On the importance of polarimetry for the future of X-ray astronomy

2006 Total Solar Eclipse, Niger, Fred Bruenjes

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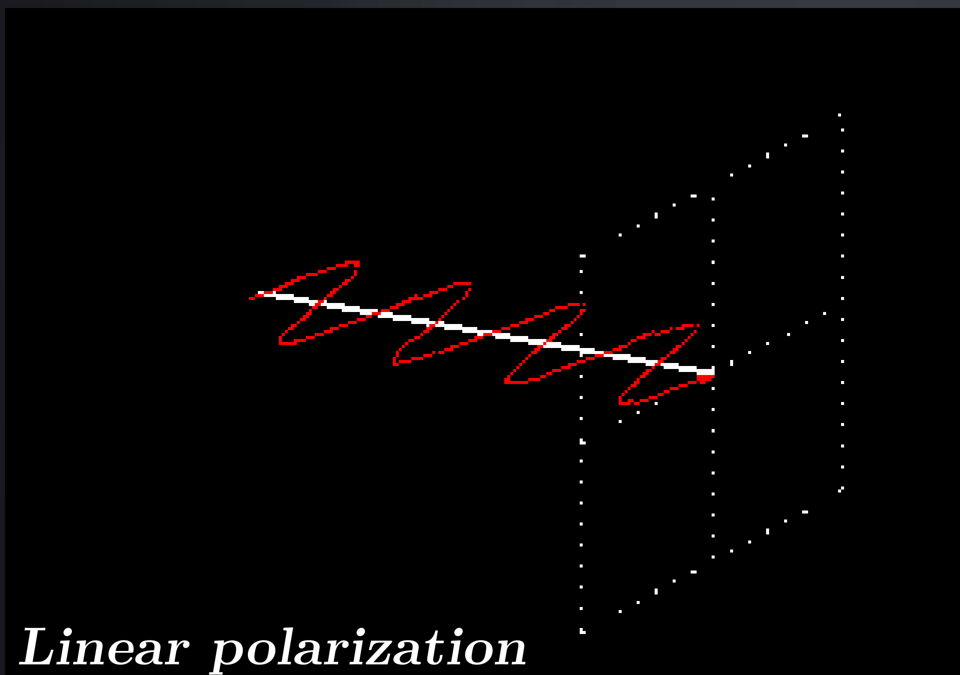
ASTRONOMICKÝ ÚSTAV
Akademie věd České republiky, v. v. i.

Polarization: principle

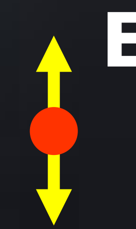
Temporal evolution of the tip of the electric vector



Linear polarization

Polarized Light

vibrations of the E-field lie on one single plane only



Unpolarized Light

superposition of many beams, in the same direction of propagation but each with random polarization

2 additional informations to intensity:

- polarization degree
- polarization angle

Polarization & Astronomy

Radio, IR, optical and UV polarization studies:

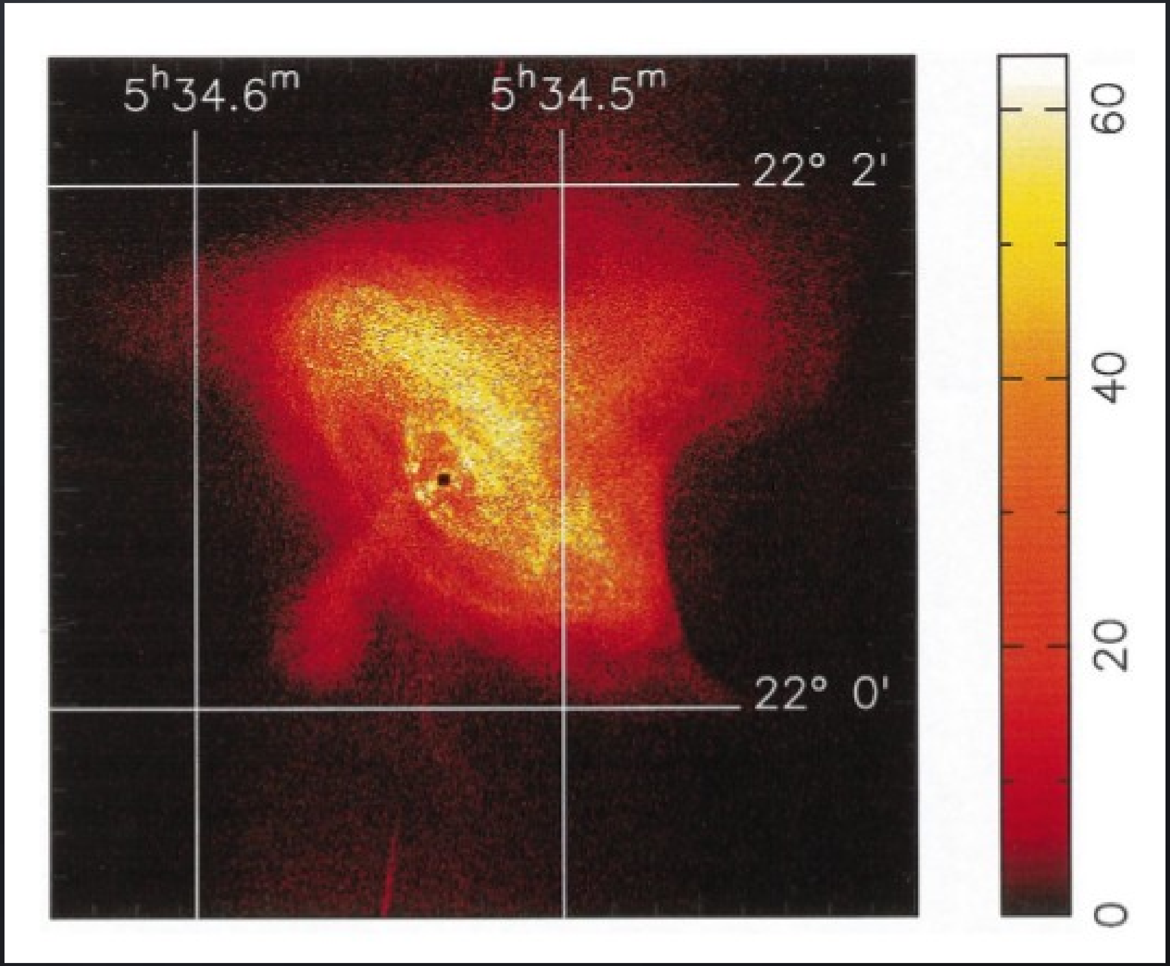
- *geometry and dynamics of stellar winds, jets and disks*
- *binary orbit inclinations + stellar masses*
- *discovery of strong magnetic fields in white dwarfs*
- *composition of interstellar grains*
- *seminal unified model of Seyfert galaxies*
- *... (Tinbergen 1996)*

Antonucci (1993) – 2164 citations

What about X-ray polarization ?

X-ray polarization measurement

1972: First astronomical X-ray polarization measurement
(Aerobee 350 rocket, Crab Nebula)



Weisskopf et al (2000) ; zoomed Chandra HETG–ACIS-S image of the central 200'' x 200'' of the Crab Nebula

X-ray polarization measurement

1972: First astronomical X-ray polarization measurement
(Aerobee 350 rocket, Crab Nebula)

1978: Last astronomical X-ray polarization measurement
(8th Orbiting Solar Observatory, Crab Nebula)

