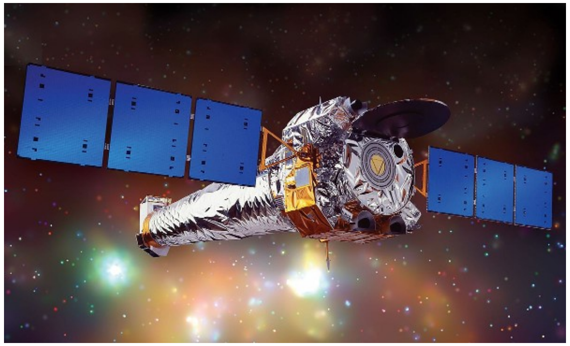

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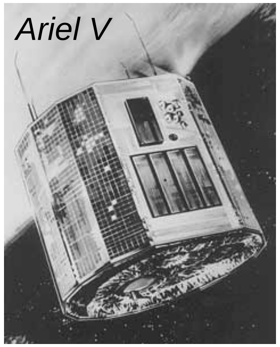

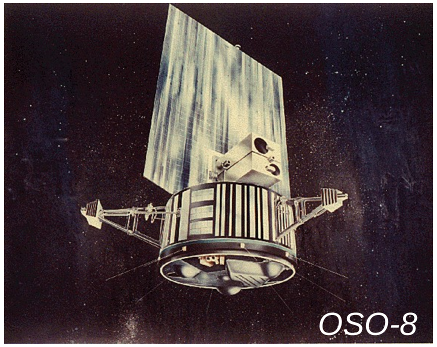

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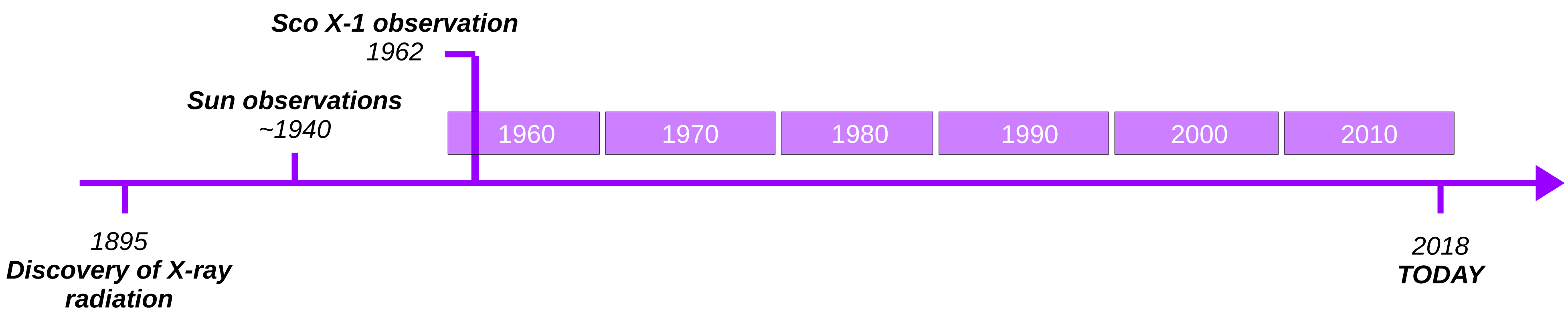
X-ray polarimetry is the least known/used method in X-ray astronomy

Why so ?



Wilhelm Röntgen

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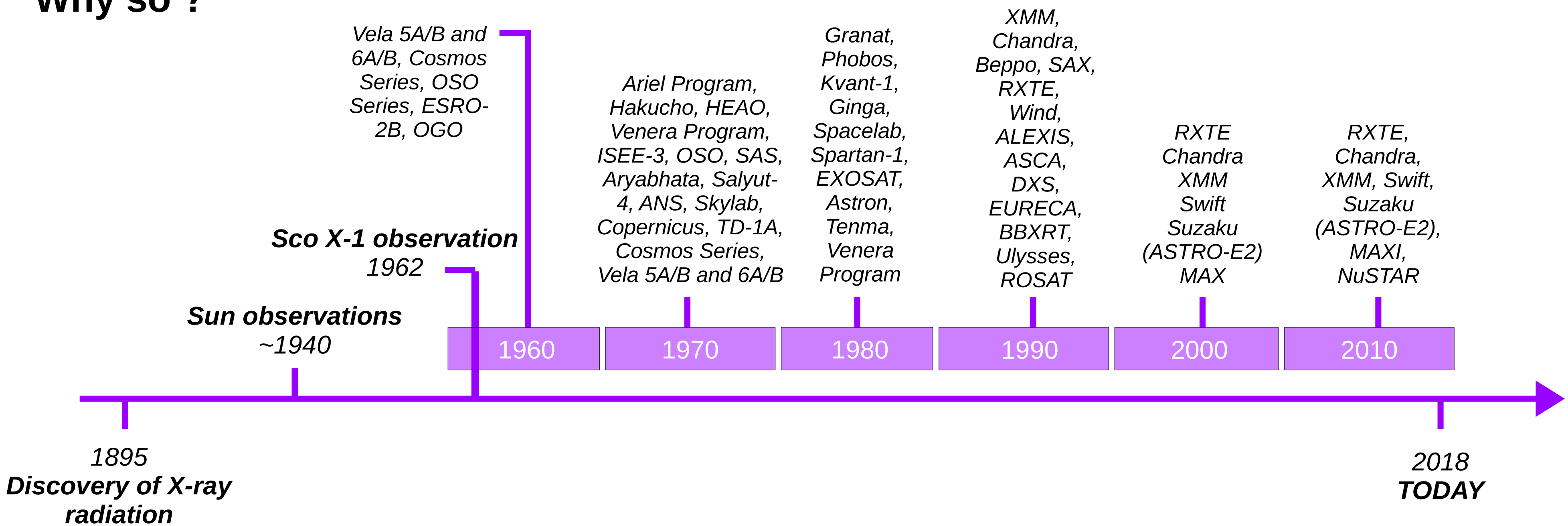

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Why so ?

1895
Discovery of X-ray radiation

Wilhelm Röntgen

Sun observations
~1940

Sco X-1 observation
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Vela 5A/B and 6A/B, Cosmos Series, OSO Series, ESRO-2B, OGO

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1968
Aerobee rockets

Bragg-crystal X-ray polarimeters
Galactic sources polarization

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Intercosmos I

Dnipropetrovsk Spoutnik satellite
Solar flares polarization

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Ariel Program, Hakucho, HEAO, Venera Program, ISEE-3, OSO, SAS, Aryabhata, Salyut-4, ANS, Skylab, Copernicus, TD-1A, Cosmos Series, Vela 5A/B and 6A/B

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2018
TODAY

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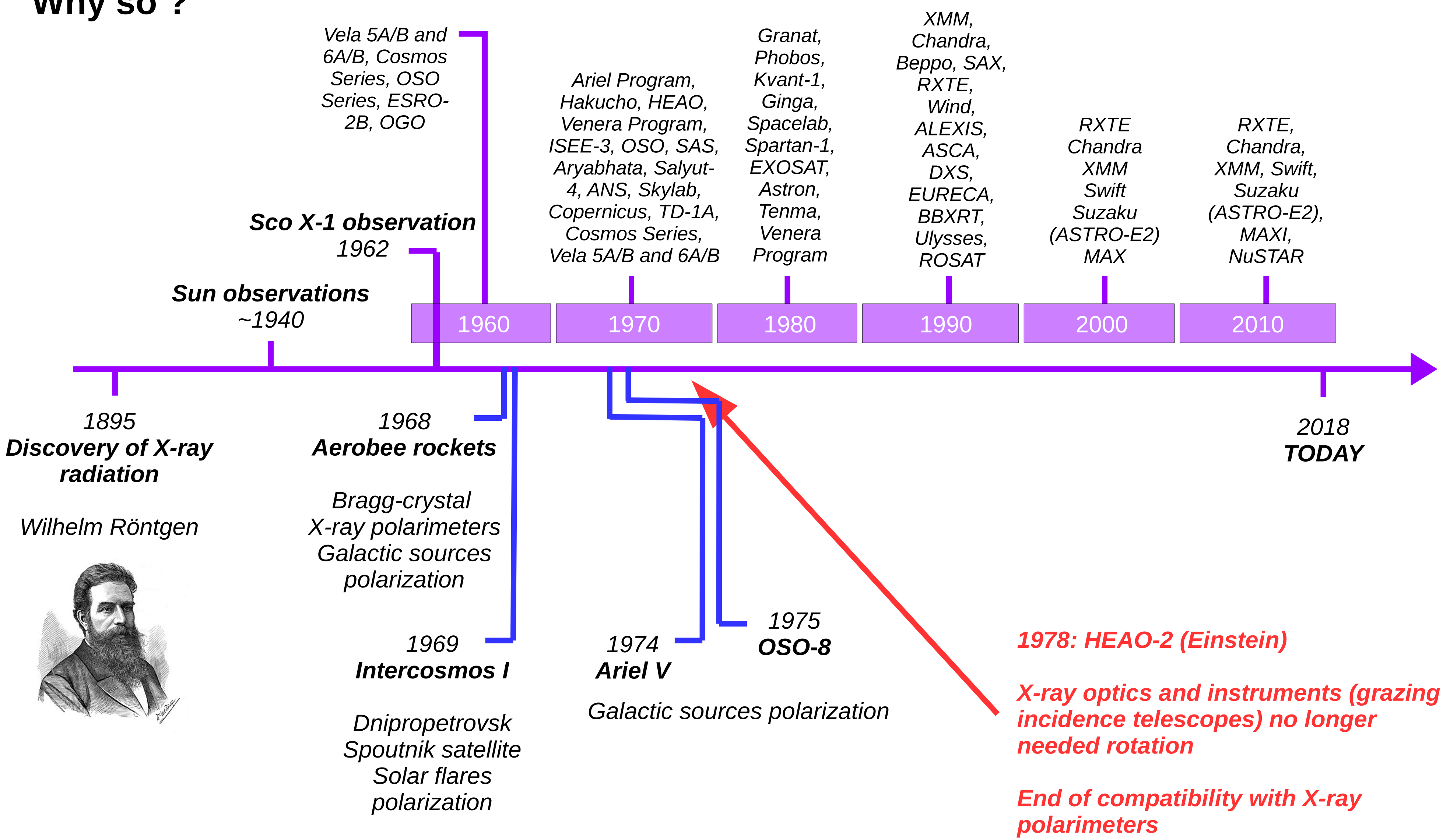

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Soft γ-ray polarization measurement of the Crab … dubious ...

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1960 | 1970 | 1980 | 1990 | 2000 | 2010

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2018
TODAY

2018
PoGO+

Hard X-ray measurement of the Crab and Cyg X-1.

