# Polarimetria X

Enrico Costa, IAPS

Paolo Soffitta, Fabio Muleri, Sergio Fabiani, Giorgio Matt, Stefano Bianchi, …….

(XIPE proposal  Brera, Pisa etc. ADAHRELIplus proposal Roma2, ….etc.)

# Different Scenarios (Concepts)

Polarimetry is an [almost] undisclosed domain of X-ray Astronomy.
It can be performed, with guaranteed results and with a large discovery space, in many different scenarios.

1) Baseline. Photoelectric Polarimetry with at 2-10keV GPD (imaging focal plane) for a:
Small (POLARIX, IXPE, XIPE, …)
Medium (NHXM-LEP)
Large (XEUS, IXO)

2) Extended versions
Extend the band of GPD to higher energies 5-35 keV (NHXM-MEP)
Non imaging focal plane scattering polarimeter (NHXM-HEP)

3) Descooped versions
Array of GPDs with collimator both LEP and/or MEP

4) Side versions
Polarimetry of transients (GRB,SGR) with Wide Field Instruments
Polarimetry of solar flares

All these concepts produce valuable results (but costs and throughput are not the same)

In sketching hot topics and possible measurements I try to fix what can be done with which scenario

# A blank blackboard

- After the suppression of IXO and GEMS no experiment of X-ray polarimetry is approved
- Only one instrument of γ-ray polarimetry is approved (ASTRO-H)

Competing techniques:
1) photoelectric polarimetry with focal plane TPC (GSFC)
More sensitive than GPD (~2)
Not imaging
Needs rotation
2) Diffractive polarimeter MIT (multilayer + CCD
Low energy ~200 eV
3) Byproduct polarimetry (CosX, NUSTAR, CCD,…)
Sensitivity: very low

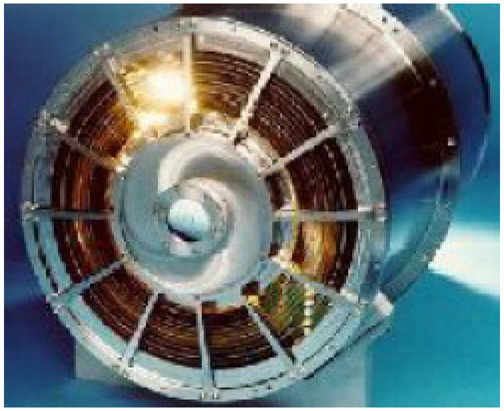
Paolo Soffitta will how the readiness of different concepts

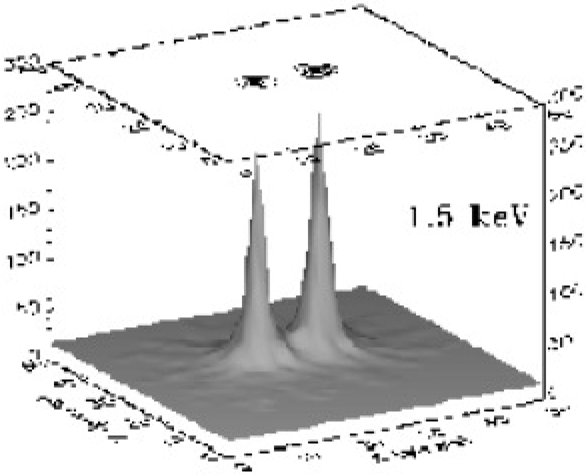
# Last attempt: XIPE proposed as ESA SM

A small mission of X-ray polarimetry is an old idea in Italy:

**Jet-X optics (3 mirror modules)**

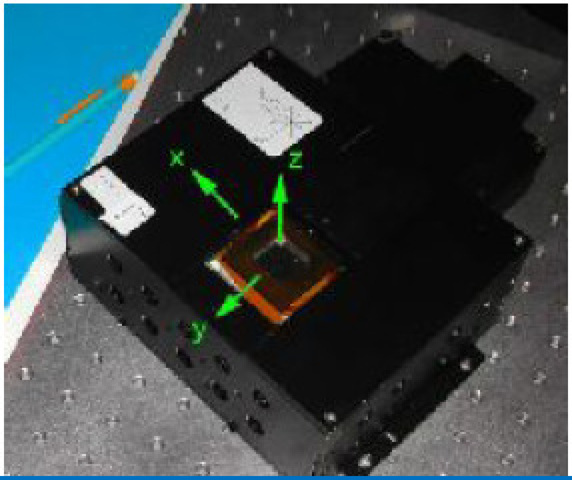
- ~ 150 $cm^2$ each
- 15 arcsec angular resolution
- calibrated and tested: TRL 9






**Gas Pixel Detector**

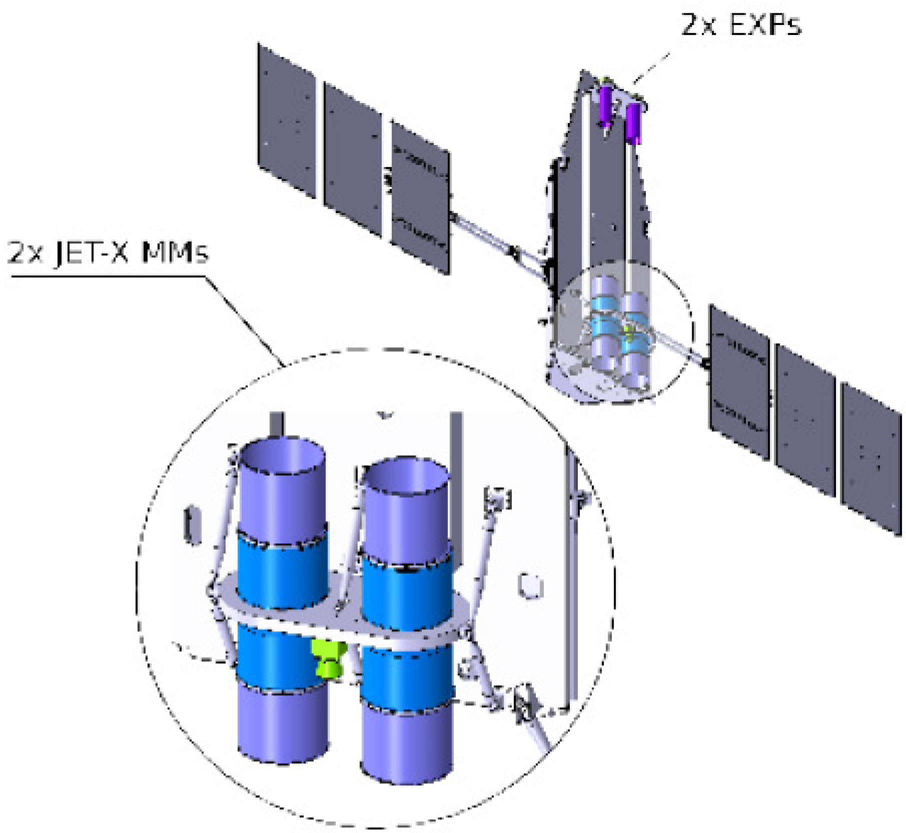
- polarimetric, imaging e spectral capability
- no need of rotation
- studied for a number of missions: XPOL on-board XEUS/IXO, NHXM, POLARIX