TABLE 3

SUMMARY OF STOKES PARAMETERS AND X-RAY POLARIZATION OF THE CRAB NEBULA

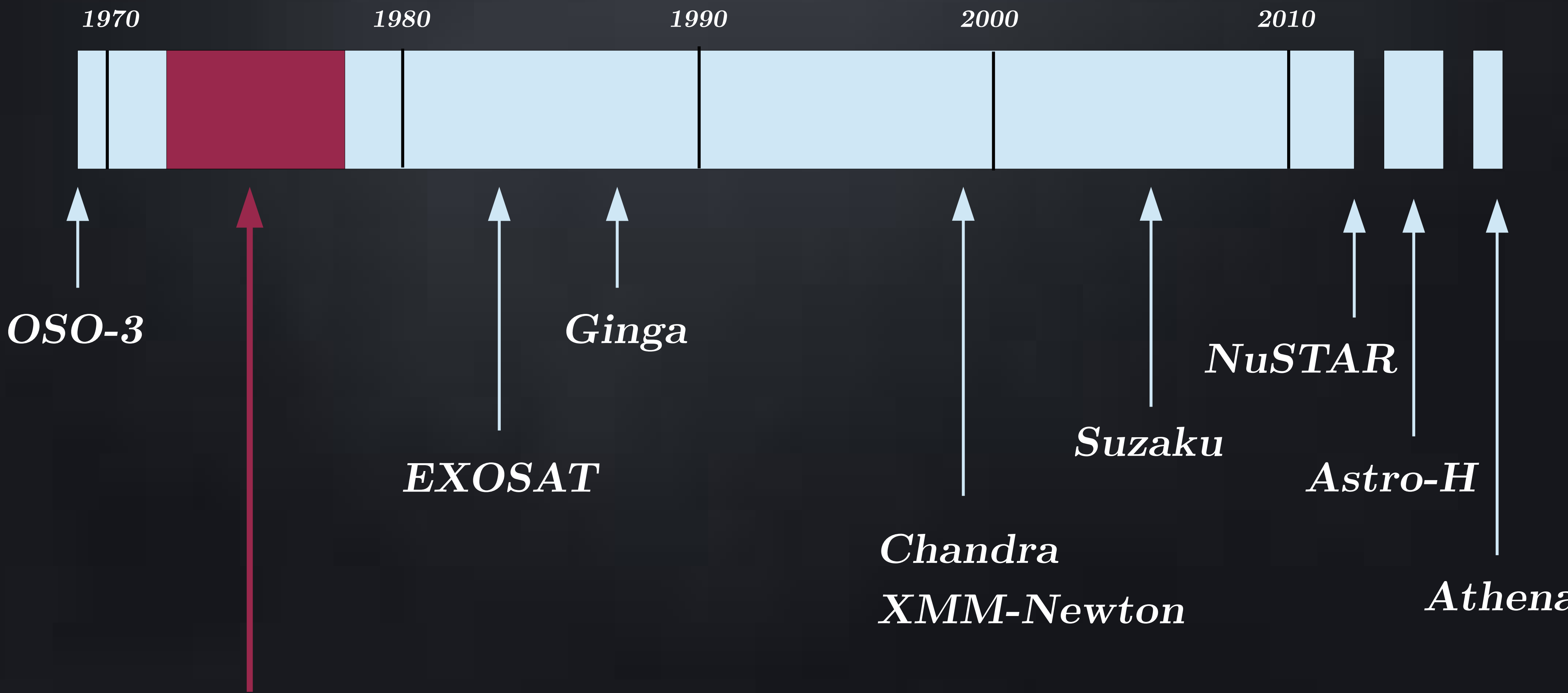
Experiment	Energy Range (keV)	q (percent)	u (percent)	P (percent)	θ (degrees)
Bragg crystal polarimeter, 2/22/71..	2.0– 3.2	15.4 ± 9.8	-18.5 ± 10.1	24.1 ± 10.2	155 ± 11
Lithium polarimeter, 2/22/71......	7.0–17.0	9.5 ± 7.7	-11.2 ± 7.9	14.7 ± 7.9	155 ± 14
This experiment combined,* 2/22/71	...	11.8 ± 6.1	-13.9 ± 6.2	18.2 ± 6.1	155 ± 10
Lithium polarimeter,† 3/7/69.......	5.5–22.0	7.2 ± 9.5	-5.0 ± 9.5	8.8 ± 9.5	163 ± 29
All X-ray data,*..................	...	10.5 ± 5.1	-11.3 ± 5.2	15.4 ± 5.2	156 ± 10

* Assumes that the polarization is energy independent.
† Wolff *et al.* 1970.

Novick et al (1972) ; Weisskopf et al. (1976), >3σ

X-ray Astronomy Satellites & Missions

(0.01 to 80 keV)



Last and unique window for X-ray polarimetry

Science with X-ray polarimetry

Theoretical X-ray polarization estimated long ago

Cyclotron	*(Rees 1975)*
Synchrotron	*(Westfold 1959)*
Non-thermal Bremsstrahlung	*(Brown 1971)*
Scattering	*(Sunyaev & Titarchuk 1985)*
General Relativity	*(Stark & Connors 1977)*
Magnetic fields	*(Gnedin & Sunyaev 1974)*

Highly sensitive to:

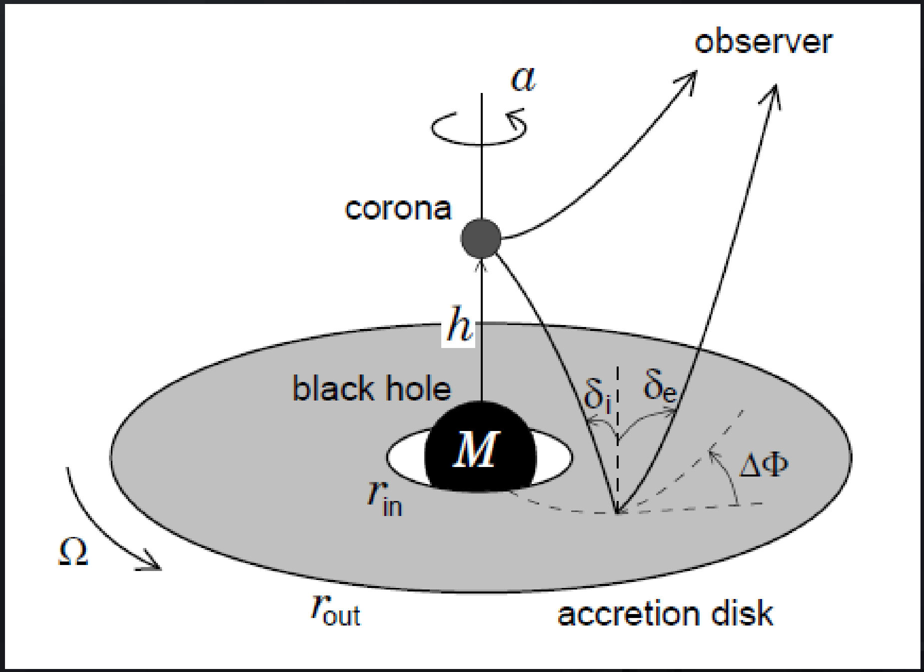
- *source morphology*
- *geometry of the reprocessing material*
- *spacetime through which the X-rays propagate*
- *strength of local magnetic fields*

Accretion disks

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

Scattering = polarization

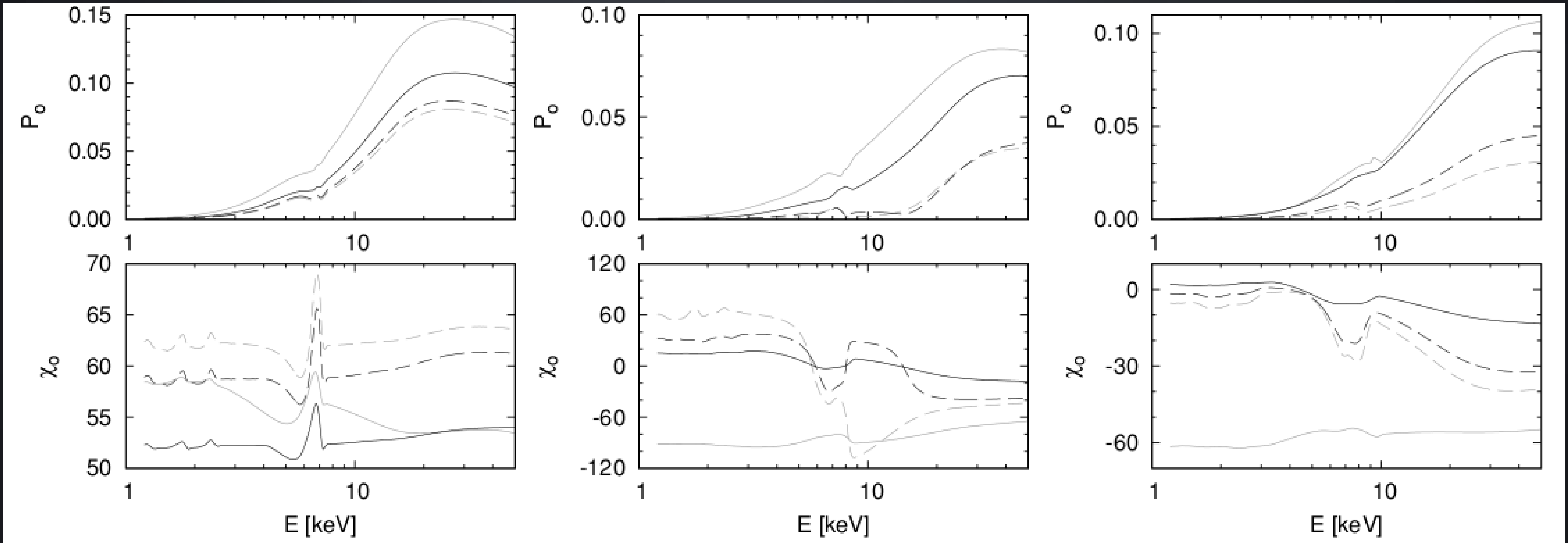
Dovciak et al. (2004)



Strong gravity fields affect the polarization of scattered radiation
(Laor et al. 1990;
Dovciak et al. 2004a,b,c)

Ionization, clumpiness ...