POLARIZATION

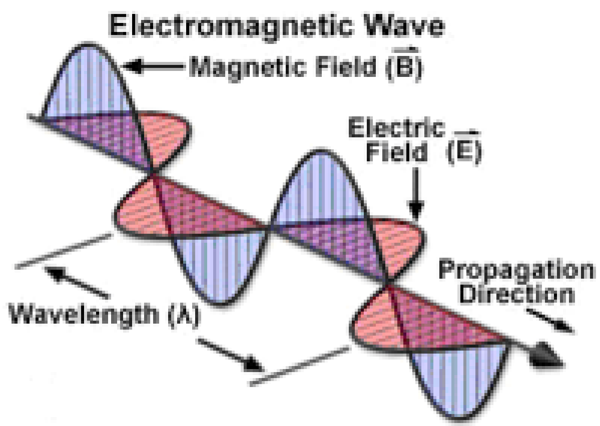
There is a clear lack of X-ray satellites mounted with an X-ray telescope

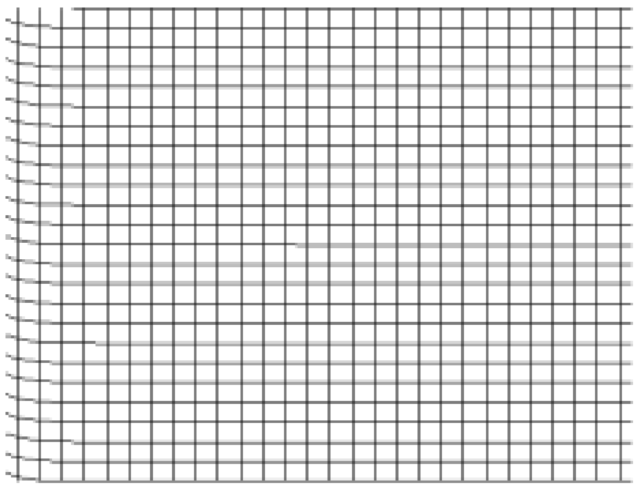
→ Polarimetry is more complicated than photometry, spectroscopy or timing

Reminder on polarization

Polarization is intrinsically connected with the transverse nature of light

The electric and magnetic field vectors oscillate perpendicularly (or right angled) to the direction of energy transfer



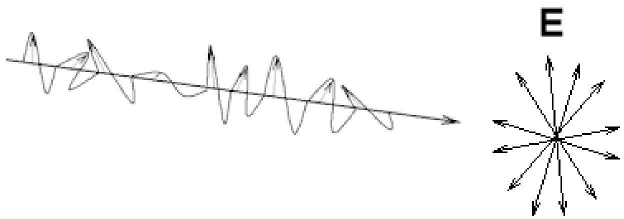


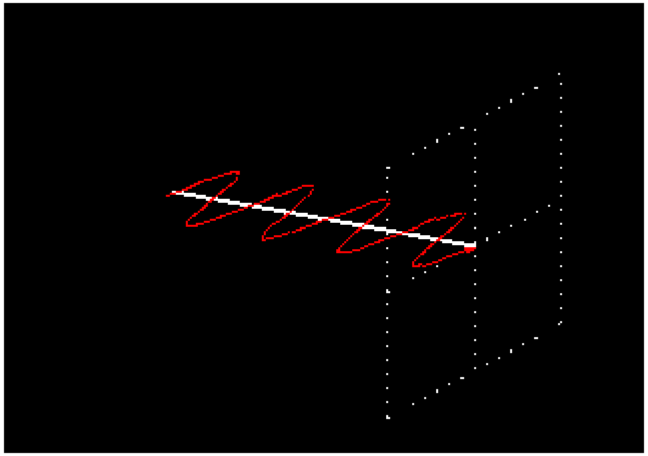
E.g.: light, transverse seismic waves, waves in a guitar string

POLARIZATION

Reminder on polarization

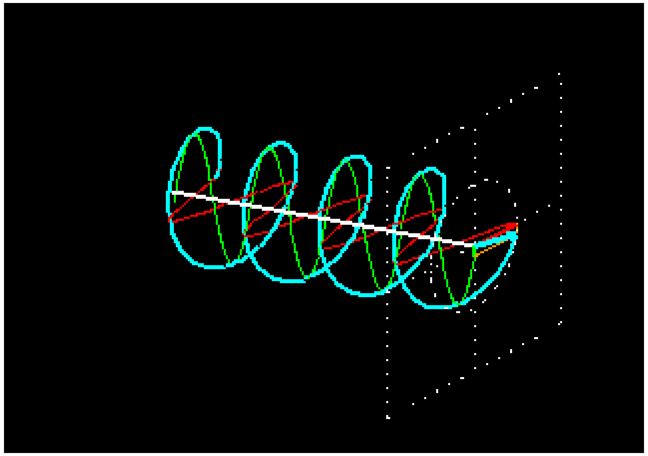
By definition, the electric vector oscillates randomly (natural light is unpolarized)





However, during the measurement time, if the temporal evolution of the tip of its transverse (electric) vector is found to be stationary, the wave is said to be polarized

→ vectorial nature of light (Young 1801, Fresnel 1821)



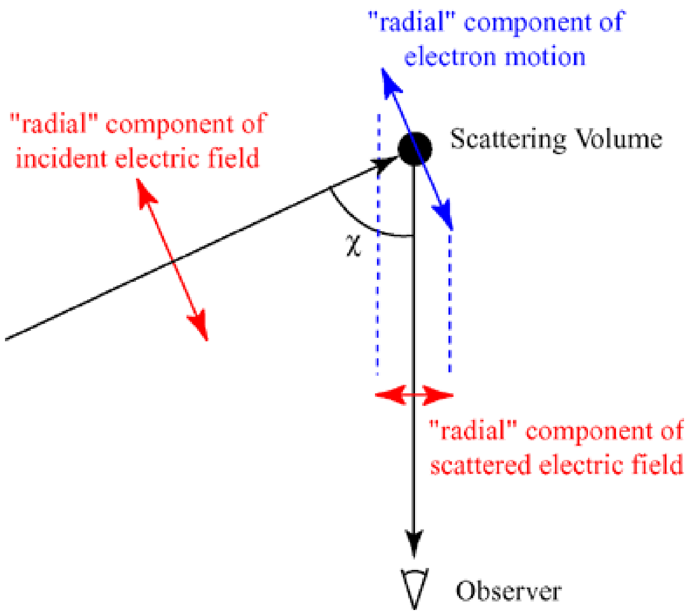
For this reason, polarization phenomena are inexistent for longitudinal waves

Polarization is thus an important information encoded in spatially asymmetric electromagnetic waves
(along with intensity, frequency and phase)

POLARIZATION

Reminder on polarization

How to produce/modify/cancel polarization ?
- Intrinsic polarization
- Absorption / re-emission
- Magnetic effects (Faraday rotation, Zeeman effect …)
- Scattering (Thomson, Mie, Compton …)
- General relativity
- Dilution by starlight



+ polarization sensitive to geometry and composition !

How do we measure polarization ?

Polarization degree

A quantity used to describe the portion of an electromagnetic wave which is polarized
Perfectly polarized wave = 100%, unpolarized wave = 0%

Polarization angle

Orientation of the plane of vibration of the electric vector (for linear polarization)

X-RAY POLARIZATION

The problem of X-ray polarization

Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies

X-ray polarimetry can be based on any of three distinct physical effects:

- Bragg diffraction
- Scattering polarimeters
- Photoelectron tracking

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Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies

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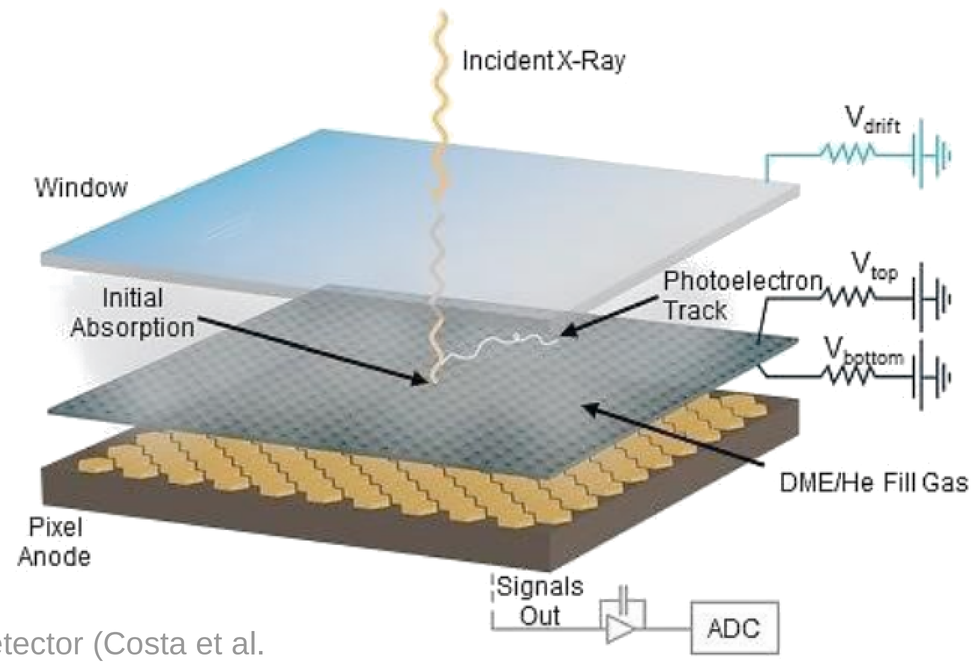
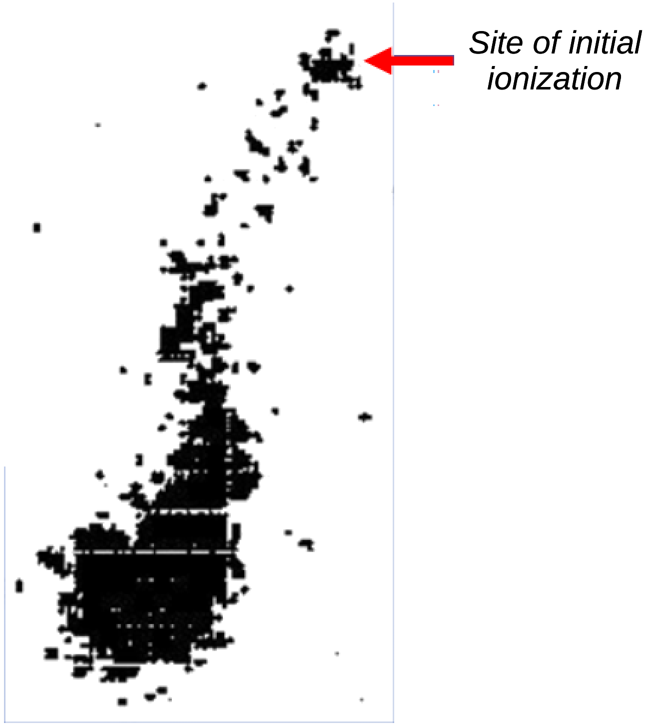
- **Photoelectron tracking** : the direction of the initial K-shell photoelectron is determined by the electric vector and the direction of the incoming photon



Gas Pixel Detector (Costa et al. 2001, Bellazzini et al. 2006, 2007)



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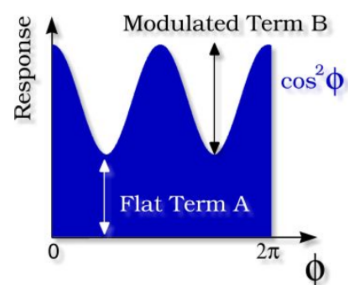
Measure of polarization using modulation

Fit function: $\mathcal{M}(\phi) = A + B\cos^2(\phi - \phi_0)$

Modulation: $\dfrac{\mathcal{M}_{\max} - \mathcal{M}_{\min}}{\mathcal{M}_{\max} + \mathcal{M}_{\min}} = \dfrac{B}{B + 2A}$

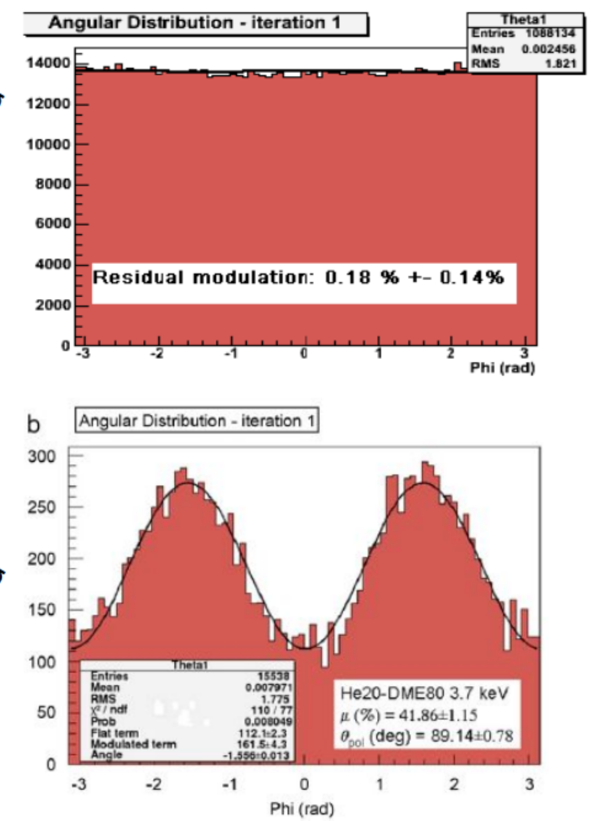
Polarization: $\dfrac{1}{\mu}\dfrac{B}{B + 2A}$

μ is the modulation factor



unpolarized

polarized



VERY SENSITIVE IN THE 1 – 40 keV RANGE
NO ROTATION
IMAGING

A MAJOR LIMIT

Even with the best technology, X-ray polarimetry is facing a big limit

Source detection >10 photons
Source spectra >100 photons
Source polarimetry >100000 photons

X-ray polarization is photon hungry !