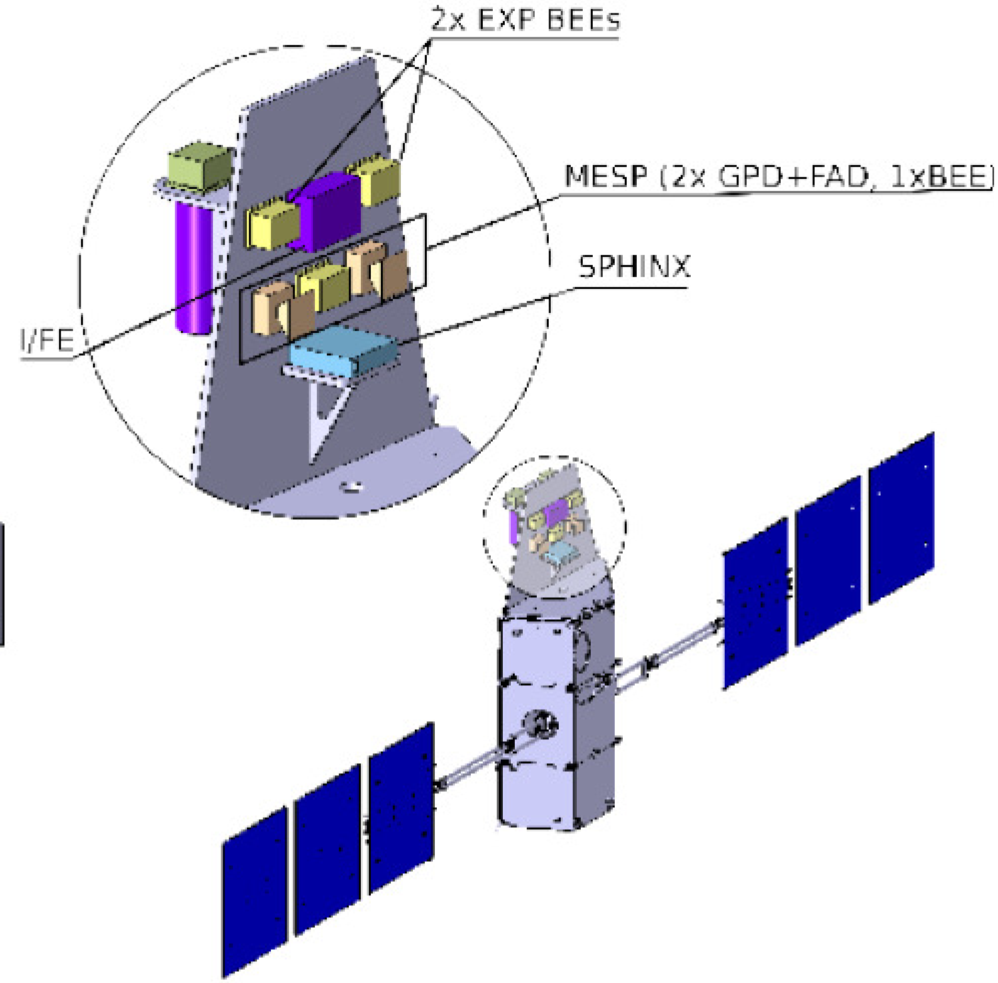


# The XIPE mission

Proposed to ESA small mission call for a launch in 2017.

- 2 Jet-X optics
- 2 + 2 GPDs
- Solar photometer
- commercial bus



# Not selected

Good evaluation by ESA from the feasibility and readiness
Weak from the budget point of view

An ecellent rating by PSWG
Rated 2d by AWG
Not selected by SSEWG

CHEOPS (exoplanets photometry) only mission selected by SSAC

# Why Polarimetry? Digging in literature

## Astrophysics

**Acceleration phenomena:**

- Pulsar wind nebulae
- μQSO
- Blazar and radiogalaxy
- Solar Flares

**Emission in magnetic fields:**

- Emission in strong magnetic fields: magnetic cataclysmic variables
- Emission in strong magnetic fields: accreting millisecond pulsars
- Emission in very strong magnetic fields: accreting X-ray pulsars

**Scattering in aspherical situations**

- X-ray binaries
- Radio-quiet AGN
- X-ray reflection nebulae

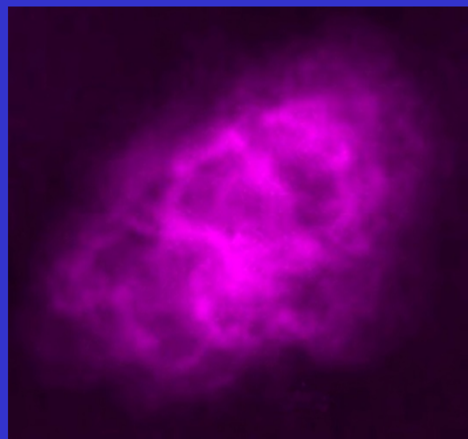
## Fundamental Physics

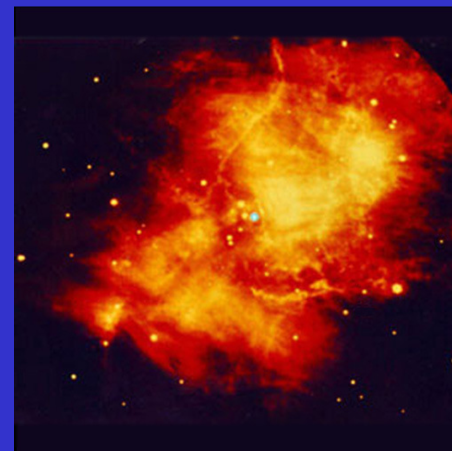
**Matter in Extreme Magnetic Fields: QED effects**
**Matter in Extreme Gravitational Fields: GR effects**
**Quantum Gravity**
**Search for axion-like particles**

# The best known PWN: the Crab nebula powered by the Crab Pulsar

Radio

(VLA)



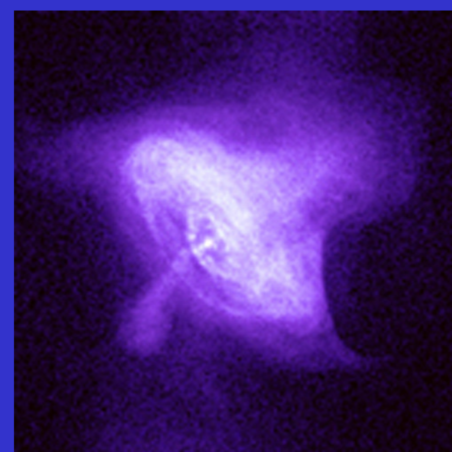


Infrared

(Keck)

Optical

(Palomar)

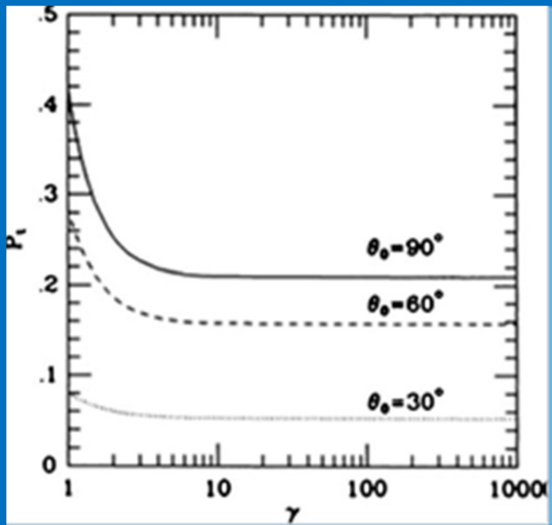


X-rays

(Chandra)

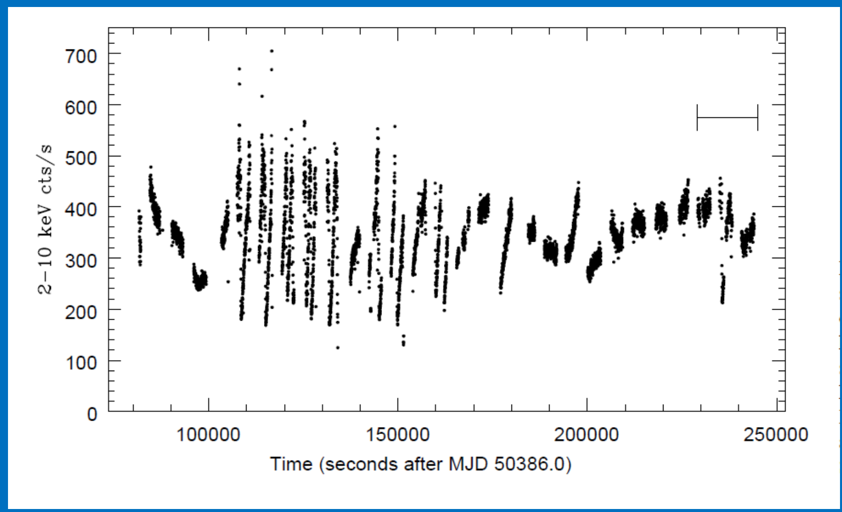
X-rays are emitted by synchrotron from freshely accelerated electrons in magnetic fields.