In polarimetry the sensitivity is a matter of photons
To describe the capability of rejecting the null hypothesis (no polarization) at 99% confidence, we use the Minimum Detectable Polarization:

$$MDP = \frac{4.29}{\mu R_S} \sqrt{\frac{R_S + R_B}{T}}$$

R_S is the source rate, R_B is the background rate,
T is the observing time, μ is the modulation factor
(the modulation of the response of the polarimeter to a 100% polarized beam)

Examples to reach a MDP of 1%:

- Crab (PWN) > 10 ks
- X-ray binary > 100 ks
- Active Galactic Nuclei ~ 1 Ms

Future instruments

IXPE: the forthcoming mission !

In 2014 NASA issued an AOO for a Small Explorer Mission (budget of ~ 175 M$)
→ Deadline Dec 2014

On July 30th 2015, NASA selected 3 missions for phase A study

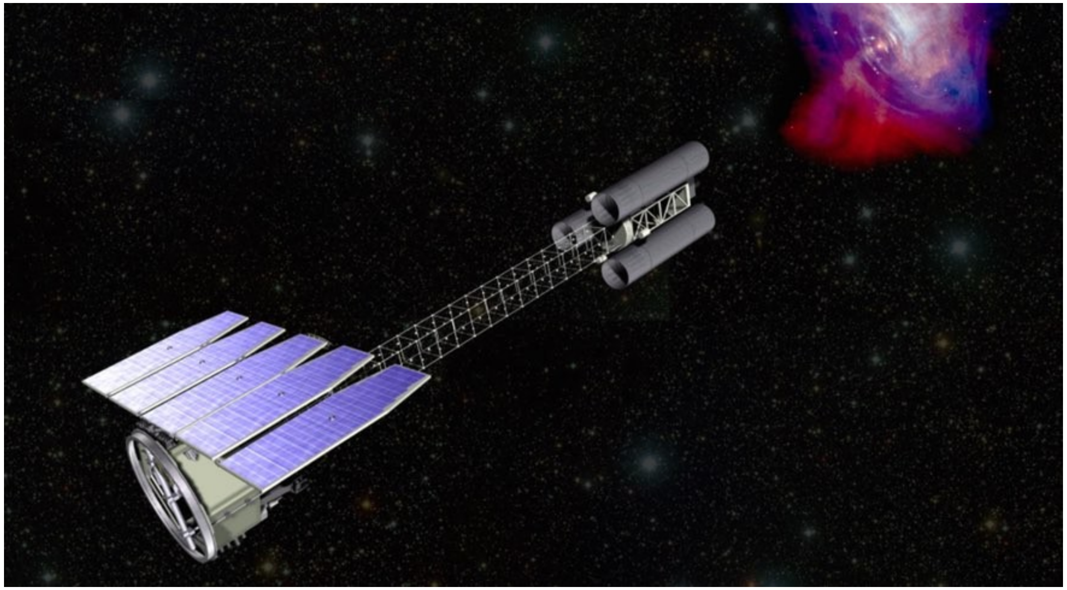
1) IXPE: X-ray Polarimetric mission based on GPD; P.I. Martin Weisskopf
2) Praxys: X-ray Polarimetric mission based on TPC
3) SPHEREx: All Sky Survey with Near IR spectroscopy

Phase A accomplished in July 2016. Site Visit at MSFC the 17th Nov 2016. On January the 3rd 2017, NASA selected IXPE

Launch in 2021

SPECTROSCOPY
IMAGING
POLARIZATION

2 – 8 keV
2 years duration
100+ targets



Future instruments

IXPE: the forthcoming mission !

Payload requirements		
Total collecting area	>1100 cm^2 at 3 keV	See Req-Sci-010
Modulation factor	>30% at 3 keV	See Req-Sci-010
Detector efficiency	>10% at 3 keV	See Req-Sci-010

Parameter	Quantity	Scientific driver
Scientific requirements		
Polarimetric sensitivity	MDP<10% for 100ks observation of source with flux $2x10^{-11}$ $erg/s/cm^2$ (1 mCrab) in the 2-8 keV band	NGC1068, GC, …
Spurious polarization	<0.5%	GRS1915, Cyg X-1
Angular resolution	<30 arcsec	Crab, jet in CenA, SNR, GC, …
Field of View	>10 arcmin	PWNe, SNRs, …
Spectral resolution	<20% at 5.9 keV	Black hole spin
Timing resolution	8 µs	Accreting millisecond pulsars
Timing synchronization with the Universal Time	10 µs	Accreting millisecond pulsars
Dead time for one telescope	<100 µs	Crab Nebula, Cyg X-1, …
Mission duration	3 yr	Core program and population studies
TOO	Repointing <12 hr during working hours	Bursters
Sky accessibility	1/3 of the sky accessible at any time	Observation of galactic and extragalactic sources
Forbidden directions	None over one year	Core program and population studies

ACCELERATION PHENOMENA

What can we do with X-ray polarimetry ?

1 – Acceleration phenomena

Supernova remnants (SNR) are believed to be the acceleration sites of cosmic rays up to very high energies

→ diffusive shock acceleration

To achieve the observed multi-TeV energies, the magnetic field must be amplified well above the adiabatic compressed magnitude (Amato 2014)

→ amplified magnetic field likely highly turbulent

High resolution imaging X-ray polarimetry :

- unique constraints on the magnetic field amplification mechanisms
- localize the regions of shock acceleration
- measure the strength and the orientation of the magnetic field at the emission sites (Vink 2012).

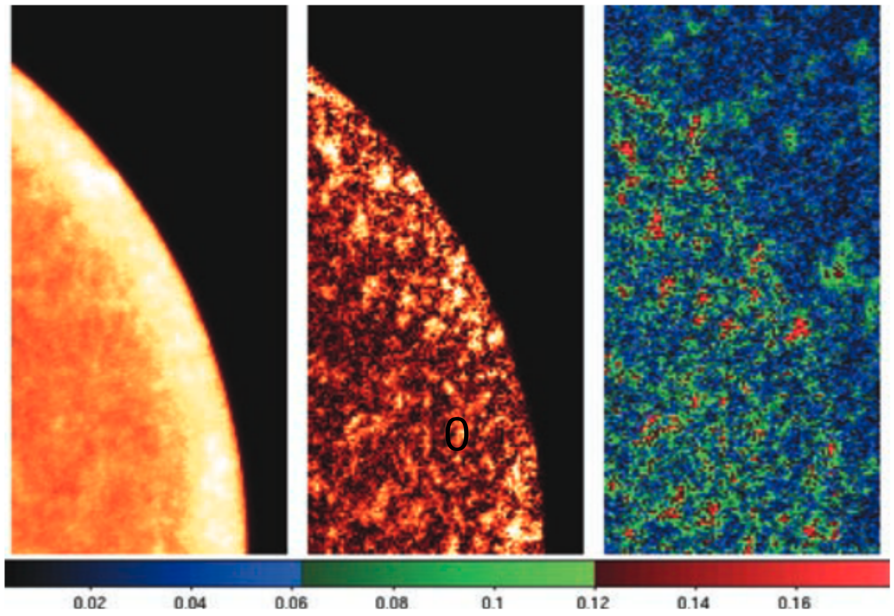


Figure 2. Simulated maps of polarized synchrotron emission in a random magnetic field at 0.5 keV. Intensity, $\nu^2\ I(\boldsymbol{R}_\perp, t, \nu)$, is shown with a linear colour scale in the left-hand panel. The central panel shows the product of intensity and polarization degree. The right-hand panel shows the degree of polarization indicated by the colour bar. The stochastic magnetic field sample has $\sqrt{\langle B^2 \rangle} = 3 \times 10^{-5}$ G and spectral index $\delta = 1.0$.

Bykov et al. (2009)

ACCELERATION PHENOMENA

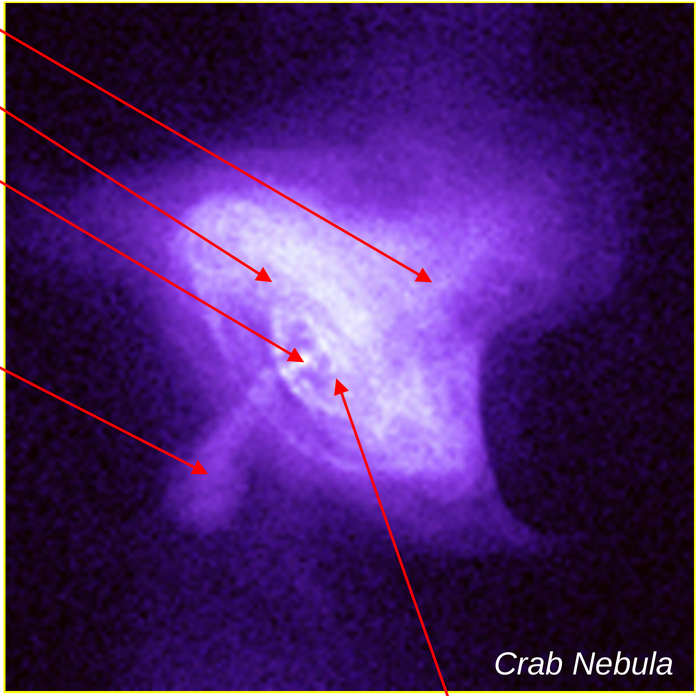
What can we do with X-ray polarimetry ?

1 – Acceleration phenomena

Magnetic fields in pulsar wind nebulae (PWN) are rather well ordered, so the emission is locally highly polarized in the radio and optical bands (up to 60%, close to the theoretical limit)

X-ray emitting electrons have a synchrotron lifetime far shorter than that of particles which emit at longer wavelengths,

→ 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



Detailed and spatially-resolved X-ray polarization measurements will allow to determine the magnetic field orientation in the torus, the jet and at various distances from the pulsar

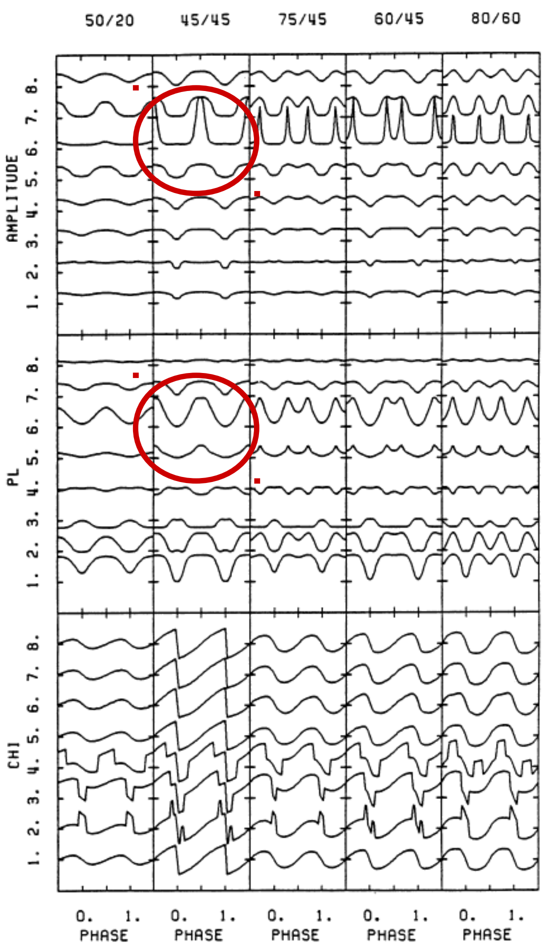
This is of significant interest because, compared to the total synchrotron emission, polarized emission is a more sensitive probe of the plasma dynamics in these nebulae

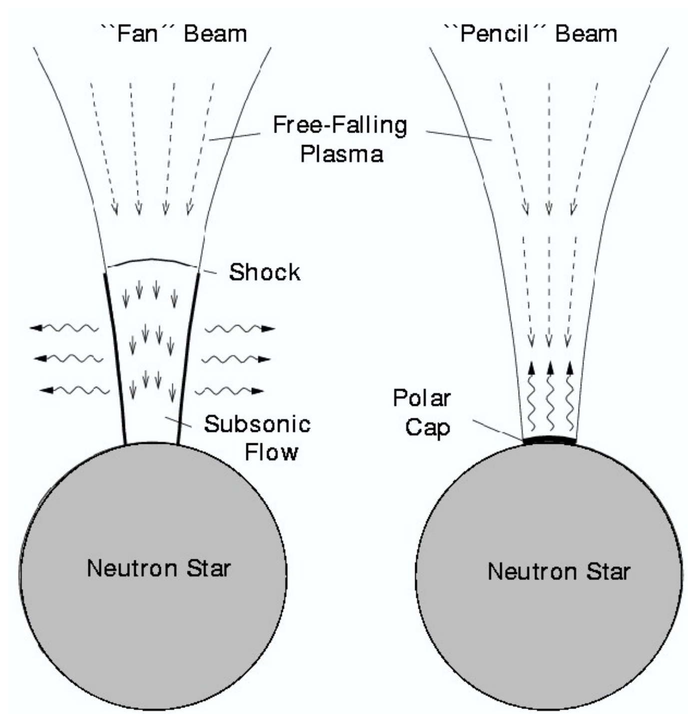
Accreting sources

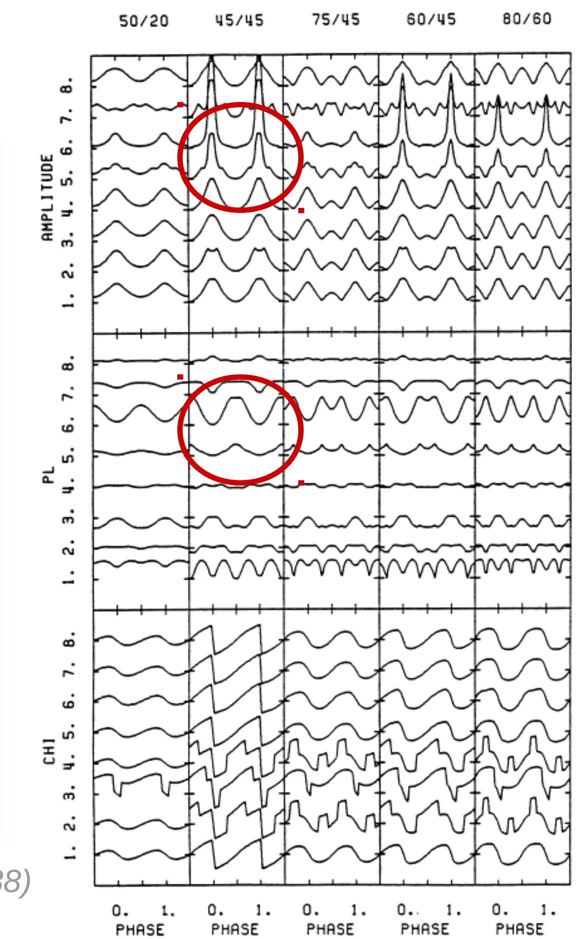
What can we do with X-ray polarimetry ?

2 – Emission in strong magnetic fields

Phase-resolved polarimetry can distinguish between “pencil” and “fan” radiation patterns
→ the degree of linear polarization is maximal for emission perpendicular to the magnetic field, the flux and degree of polarization are in-phase for fan beams, but out-of-phase for pencil beams







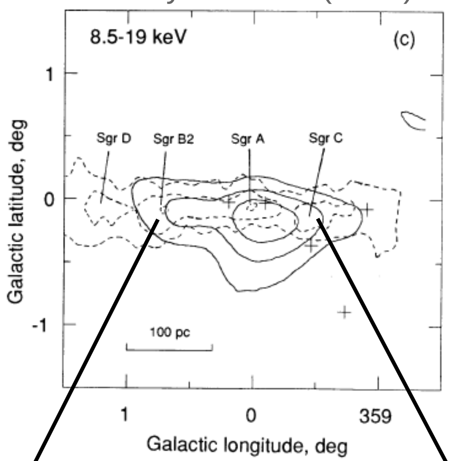
Meszaros et al. (1988)

SCATTERING

What can we do with X-ray polarimetry ?

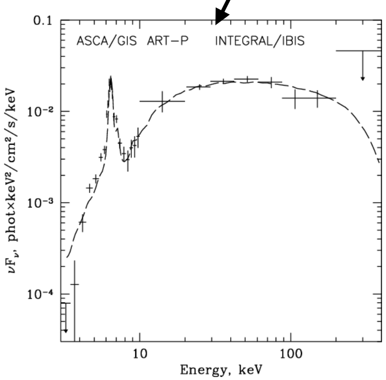
3 – Scattering in aspherical geometries

Sunyaev et al. (1993)

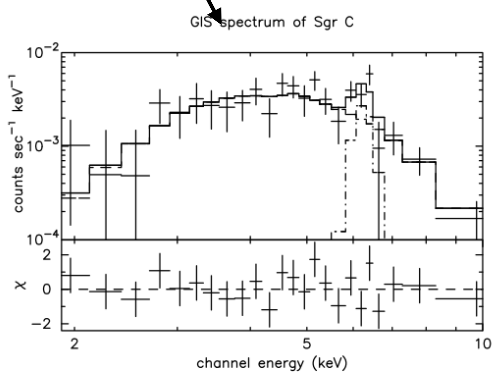


Demonstrating past activity from Sgr A* through polarization measurements of the X-ray flux from nearby molecular clouds

Sgr A* has a very low accretion rate ~ 10^{-8} M_{sol} y^{-1} near the event horizon (Baganoff et al. 2003)



Koyama et al. (1996)
Terrier et al. (2010)



Murakami et al. (2001)

→ X-ray luminosity of the order 2 × 10^{33} erg s^{-1}
(Baganoff et al. 2001; Quataert 2002)

Pure reflection spectra (L_X ~ 10^{35} erg s^{-1}) …
but no nearby sources bright enough !

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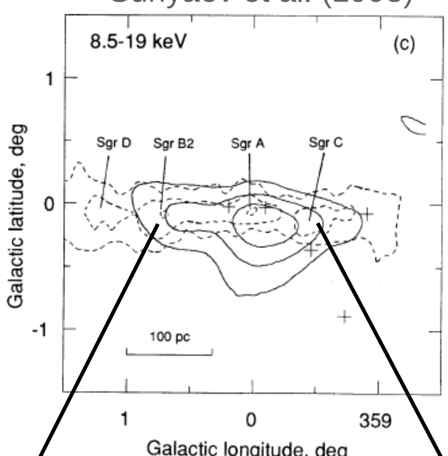
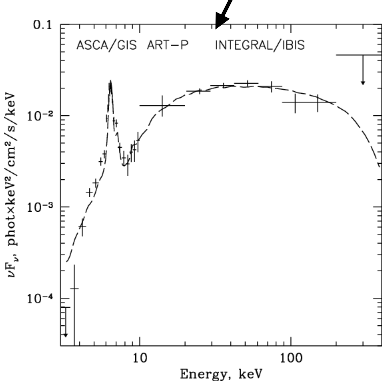


Demonstrating past activity from Sgr A* through polarization measurements of the X-ray flux from nearby molecular clouds

- the degree of polarization is related to the source-cloud-observer (scattering) angle

- the position angle is perpendicular to the source direction



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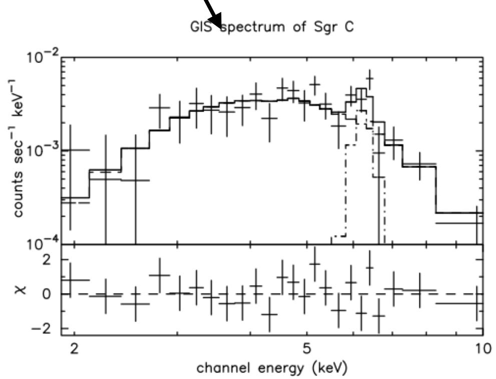

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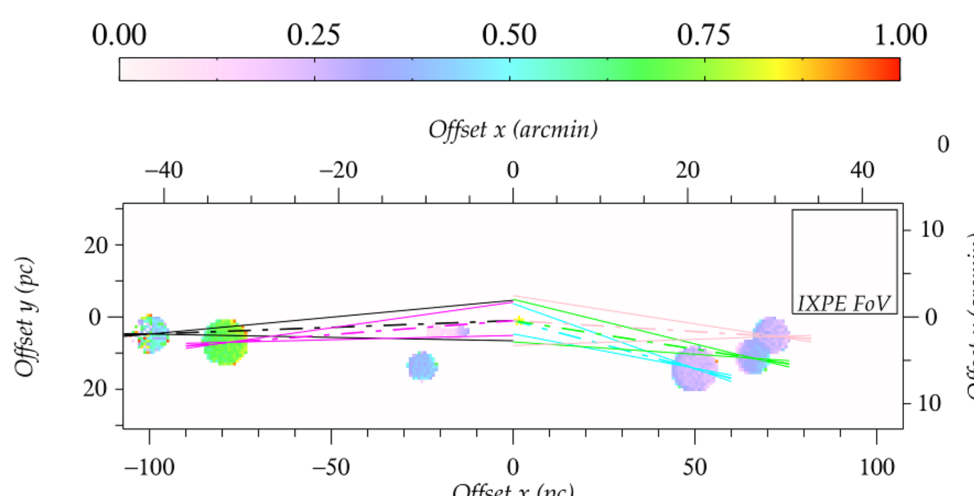

Marin et al. (2014,2015)

SCATTERING

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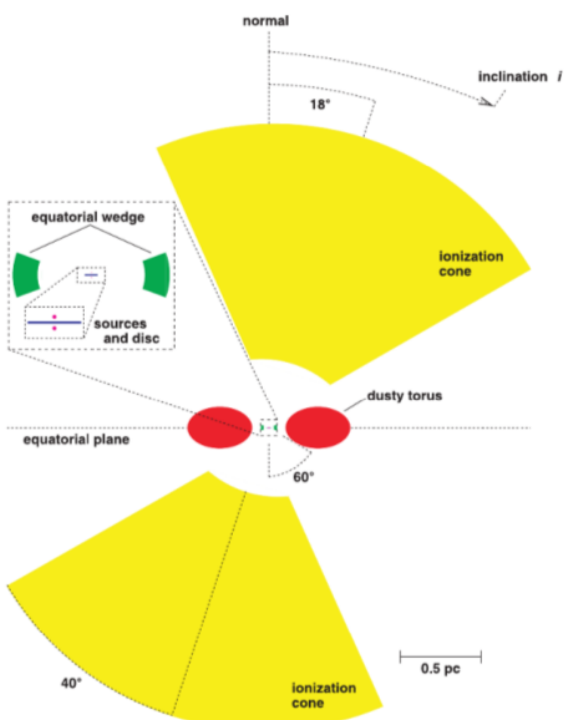
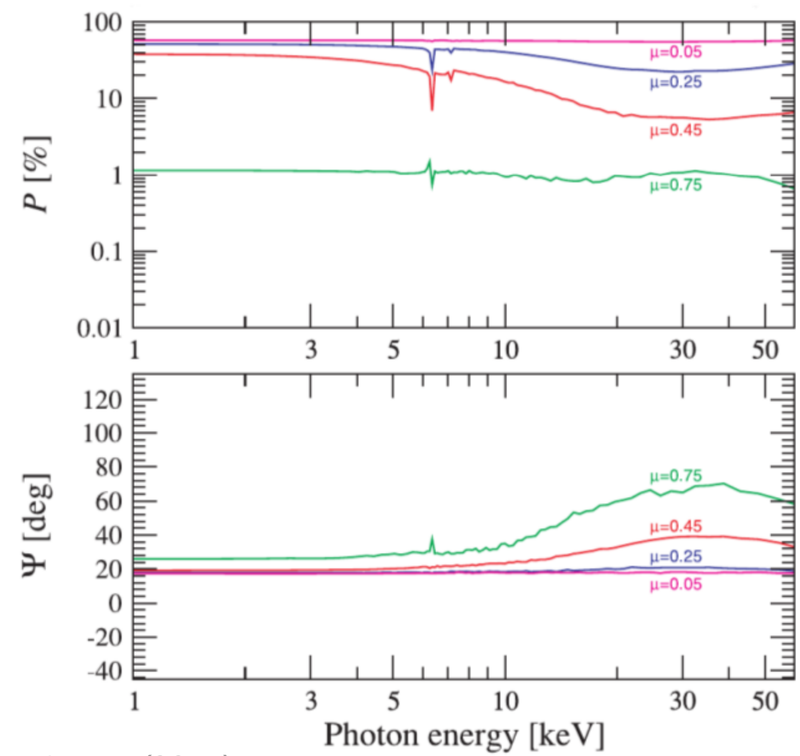
3 – Scattering in aspherical geometries

Active galactic nuclei (AGN) are scaled up version of galactic black holes (micro-quasars)
- black hole
- accretion disk
- winds
- jets (sometimes)

At first order:
axisymmetry

Unresolvable scattering regions
→ polarization as a tracer of any asymmetry





Goosmann & Matt (2011)

Vacuum birefringence

What can we do with X-ray polarimetry ?