# Acceleration phenomena: μQSO



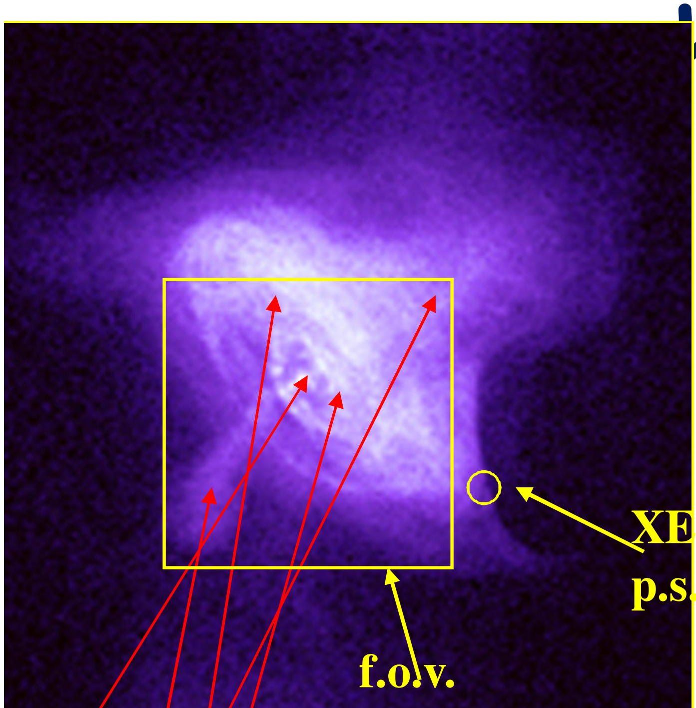

The polarization degree of the SSC emission as a function of the Lorentz factor of the electrons θo is the angle between the observer and the magnetic field (from Celotti&Matt, 1994).

The study of their time and energy-dependent polarization properties (possibly combined with simultaneous radio and optical polarization measurements) can help shading light on jet formation and evolution, and its relation to accretion disk emission. These studies may also be applicable to AGN (e.g. Mirabel 2007), but in μQSO we have the possibility, thanks to the much smaller time scales, to study their behavior over a wide interval of accretion rates




Flares of GRS1915+105 detected from BeppoSAX MECS (Feroci et al. 1999)

# PWN The only polarized source already known



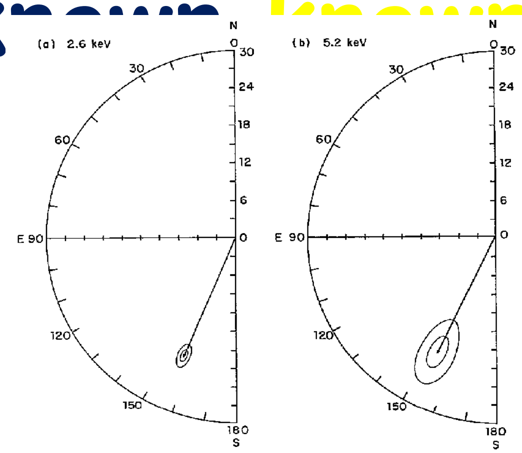

PSR

NW jet

SE jet

Inner torus

Outer torus

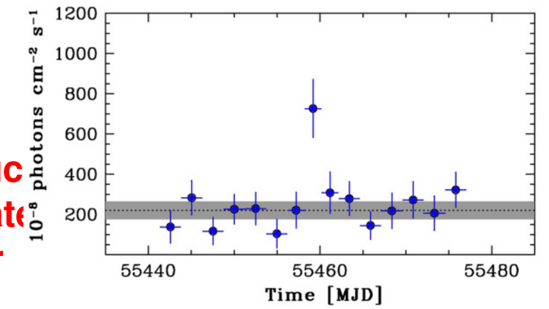


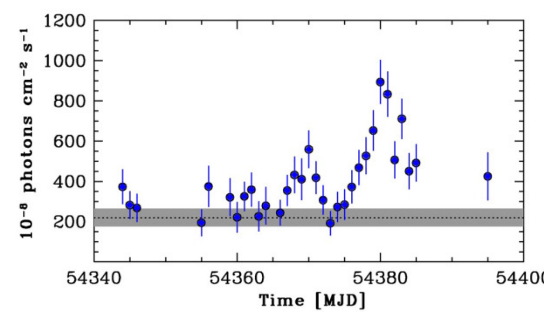

Positive measurement: of X-ray polarization of the Crab Nebula without pulsar contamination (by lunar occultation, Weisskopf et al., 1978).

$P = 19.2 \pm 1.0\ \%$

$\theta = 156.4^{o} \pm 1.4^{o}$

But this is only the average measurement The structure is muc more complex! To perform separate polarimetry of details of the major structures we need imaging!




Tavani et al. 2011

**How turbulent is the field? How polarized is the PSR?**

At much higher energies INTEGRAL finds polarization oriented as the jet axix.
Morover we know from AGILE (confirmed by Fermi) that the Crab (not the PSR) is varying on the scale of days at E>100 MeV. These corresponds to a physical region on the arcsecond timescale!

# **Acceleration phenomena:** Blazar and radiogalaxy

While the polarization angles of synchrotron and SSC emission are expected to be the same, and perpendicular to the magnetic field (Celotti & Matt 1994), in the external photons model the IC polarization is related to the jet axis (Begelman & Sikora 1987), and the polarization angle in the two peaks needs no longer to be the same. In both models, the polarization degree (see Figure 2) is expected to be very high, up to 50% or more unless the electrons responsible for the IC emission are hot (see also Poutanen 1994).

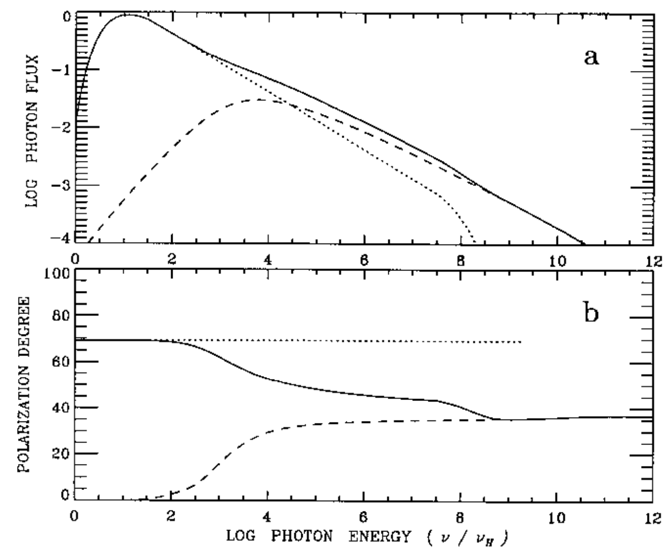



FIG. 1.—(*a*) Intensity and (*b*) polarization of synchrotron self-Compton radiation. *Dotted lines*—initial synchrotron radiation; *dashed lines*—inverse Compton scattered radiation; *solid lines*—intensity and polarization of the total radiation. Here $\tau = 0.1$, $\alpha = 0.5$, $\sin \zeta = 1$, and $\gamma_{min} = 10$.