4 – Fundamental physics

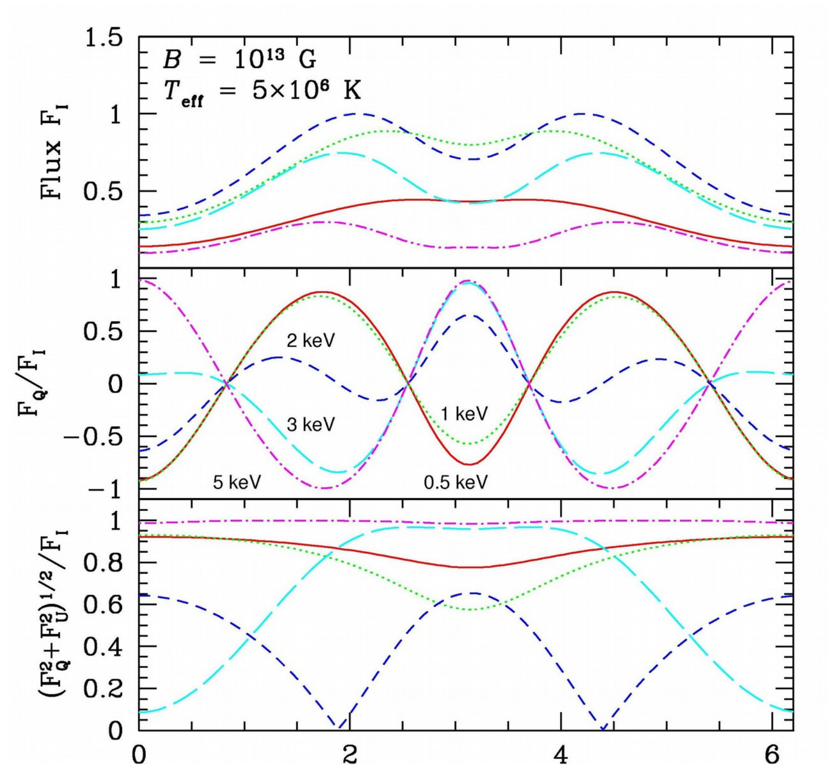
X-ray polarimetry of NS emission gives the opportunity to observe a QED effect predicted nearly 80 years ago (Heisenberg & Euler 1936) but still to be experimentally confirmed

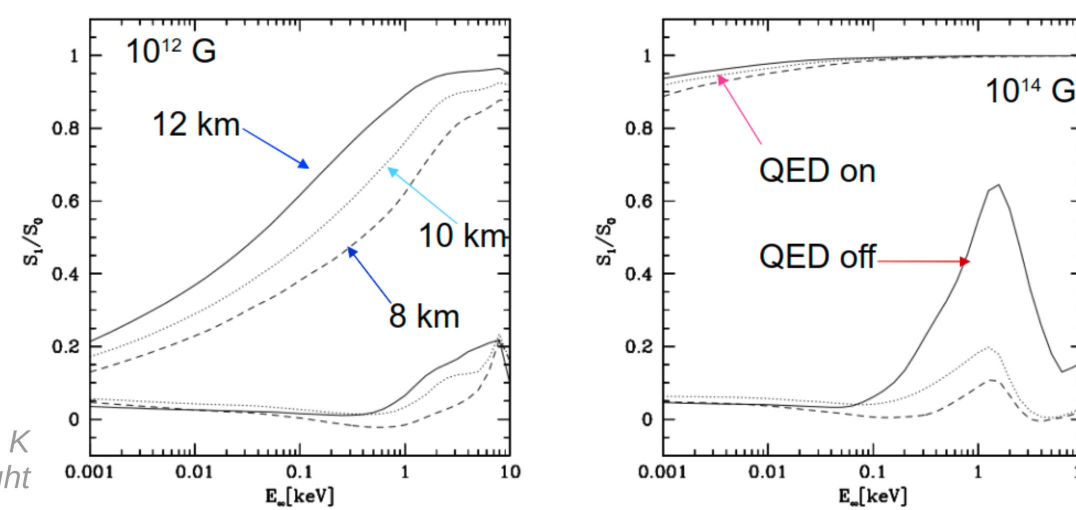
Photons propagating in strong magnetic fields are subject to a phenomenon called the "vacuum birefringence" where refractive indices of two physical modes both deviate from unity and differ from each other

→ significant change in the dependence on the phase and the energy of the polarization

→ a strong test of the magnetar paradigm and a probe of strong-field QED

Van Adelsberg & Lai (2006)





Linear polarization for hydrogen atmospheres with Teff=106.5 K NS and magnetic moment 30 degrees from the line of sight

Strong gravity effects

What can we do with X-ray polarimetry ?

4 – Fundamental physics

Disk illuminated by a hot corona (geom., temp., … ?)
→ soft X-rays: absorption + reemission
→ hard X-rays: Compton scattering

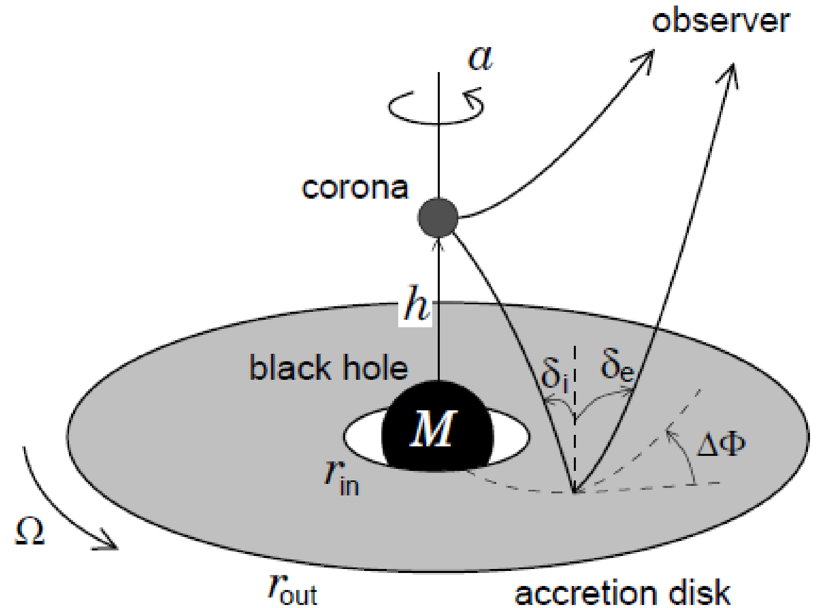
Scattering = polarization

Strong gravity fields affect the polarization of scattered radiation (Connors et al. 1980)

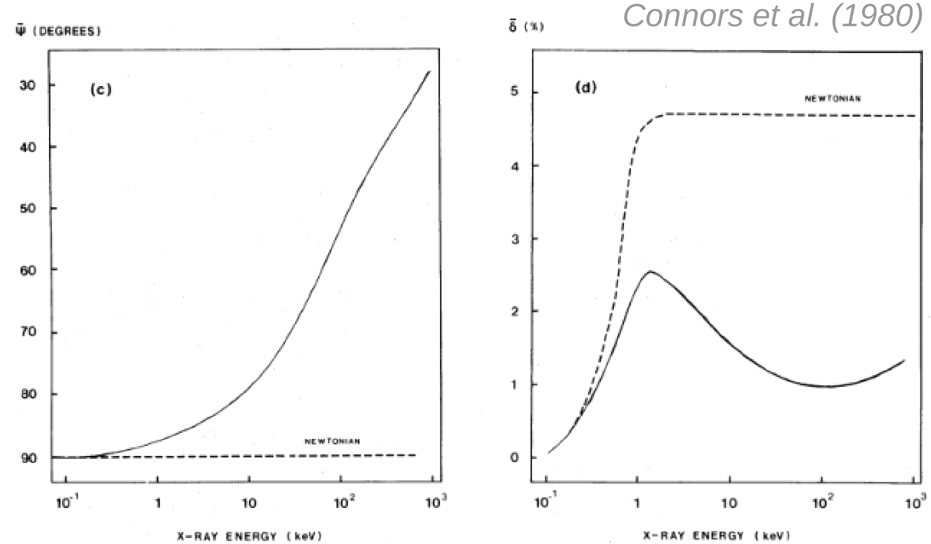
→ the polarization angle as seen at infinity is rotated due to aberration (SR) and light bending (GR) effects

The rotation is larger for smaller radii and higher inclination angles and it depends on the spin of the BH !

Dovciak et al. (2004)



Connors et al. (1980)



Strong gravity effects

What can we do with X-ray polarimetry ?

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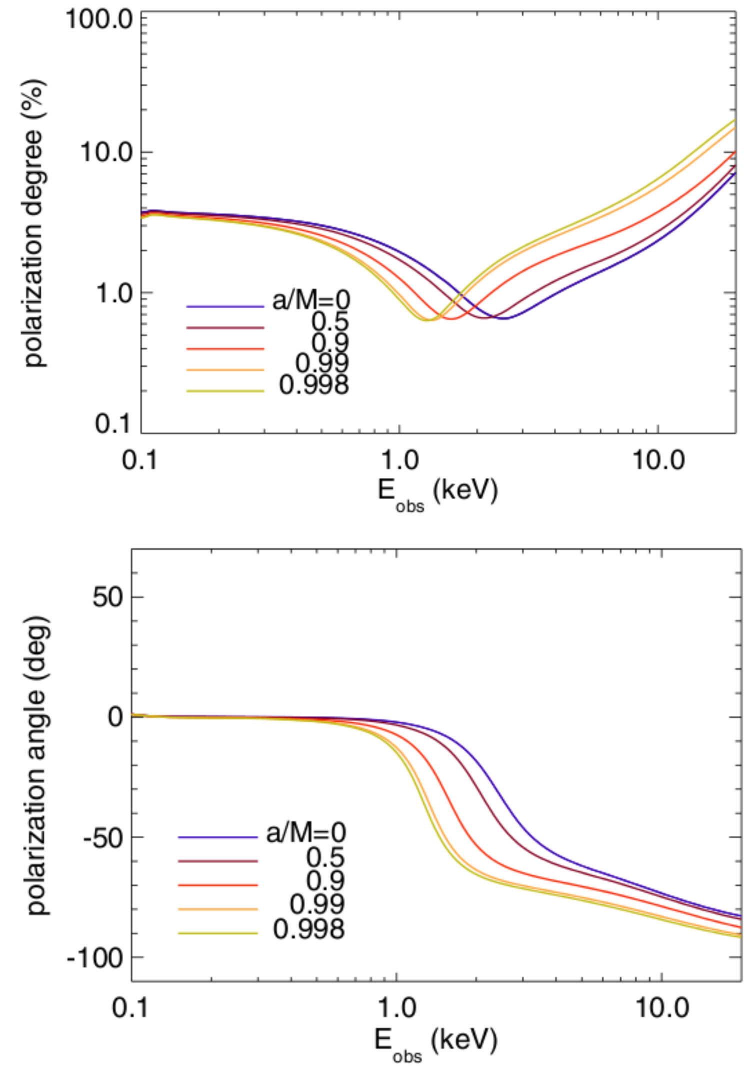
Schnittmann & Krolik (2009)



First balloon-borne results

nature astronomy

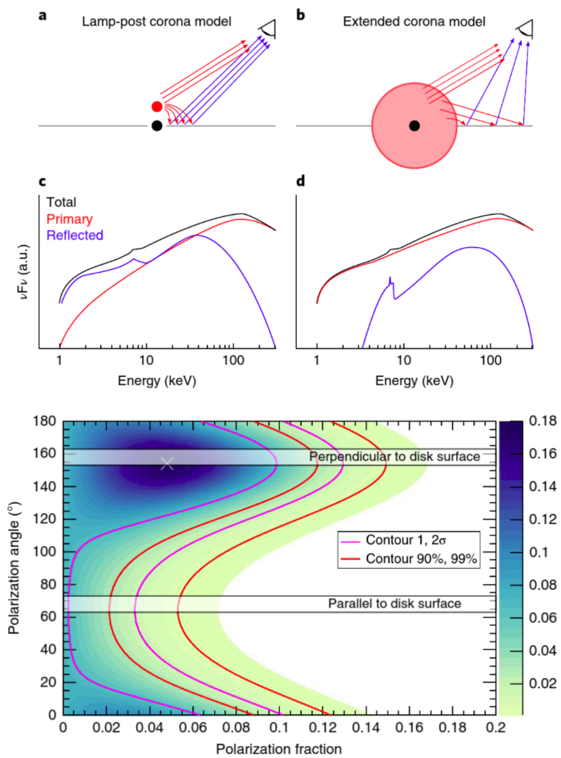
LETTERS

https://doi.org/10.1038/s41550-018-0489-x

Accretion geometry of the black-hole binary Cygnus X-1 from X-ray polarimetry

M. Chauvin[1,2], H.-G. Florén[3], M. Friis[1,2], M. Jackson[1,9], T. Kamae[4,5], J. Kataoka[6], T. Kawano[7], M. Kiss[1,2], V. Mikhalev[1,2], T. Mizuno[7], N. Ohashi[7], T. Stana[1], H. Tajima[8], H. Takahashi[7*], N. Uchida[7] and M. Pearce[1,2]

Black hole binary (BHB) systems comprise a stellar-mass black hole and a closely orbiting companion star. Matter is transferred from the companion to the black hole, forming an accretion disk, corona and jet structures. The resulting release of gravitational energy leads to the emission of X-rays[1]. The radiation is affected by special/general relativistic effects, and can serve as a probe for the properties of the black hole and surrounding environment, if the accretion geometry is properly identified. Two competing models describe the disk–corona geometry for the hard spectral state of BHBs, based on spectral and timing measurements[2,3]. Measuring the polarization of hard X-rays reflected from the disk allows the geometry to be determined. The extent of the corona differs between the two models, affecting the strength of the relativistic effects (such as enhancement of the polarization fraction and rotation of the polarization angle). Here, we report observational results on the linear polarization of hard X-ray emission (19–181 keV) from a BHB, Cygnus X-1[4], in the hard state. The low polarization fraction, <8.6% (upper limit at a 90% confidence level), and the alignment of the polarization angle with the jet axis show that the dominant emission is not influenced by strong gravity. When considered together with existing spectral and timing data, our result reveals that the accretion corona is either an extended structure, or is located far from the black hole in the hard state of Cygnus X-1.



Conclusions

X-ray polarization will rebirth from its ashes in 2021 !

Despite the difficulty to measure X-ray polarization, numerous missions have been proposed and many of them are already accepted

A new observable window
- High energy cosmic sources
- Considerations for stellar/solar polarimetry too

IXPE will explore a new observational window after 42 years from the last positive space measurement, with a dramatic improvement in sensitivity: from 1 to 100+ sources !

In the violent X-ray sky, polarimetry is expected to have a much greater impact than in most other wavelengths

Additional material

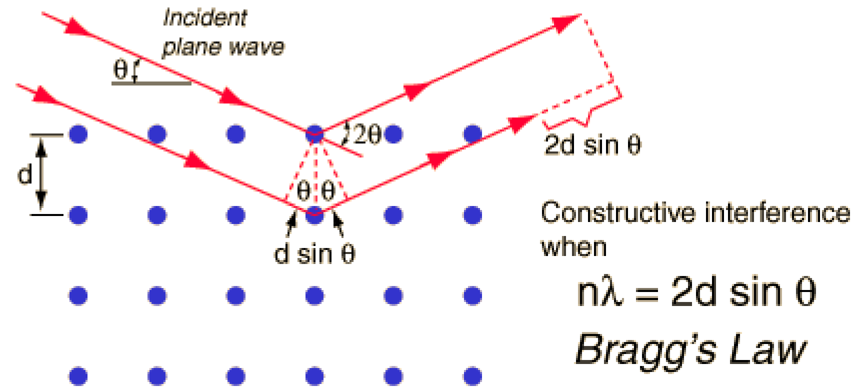
X-RAY POLARIZATION

The problem of X-ray polarization

Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies

X-ray polarimetry can be based on any of three distinct physical effects
- **Bragg diffraction**

Light with sufficiently short (less than a few nanometers) wavelength falling onto a crystal is reflected by the crystal according to Bragg's law: $n\lambda = 2d\sin\theta$ (n= 1,2,3,...)



"d" : distance between two consecutive atomic layers
"θ" : angle of incidence
"n" : order of diffraction

Bragg diffraction polarimetry was the method used for the X-ray polarimeters implemented in Ariel V and OSO-8 satellites (and rockets)

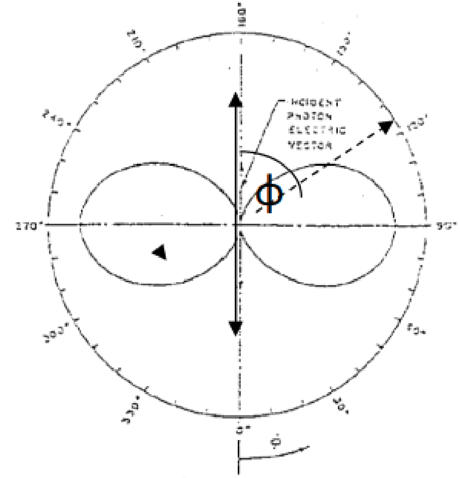
ROTATION OF THE CRYSTAL IS NECESSARY

X-RAY POLARIZATION

The problem of X-ray polarization

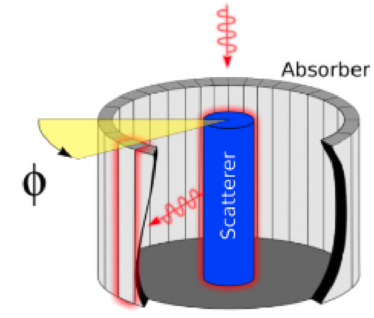
Due to the high photon energies and short wavelengths involved, optical elements used at longer wavelengths become transparent at high energies

X-ray polarimetry can be based on any of three distinct physical effects
- Bragg diffraction
- **Scattering polarimeters**



Thomson / Compton scattering of photons by electrons is sensitive to the (linear) polarization of the incident photons

A calorimeter will measure the distribution of scattered radiation:
- in case of no polarization, the distribution of scattered photons will be isotropic
- if the light is partially polarized, photons will be scattered preferentially perpendicular to the direction of polarization projected onto the xy plane



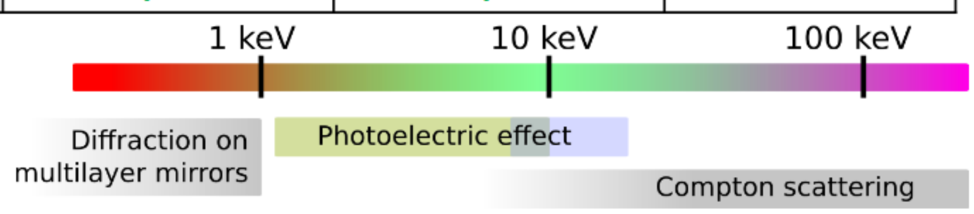
ADEQUATE FOR >10 keV POLARIMETRY
ROTATION NOT NECESSARLY NEEDED

Additional slides

Why the 1 – 10 keV for the first accepted mission ?

Scientific goal	Sources	< 1keV	1-10	> 10 keV
Acceleration phenomena	PWN	yes (but absorption)	yes	yes
	SNR	no	yes	yes
	Jet (Microquasars)	yes (but absorption)	yes	yes
	Jet (Blazars)	yes	yes	yes
Emission in strong magnetic fields	WD	yes (but absorption)	yes	difficult
	AMS	no	yes	yes
	X-ray pulsator	difficult	yes (no cyclotron ?)	yes
	Magnetar	yes (better)	yes	no
Scattering in aspherical geometries	Corona in XRB & AGNs	difficult	yes	yes (difficult)
	X-ray reflection nebulae	no	yes (long exposure)	yes
Fundamental Physics	QED (magnetar)	yes (better)	yes	no
	GR (BH)	no	yes	no
	QG (Blazars)	difficult	yes	yes
	Axions (Blazars, Clusters)	yes ?	yes	difficult

IXPE/XIPE books

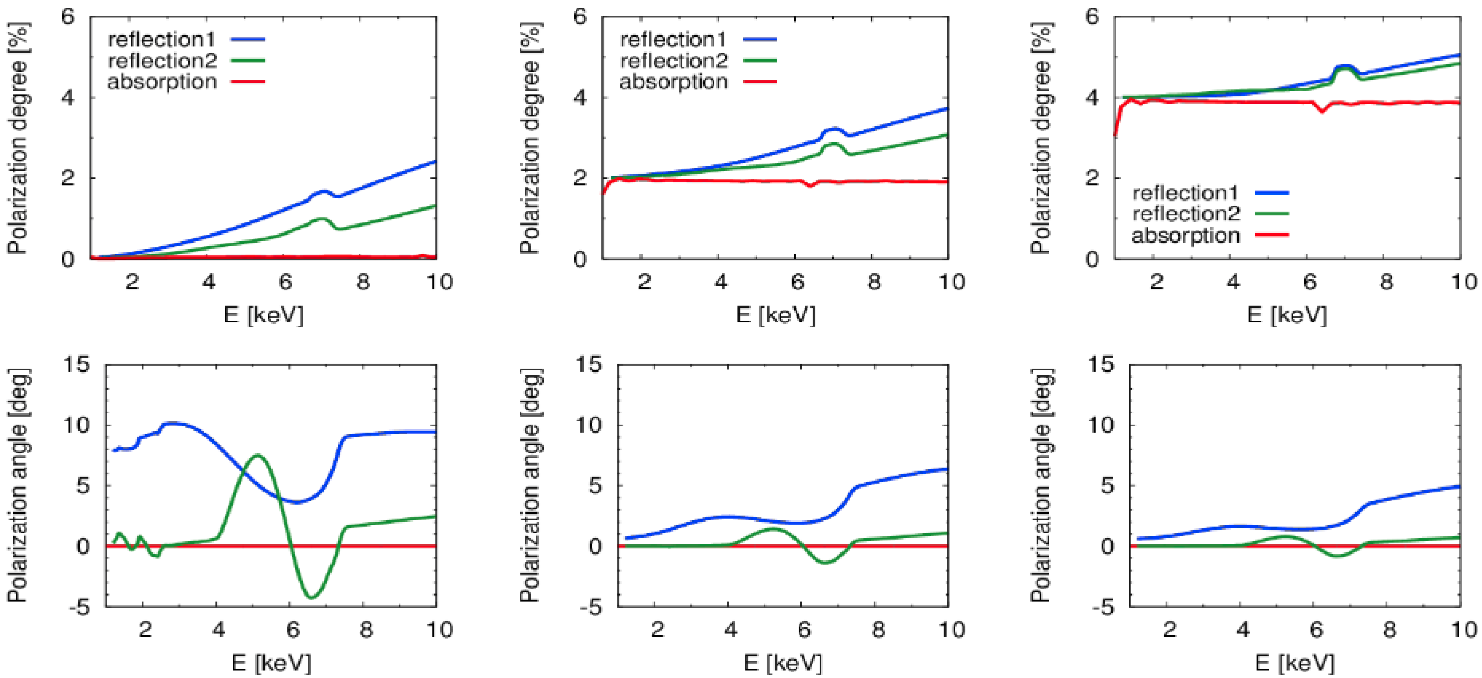


Additional slides

Complex absorption versus strong gravity effects in AGN

Not everybody believes that we are really seeing relativistic reflection in AGN
Complex ionized absorption?