# Acceleration: SNR

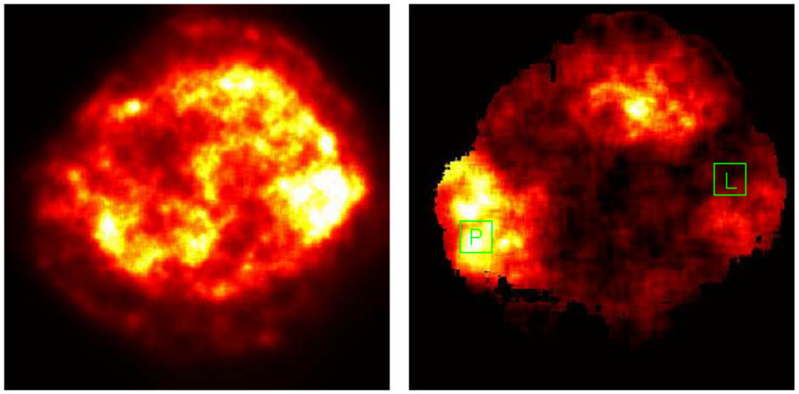
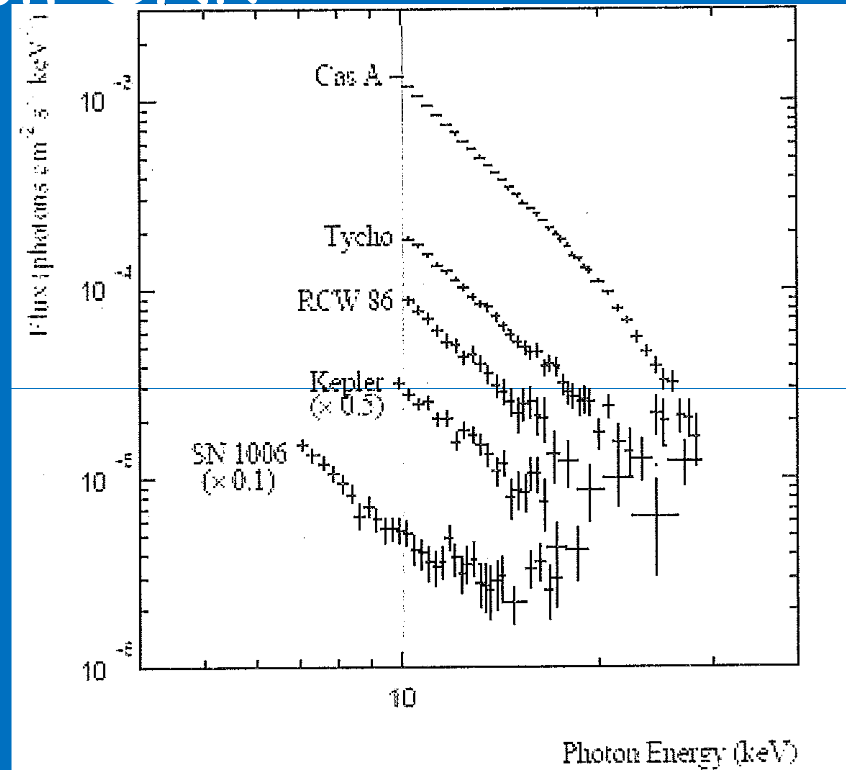
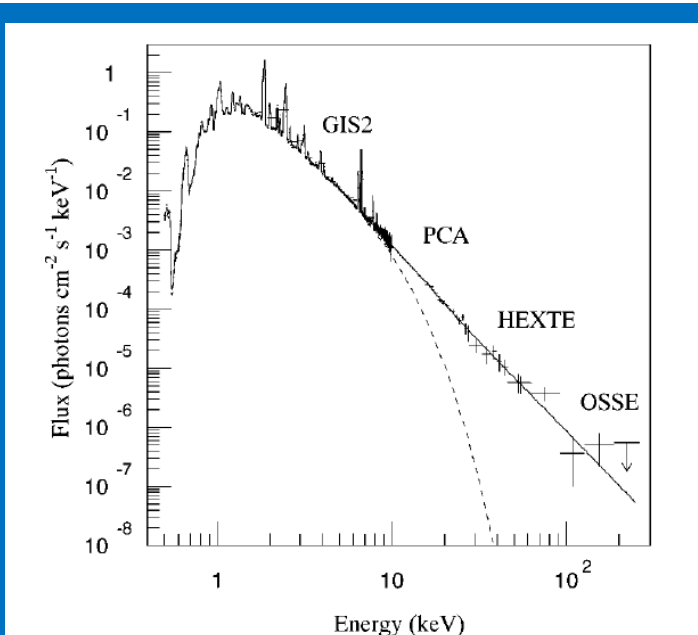



**Fig. 2.** Continuum 4.06−6.07 keV (left) and Fe K equivalent width (right) black 0 keV to white 4 keV and above.

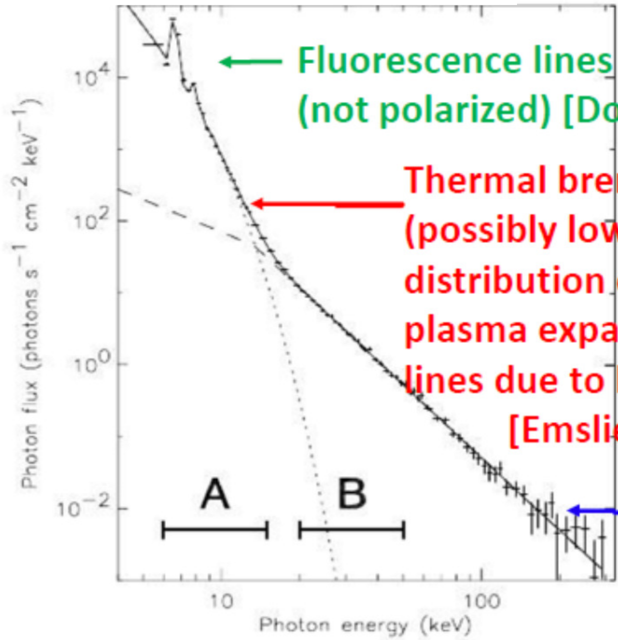



In a shell-like SNR the emssion <10keV is dominated by thermal (not in equilibrium). The polarimetry, as diagnostics oof shocks, can single out the non thermal component <10 keV estimated to be ~ 10%. With Hard X-rays (multilayer optics) the non-thermal component is dominant. In any case imaging is imperative.

# Acceleration phenomena : Solar Flares

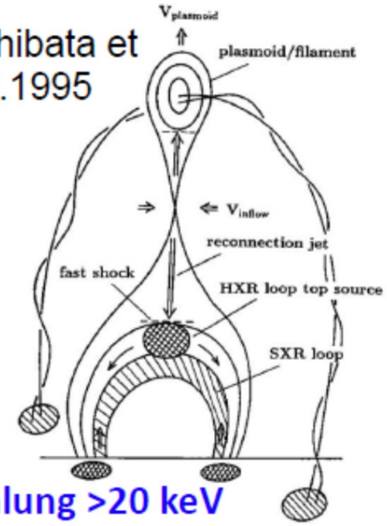
## ) SOLAR X-RAY POLARIMETRY




Fluorescence lines emission < 10 keV (not polarized) [Doschek 2002]

Thermal bremsstrahlung up to 20 keV (possibly low polarized if Maxwellian distribution of velocity is perturbed by plasma expansion along magnetic field lines due to heat propagation) [Emslie & Brown 1980]

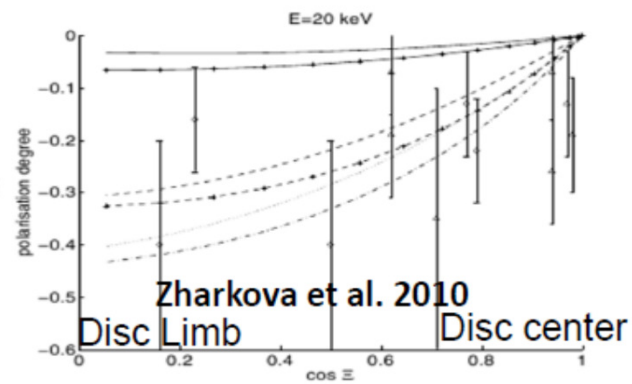
Shibata et al.1995




Non-thermal bremsstrahlung >20 keV (highly polarized up to 40%) [Zharkova et al. 2010]