Polarimetry can tell (Marin et al. 2012, 2013)



Absorption scenario – clumpy wind:
→ constant polarization degree and angle

Reflection scenario:
→ energy dependent polarization degree and angle

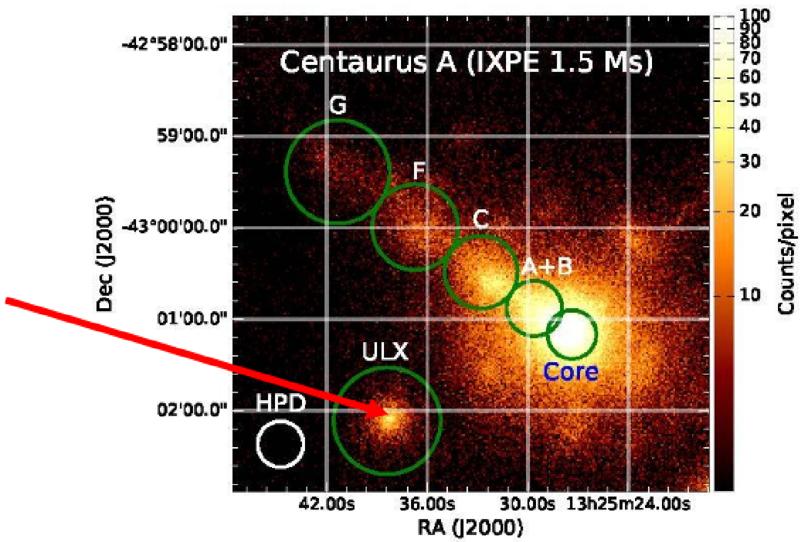
Accreting sources

What can we do with X-ray polarimetry ?

2 – Radio-loud AGN and ULX

Active galaxies are powered by supermassive BHs with jets
- Radio polarization implies the magnetic field is aligned with jet
- Different models for electron acceleration predict different dependencies in X-ray polarization

Imaging **Centaurus A** allows to isolate other sources in the field (2 ULXs)



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%**

Includes effects of dilution by unpolarized diffuse emission

Poutanen (1994)
Celotti & Matt (1994)
IXPE book

Additional slides

Magnetic cataclysmic variables

CV = accreting white dwarf
= X-ray bright during active states

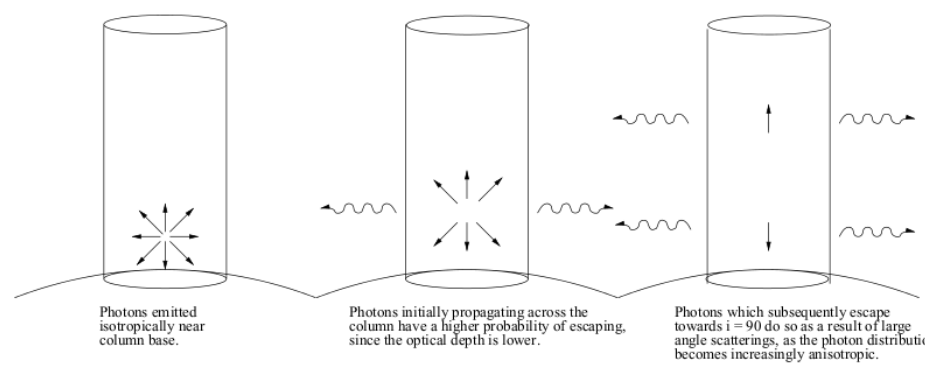
In magnetized systems, the accretion flow is confined by the magnetic fields near the WD (Warner 1995)

If strong mag. fields, cyclotron cooling is very efficient
→ non isotropic Maxwellian distrib. of electron
→ Bremsstrahlung X-rays intrinsically polarized

If high accretion rate, τ accretion column is high
→ Compton scattering (polarization)

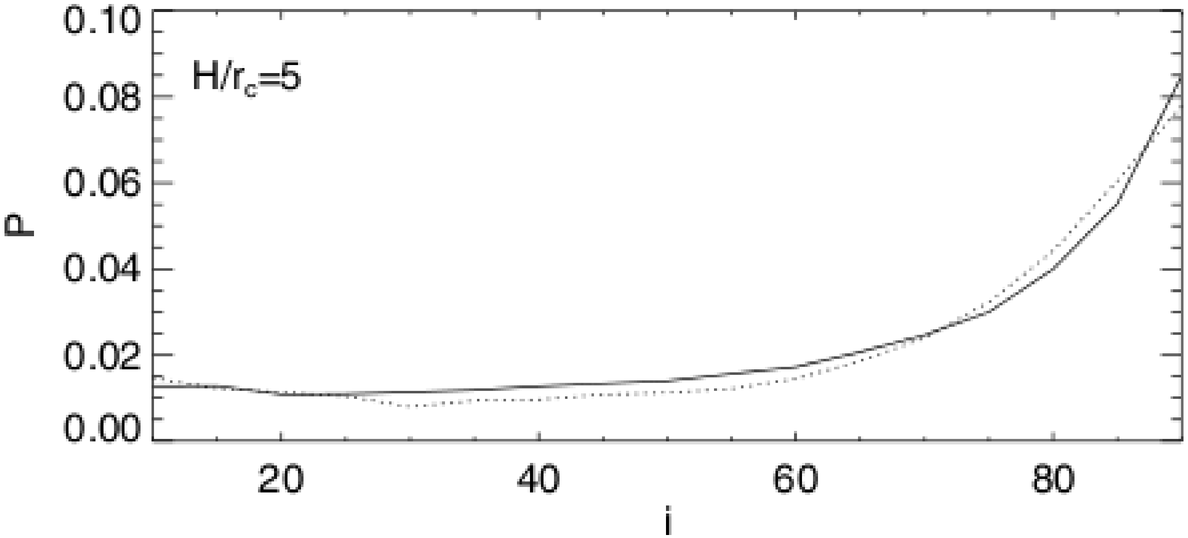
Photons escaping from the base of the accretion column should be less polarized than those that scatter several time

McNamara et al. (2008)



Additional slides

Magnetic cataclysmic variables



McNamara et al. (2008)

M_{WD} = 0.5 Msol
r_{acc} = 10 g/cm^2/s

Cycl/Brems cooling
rate = 0 and 10

Cooling rate unlikely important

Polarization up to 8% (may vary with rotation phase)
→ Sensitive to density structure

Additional slides

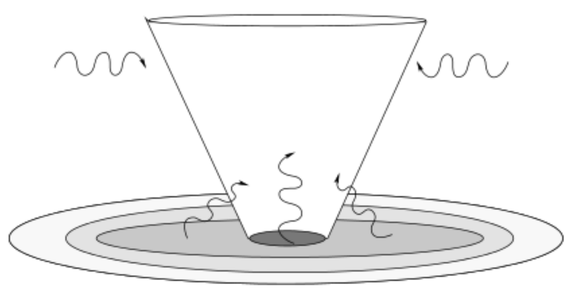
Magnetic cataclysmic variables

BL Lac objects, OVV : parsec-scale jets (b ~ 0,995)

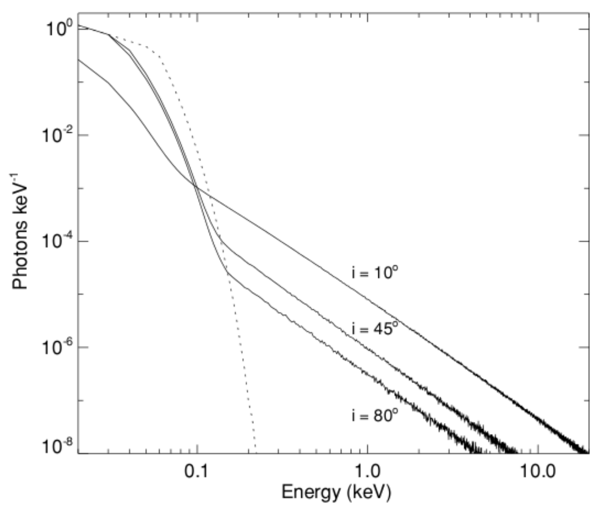
X-ray spectrum steeper than optical spectrum
→ X-ray produced by accelerated, high energy e^- (base of the jet ? Shocks ?)

3 scenarios: disk/Compton, CMB or SSC ?
→ constrains on the directionality of the magnetic field

disk



i	P (per cent) (E = 1–10 keV)	Average number of scatterings per photon
10°	3.2	3.0
45°	14.0	2.8
80°	20.6	2.8



McNamara et al. (2009)

<u>Relativistic jet</u>
- central BH 10^8 Msol
- jet Lorentz factor 5
- jet opening angle 11°
- Accr. rate 0.1 Msol/yr
- z = 2
- 50% conversion accr/jet

Additional slides

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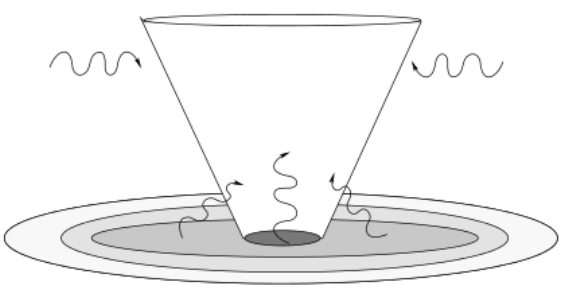
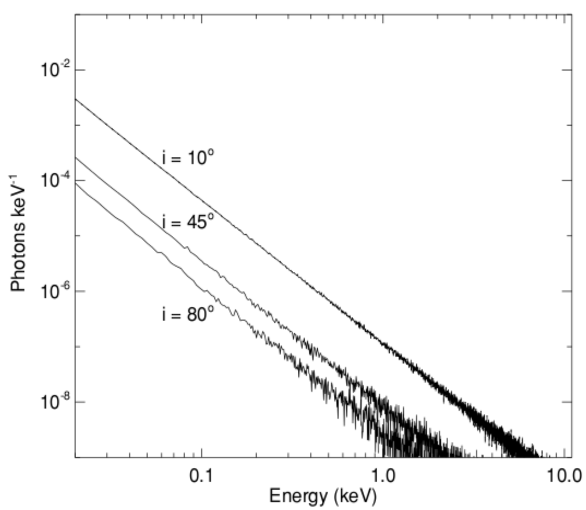
CMB



(a)

i	P (per cent) (E = 1–10 keV)	Average number of scatterings per photon
10°	4.2	3.2
45°	16.5	2.6
80°	23.9	3.2



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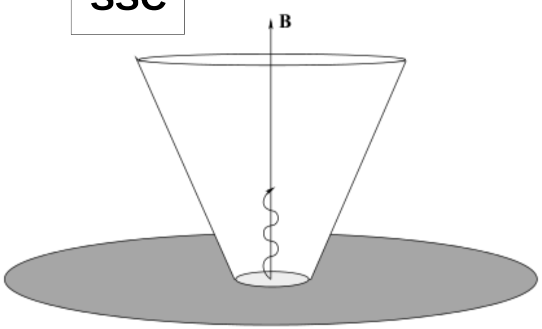
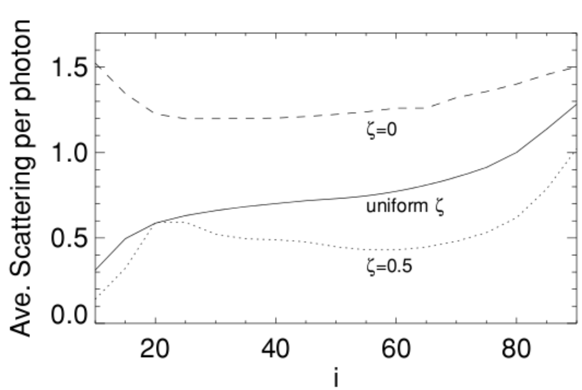
SSC



(b)



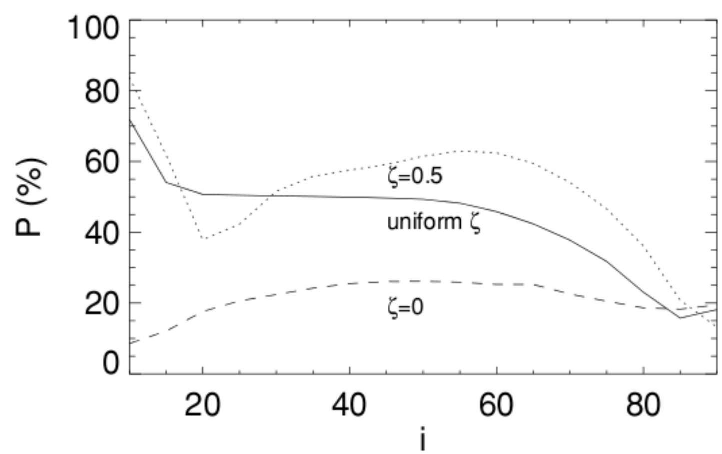


Figure 6. Polarization degree P of SSC photons with energies between 1 and 10 keV plotted as a function of the inclination angle i. The solid line is for the case where the seed photons are emitted uniformly throughout the jet (uniform ζ). The dashed and dotted lines are for the cases where the seed photons are emitted at the jet base ($\zeta = 0$) and in the middle of the jet ($\zeta = 0.5$).

McNamara et al. (2009)

<u>Relativistic jet</u>
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STRONG MAGNETIC FIELDS

What can we do with X-ray polarimetry ?

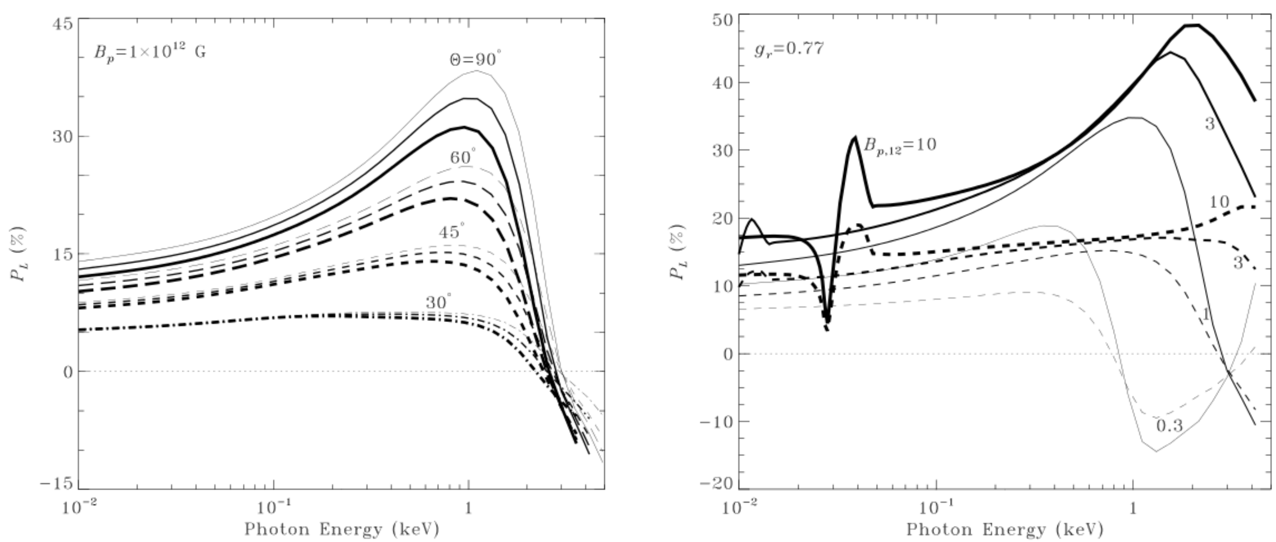
2 – Emission in strong magnetic fields

Isolated neutron stars and X-ray binaries are perfect targets since they are bright sources

The radiation emergent from atmospheres of neutron stars with strong magnetic fields is expected to be strongly polarized (~10% – 30%)

Depends on:
- photon energy
- effective temperature
- magnetic field

Polarimetry is more sensitive than spectroscopy to magnetic fields !



Pavlov & Zavlin (2000)

The shape of polarization pulse profiles depends on the orientation of the rotational and magnetic axes

+ polarization substantially modified by general relativistic effects

→ X-ray polarization as a new method for evaluating the mass-to-radius ratio of NS

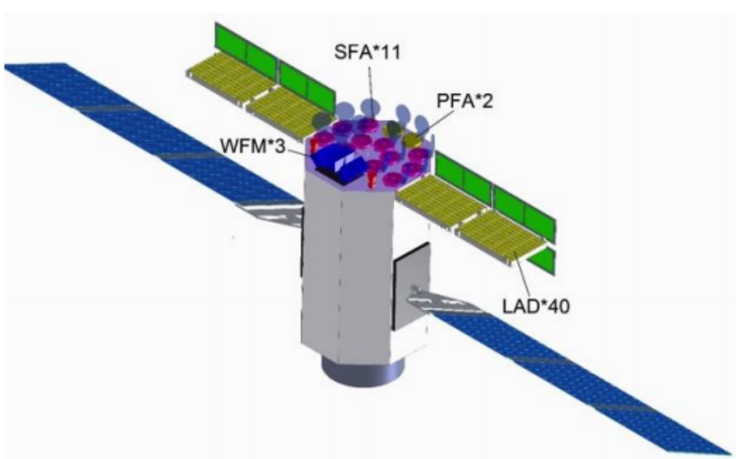
Future instruments

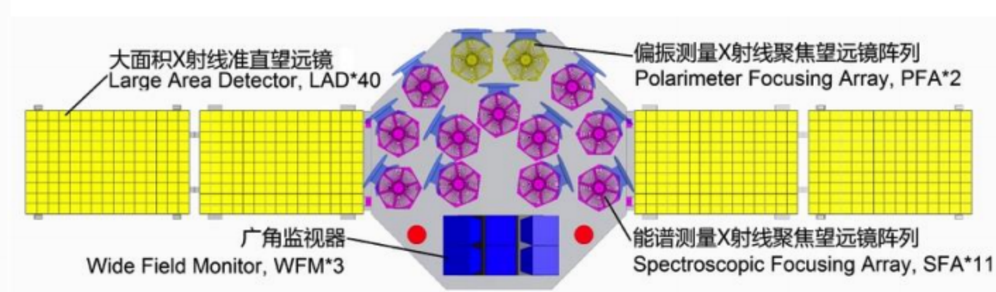
enhanced X-ray Timing and Polarimetry (eXTP):
Chinese + Italian (polarimetric detectors) mission

enhanced version of the XTP mission which, in 2011, has been selected and funded for Phase 0/A as one of the background concept missions in the Strategic Priority Space Science Program of the Chinese Academy of Sciences

Launch > 2025

→ simultaneous spectral-timing-polarimetry studies of cosmic sources in the energy range from 0.5-30 keV (and beyond)





Future instruments

enhanced X-ray Timing and Polarimetry (eXTP):

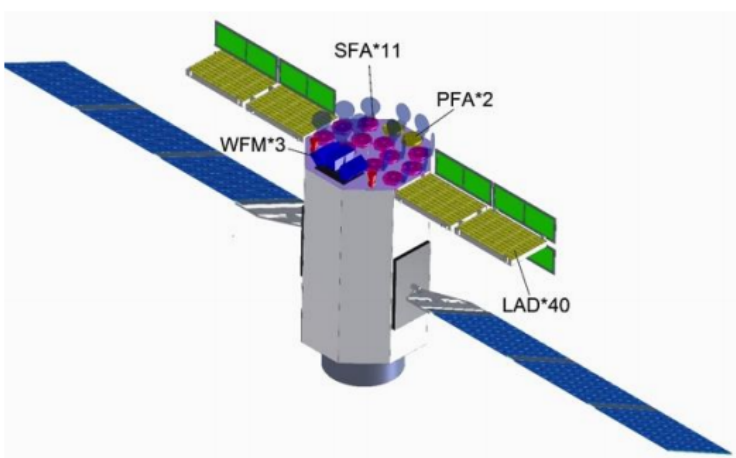
The scientific payload of eXTP consists of four main instruments:

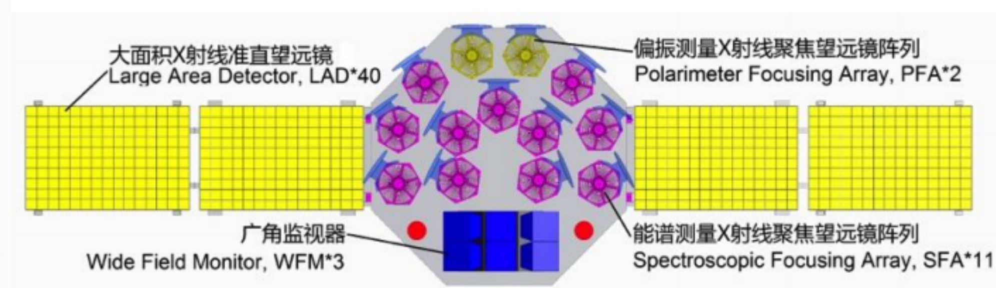
- **Spectroscopic Focusing Array (SFA)**: 9 X-ray optics (total eff. area ~0.9 m2 @ 2 keV; 0.6 m2 @ 6 keV), equipped with Silicon Drift Detectors offering <180 eV spectral resolution

- **Polarimetry Focusing Array (PFA):** 4 X-ray telescope (total eff. area 250 cm2 @ 2 keV) equipped with imaging gas pixel photoelectric polarimeters

- **Large Area Detector (LAD):** a deployable set of 640 Silicon Drift Detectors (total eff. area ~3.4 m2, 6 - 10 keV) for spectral resolution better than 250 eV

- **Wide Field Monitor (WFM):** 3 coded mask wide field units, equipped with position-sensitive Silicon Drift Detectors, each covering a 90 degrees x 90 degrees field of view





Future instruments

Polarization Spectroscopic Telescope Array (PolSTAR):
American mission

→ satellite-borne experiment measuring the linear polarization of X-rays in the energy range from 3-50 keV (requirement; goal: 2.5-70 keV)

The mission was proposed to NASA's 2014 Small Explorer (SMEX) announcement of opportunity … but another polarimetric mission was selected (GEMS)

The PolSTAR design is based on the technology developed for the Nuclear Spectroscopic Telescope Array (NuSTAR) mission launched in June 2012 (same X-ray optics, extensible telescope boom, optical bench, and CdZnTe detectors)


NuSTAR optics module


deployable mast which extends to 10.14-m after launch

Future instruments

Polarization Spectroscopic Telescope Array (PolSTAR):

Parameter	Requirement	Current Best Estimate
Telescope bandpass (keV)	3-50	2.5-70
Telescope effective area (effective # of *NuSTAR* optics)	≥ 0.9	1.1
Energy resolution (FWHM at 6 keV)	≤ 1 keV	0.45 keV
Absolute timing accuracy (msec)	≤ 15	2
Angular resolution (half power diameter; arcsec)	≤ 80	60
Pointing, during science portion of orbits (99.7% CL)	$\leq 62''$ from stick center	$17''$ from stick center
Instrument reconstructed pointing knowledge (99.7% CL)	$\leq 15''$	$8''$
Minimum Detectable Polarization (3-15 keV, 25 ks obs'n of 1 Crab source, 99% CL)	$\leq 1\%$	0.5%
Polarization fraction systematic error (3-15 keV; 99.7% CL)	$\leq 1.5\%$	0.25%
Polarization angle systematic error ($\geq 6\%$ polarized source; 99.7% CL)	$\leq 20°$	2°
Bad pixel fraction	$\leq 2\%$	1%
Instrument mass (kg)	≤ 170	131
Instrument power (W; orbital avg.)	≤ 45	28

Future instruments

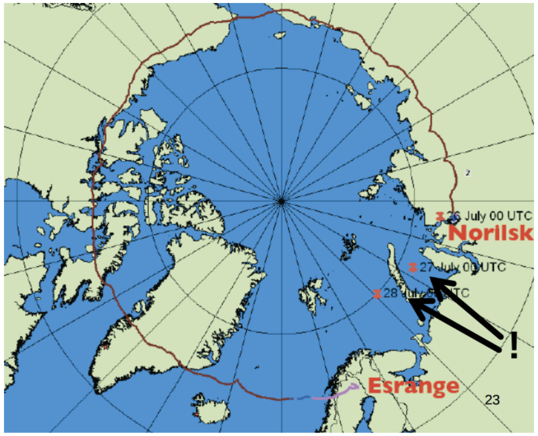
The Polarised Gamma-ray Observer (PoGOLite):
Swedish mission

X-ray telescope lifted to an altitude of ~40 km with an enormous helium-filled balloon (one million cubic metres)

→ The PoGOLite balloon experiment is designed to measure the polarization of soft gamma rays in the 20 keV- 240 keV energy range (main targets: NS)

Several preliminary flights: 2011 (failure), 2013 (14 days duration was completed)

New design (2017): POGO+
→ With this new design, PoGO+ is expected to reduce the MDP from 34.5% to 17.6% for a 6 hour Crab observation



Balloon facilities, Hang test