SOLAR FLARES X-RAY EMISSION

- **Magnetic reconnection** (magnetic field geometry form polarization)
- **Acceleration of particles** (directivity informati from polarization)
- Particles come to rest heating plasma and emitting via **Bremsstrahlung**

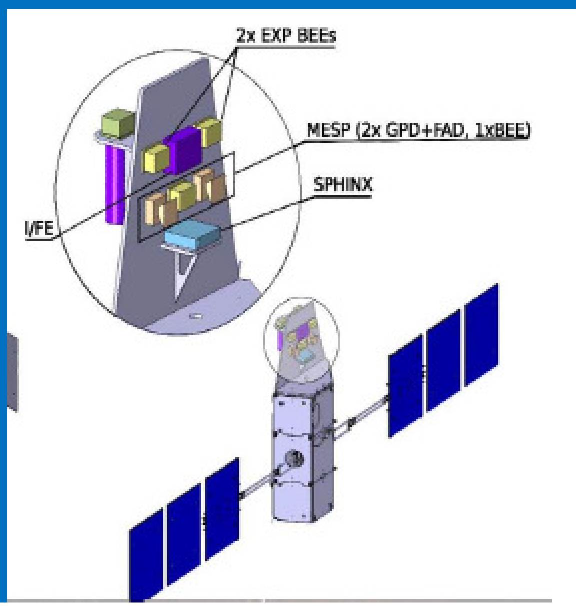



Sergio Fabiani PhD thesis 2012

# Solar Flare Polarimetry

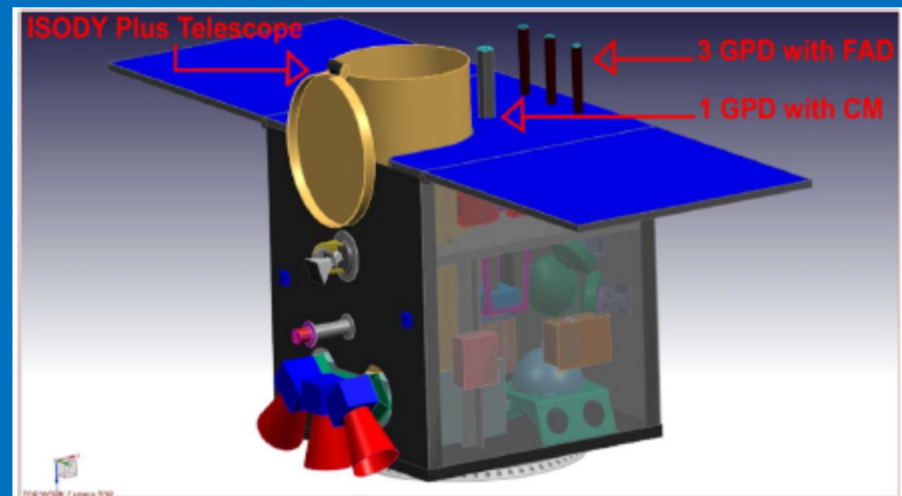
Data on solar flare polarimetry are not conclusive but suggest that a high polarization degree is there.
A small mission with collimated (or wide field) MEP polarimeters would give very constreining measurements. In XIPE 2 MEPs on the side of solar panels would

XIPE




| Flare Class | MDP (%) | Integration Time (s) |
|---|---|---|
| X10 | 0.6 | 748 |
| X5.1 | 1.3 | 989 |
| X1.2 | 4.8 | 239 |
| M5.2 | 6.6 | 489 |
| M1 | 46.4 | 128 |

Spectra from Saint-Hilaire et al. 2008




ADAHELI-PLUS

*4 MEP*, 1 coupled with a coded mask aperture to allow the flare localization onto the solar disc, 3 coupled with a field angular delimiter.

| Flare Class | MDP (%) | Integration Time (s) |
|---|---|---|
| X10 | 0.5 | 748 |
| X5.1 | 1.0 | 989 |
| X1.2 | 3.7 | 239 |
| M5.2 | 5.0 | 489 |
| M1 | 35.5 | 128 |

Spectra from Saint-Hilaire et al. 2008

# Emission in strong magnetic fields: accreting millisecond pulsars

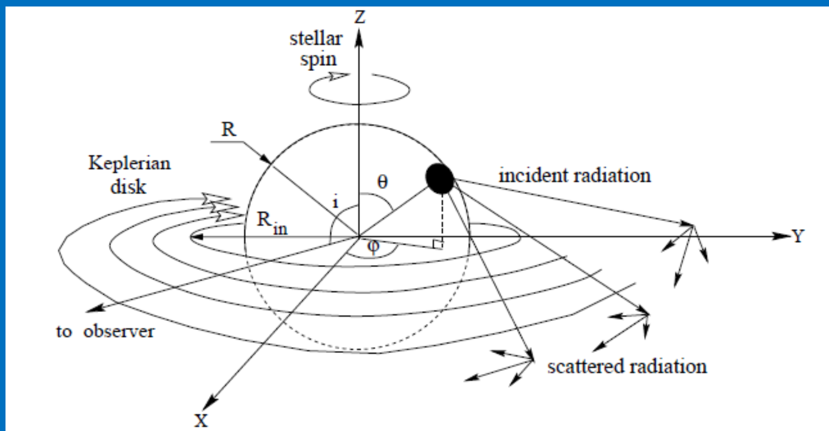
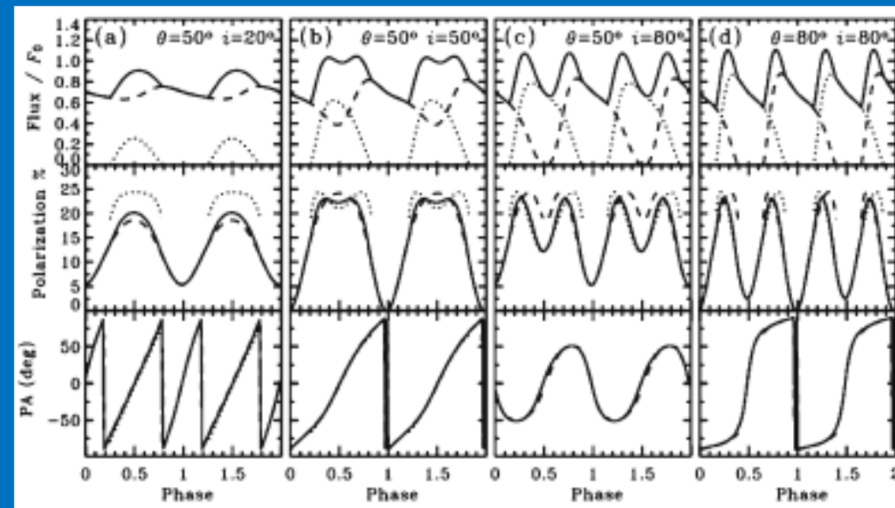
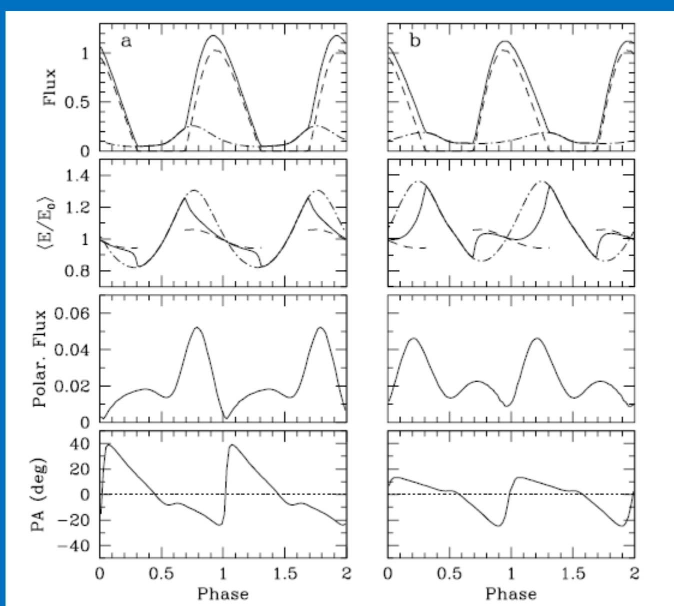



Fig. 1. Schematic picture of scattering of radiation emitted by a spot on the surface of a spinning neutron star from a surrounding Keplerian accretion disk.



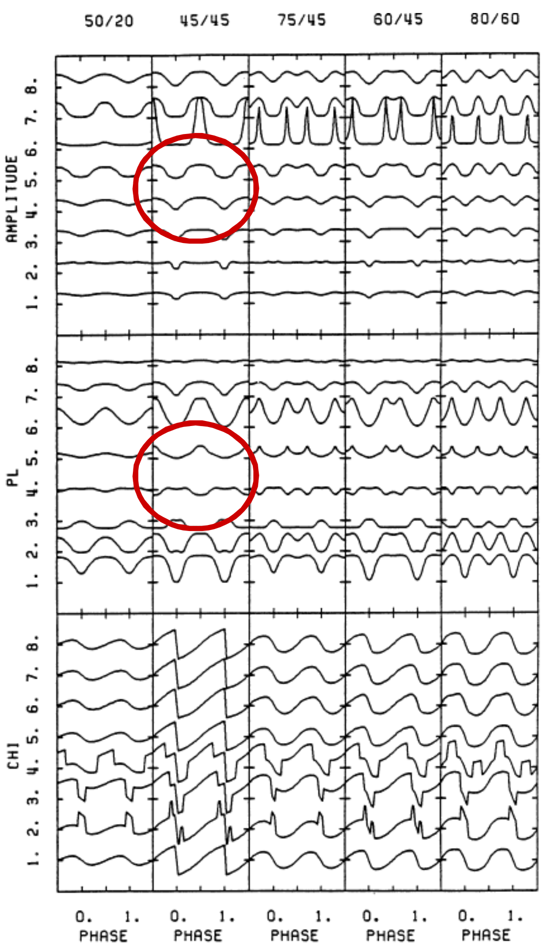

Lightcurves of the flux, polarization degrees and angle in an accreting millisecond pulsar for different set of geometrical parameters. From Viironen and Poutanen (2004).

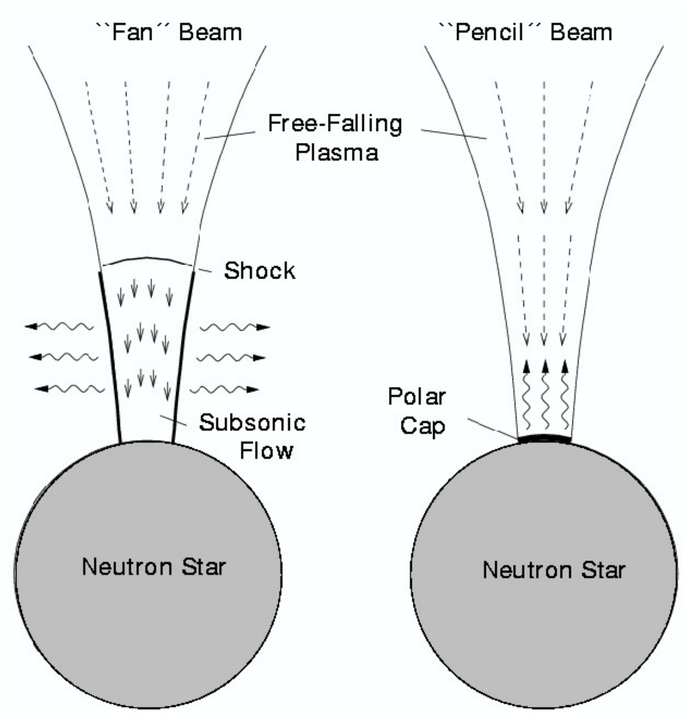


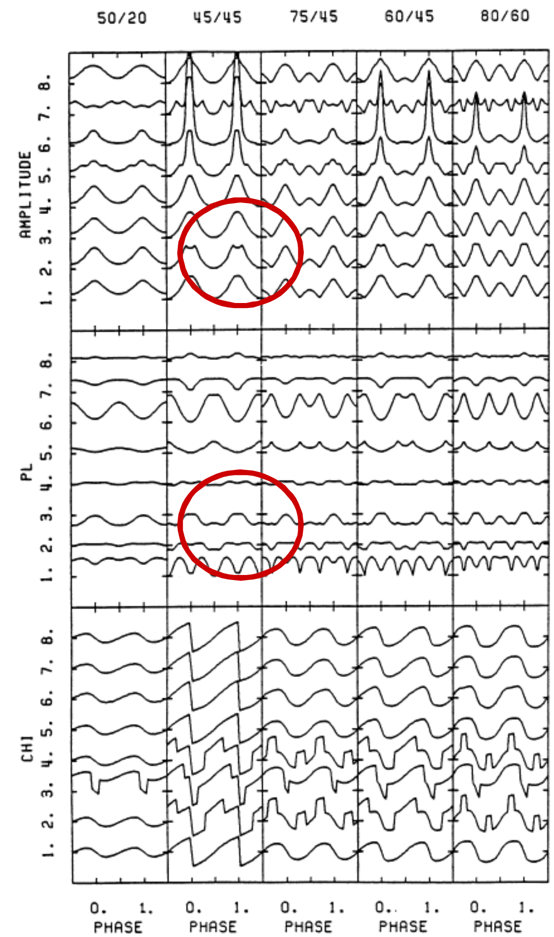

A completely different approach, Sazonov 2001

# Emission in very strong magnetic fields:  magnetic NS

Spectropolarimetry may constraint the accretion geometry.
Electron (in strong B) or proton (in extreme B) cyclotron lines may




*Meszaros et al. (1988)*

# Cyclotron lines with 100 ks of observation with NHXM-MEP

**The extension of polarimetry to Hard X-Ray can allow for a detailed study of cyclotron lines.**
**All detected lines are above 10 keV. Photoelectric polarimetry extended to higher energies (such as in NHXM) or good quality compton polarimetry can allow for a direct exploration of the cyclotron resonances.**

**Here we need the high energy**

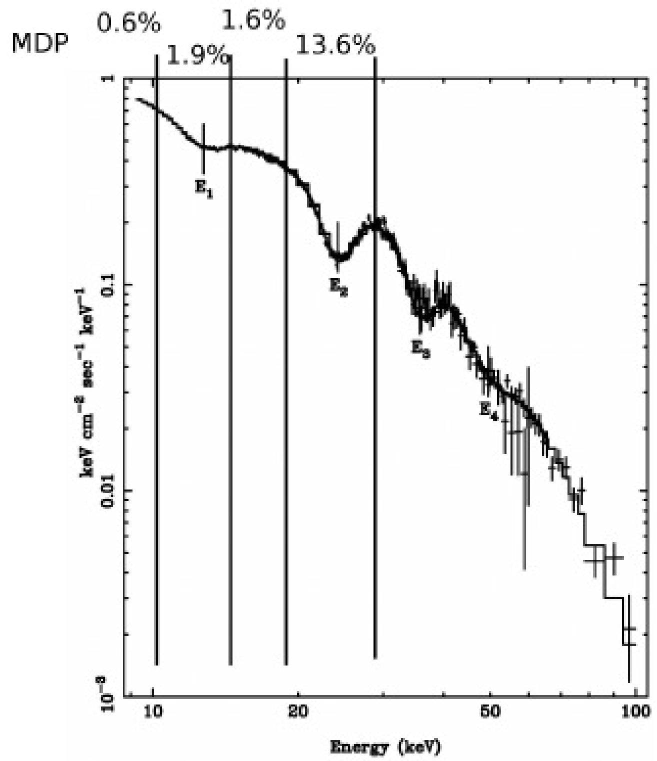
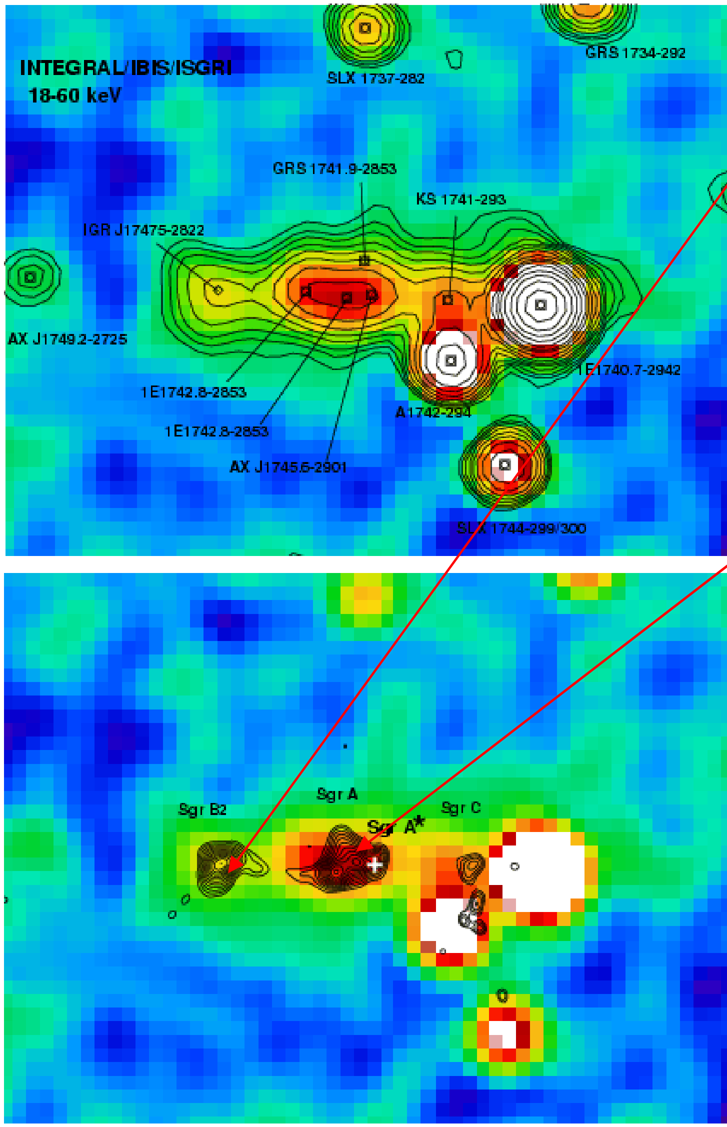



Figure 11. The cyclotron lines of the transient X-ray pulsar X0115+634.

# Scattering in aspherical situations: Radio-quiet AGN

Despite the name, the actual geometrical shape of the 'torus' is basically unknown, and polarimetric observations can help to solve this issue, as well as to determine its orientation and relation with the optical ionization cones (Goosmann & Matt 2011).

# Scattering in aspherical situations: X-ray reflection nebulae?

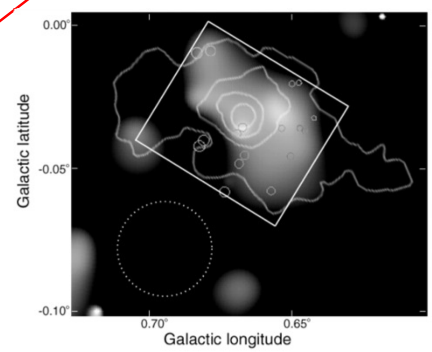



Integral Image of GC, Revnivtsev 2004

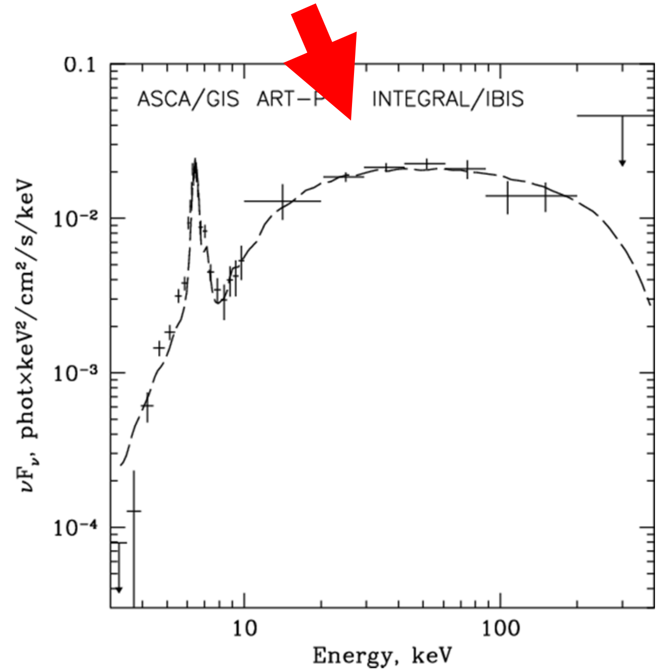
SgrB2 is a giant molecular cloud at 100pc projected distance from SgrA

The spectrumof SgrB2 is pure reflection spectrum

Reflection of what?
No bright enough source is there




The emission from SgrB2 is extended and brighter in the direction of SgrA,Murakami 2001

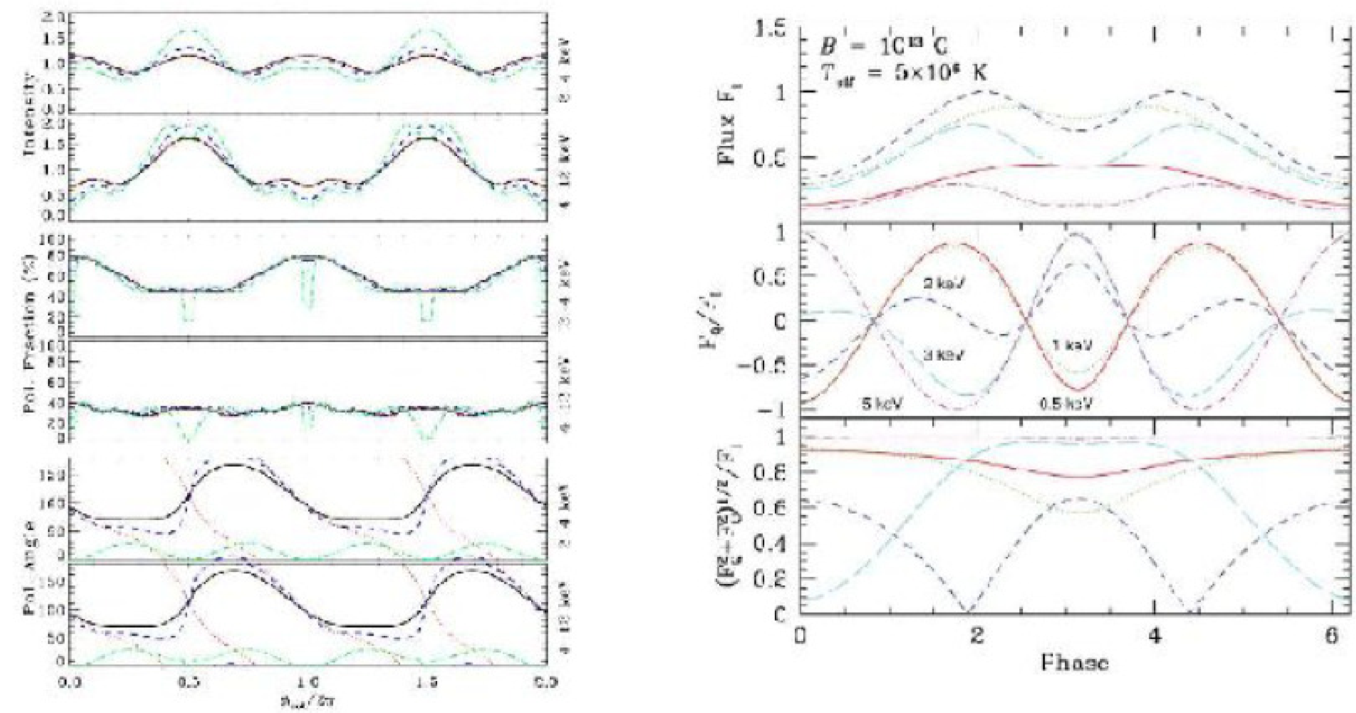



Rashid Sunyaev suggested that SgrB2 is reflecting the emission from the Black Hole in SgrA as it was a few hundred years ago.

# Fundamental Physics

# Matter in Extreme Magnetic Fields: QED effects

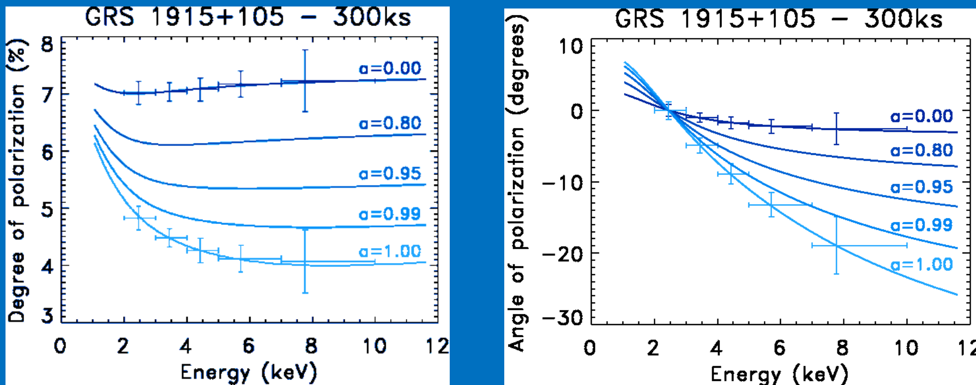
Behavior of matter in strong B field




"normal" NS magnetar

**Polarization expected for "normal" pulsars (B=$10^{13}$ G, left) and magnetars (B=$10^{14}$ G, right) as a function of the spin phase for different energy bands. Note that low energy radiation is opposite to high energy radiation in the first case (Adelsberg & Lai 2006; Fernandez & Davis 2011).**

# Matter in Extreme Gravitational Fields: GR effects




The polarization degree (left panel) and angle (right panel) as a function of energy, expected to be measure by XIPE in GRS1915+105 with a 200ks observation (Dovciak et al. 2008).

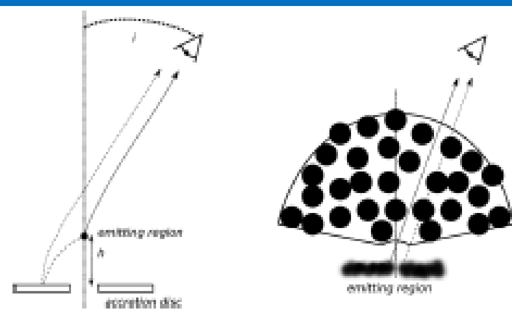



**Figure 1.** Schematic view of the scenarios considered. Left-hand panel: reflection with a lamppost geometry and light bending. Right-hand panel: partial covering with a clumpy wind.

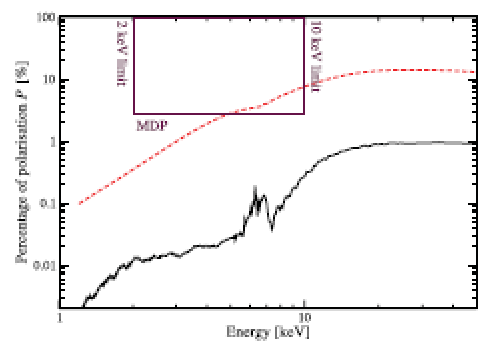



**Figure 3.** *XIPE* minimum detectable polarization of the two scenarios for a 1 Ms observation of MCG-6-30-15 in the 2–10 keV band (maroon box). The observer's line of sight lies at 30° with respect to the symmetry axis. Legend: clumpy absorption (solid curve) and relativistic reflection induced by a Kerr SMBH with $a = 1$ (red dashed curve).

Marin 2012

Polarimetry (even with a small mission like XIPE can discriminate partial covery from reflection)

# Quantum Gravity

Quantum Gravity should be effective on the Planck Energy scale ($E_{QG}=10^{19}$ GeV). But the hypothized existence of space-time foam can produce detectable effects on radiation propagating on very long distance scale.

One of the major approach to quantization of Gravity is the Loop QG that predicts birefringence effects.

The result is a difference of light velocity for the two states of circular polarization:

$V_{+}=c[1+c(E/E_{QG})^{n}]$ $\qquad$ $V_{-}=c[1-c(E/E_{QG})^{n}]$

# The plane of linear polarization is subject to a rotation along the path

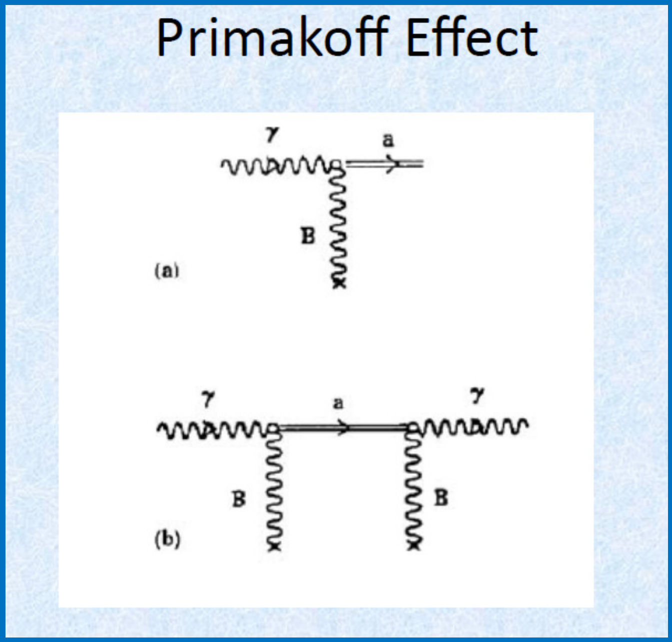
Upper limits to the coupling constant c for the linear dependence of the velocity on ($E/E_{QG}$) are derived by various data. One of these $c<10^{-4}$ is the 1976 measurement of X-ray polarization of Crab, the only positive detection of X-ray polarization so far (Kaaret 2003). A similar limit is derived from UV data on remote QSOs. A limit of $c<10^{-8}$ is claimed from optical data of a GRB but at different times. A stronger limit was derived from polarization of Crab with INTEGRAL. But is all based on the assumtion that optic and gamma come from the same source.

Gamma rays are sensitive because of the energy. But X-rays are the band where we can build a real Cosmic Ladder. Blazars in the synchrotron regime can be the ingredient of this ladder .

With an observation of $10^6$ s, values of $\eta$ down to $3\times10^{-10}$ can be measured with XIPE using e.g. the known Blazar 1ES1101+232, at z=0.186, with clear synchrotron spectrum and high optical polarization, assuming it has a 10% polarization degree in the X-ray band. Several bright enough Blazars at different distances are available to put the result on a firm statistical basis.

# Search for axion-like particles

Axion-like particles (ALPs) are spin-zero bosons predicted by many extensions of the Standard Model of particle physics, like four-dimensional models, compactified Kaluza-Klein and superstring theories. Depending on the actual values of their mass and on the *agg* photon coupling constant, ALPs can play an important role in cosmology, either as cold dark matter particles responsible for the formation of structures in the Universe or as quintessential dark energy which presumably triggers the present accelerated cosmic expansion (Bassan,Mirizzi,Roncadelli 2010).




Axions are one of the most elusive but of the most exotic candidate for Dark Matter.

If the magnetic field is oriented the photons will be polarized.
Various papers proposed the search of axions on he basis of measurements of X-ray polarimetry (e.g. Bassan 2010)

# Relative Weight of Astrophysics vs Fundamental Physics

From the experience of XIPE it seems that FP with Polarimetry can be appreciated by the Physics Community.