Accretion disks: AGN



Dovciak et al. (2011)

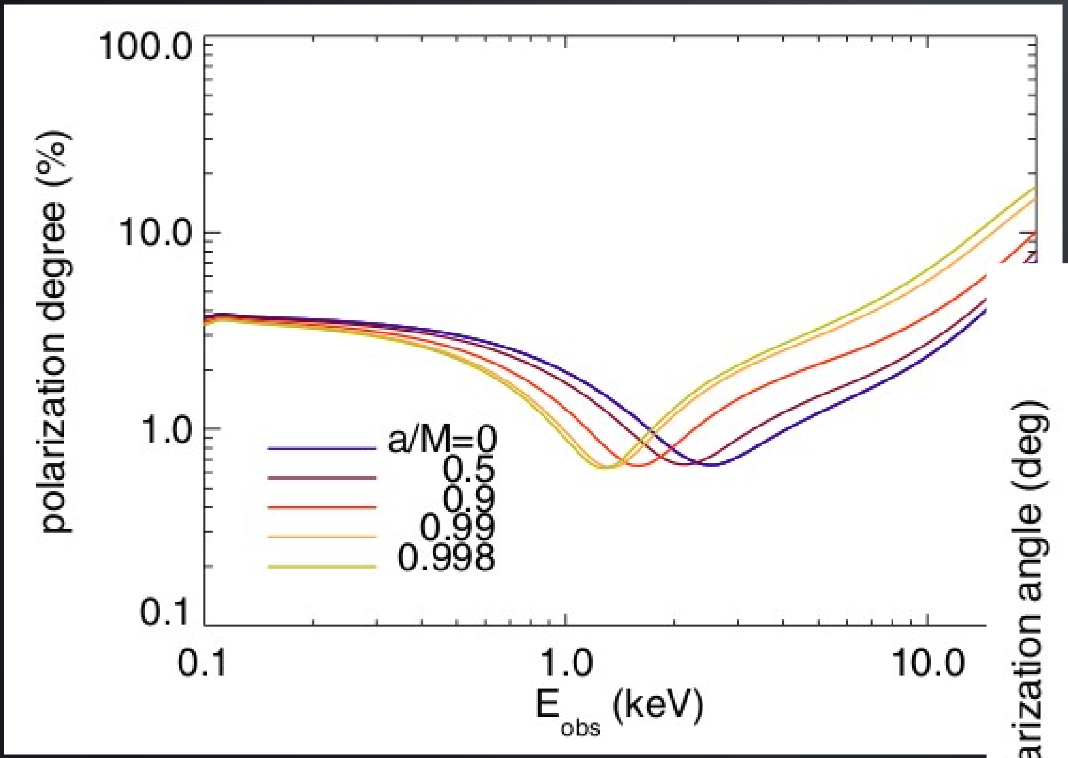
Inclination i = 30°, 60°, and 80°

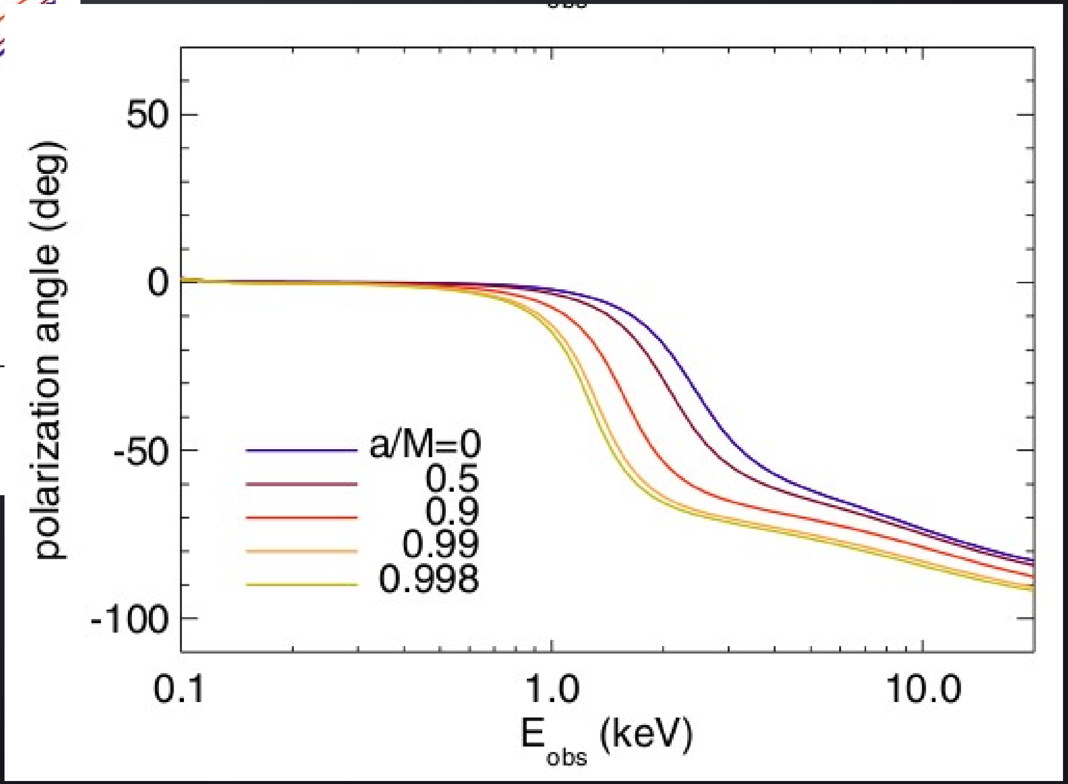
Black: a = 0, gray: a = 1

Height of the primary source = 3 GM/c² (solid), 15 GM/c2 (dashed)

Total radiation (primary + reflected components) at infinity

Accretion disks: XRB





inclination i = 75°

BH mass 10 Msol

L/LEdd = 0.1

Novikov–Thorne radial emission profiles

Schnittmann & Krolik (2009)

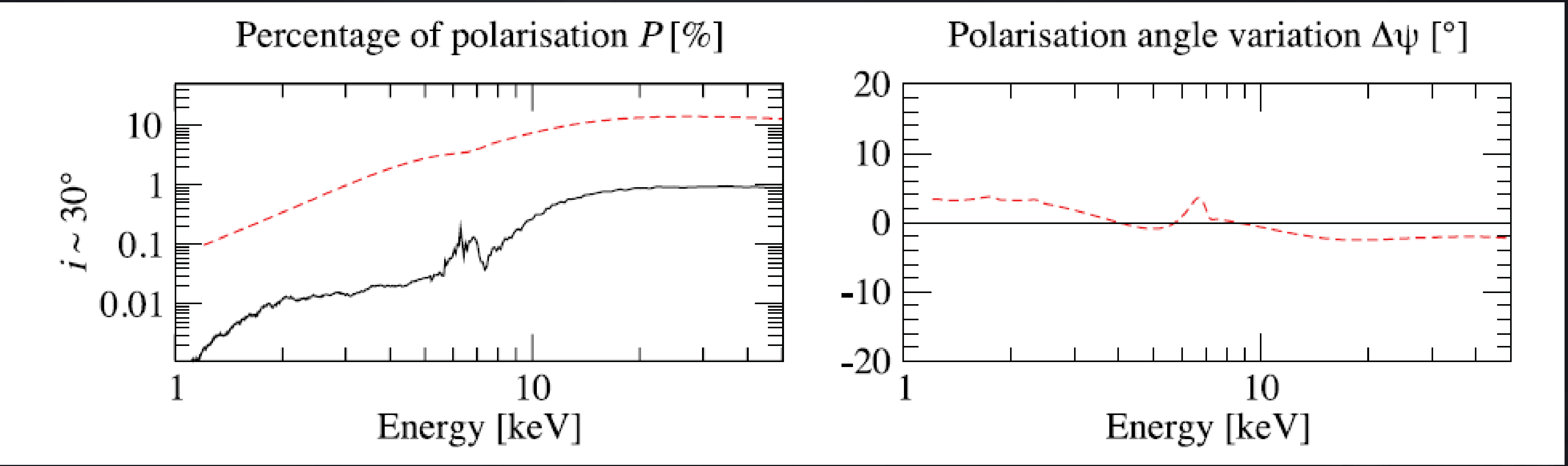
Hard UV and soft X-ray complementarity

AD+GR vs Complex absorption

X-ray reprocessing onto AD can be compared to complex, distant absorption where GR effects no longer occur

- → ***disentangle the dominant Fe Kα skewing mechanism***
- → ***impact of pure absorption and Compton scattering by a cloudy medium***

Marin et al. (2012)
Marin & Tamborra (2013)



Pulsars and Low-Mass XRB

Isolated neutron stars (NS) and XRB = bright sources

Opacity of a magnetized plasma depends on polarization of radiation

$\rightarrow$ emerging radiation should be strongly polarized.

Depends on:

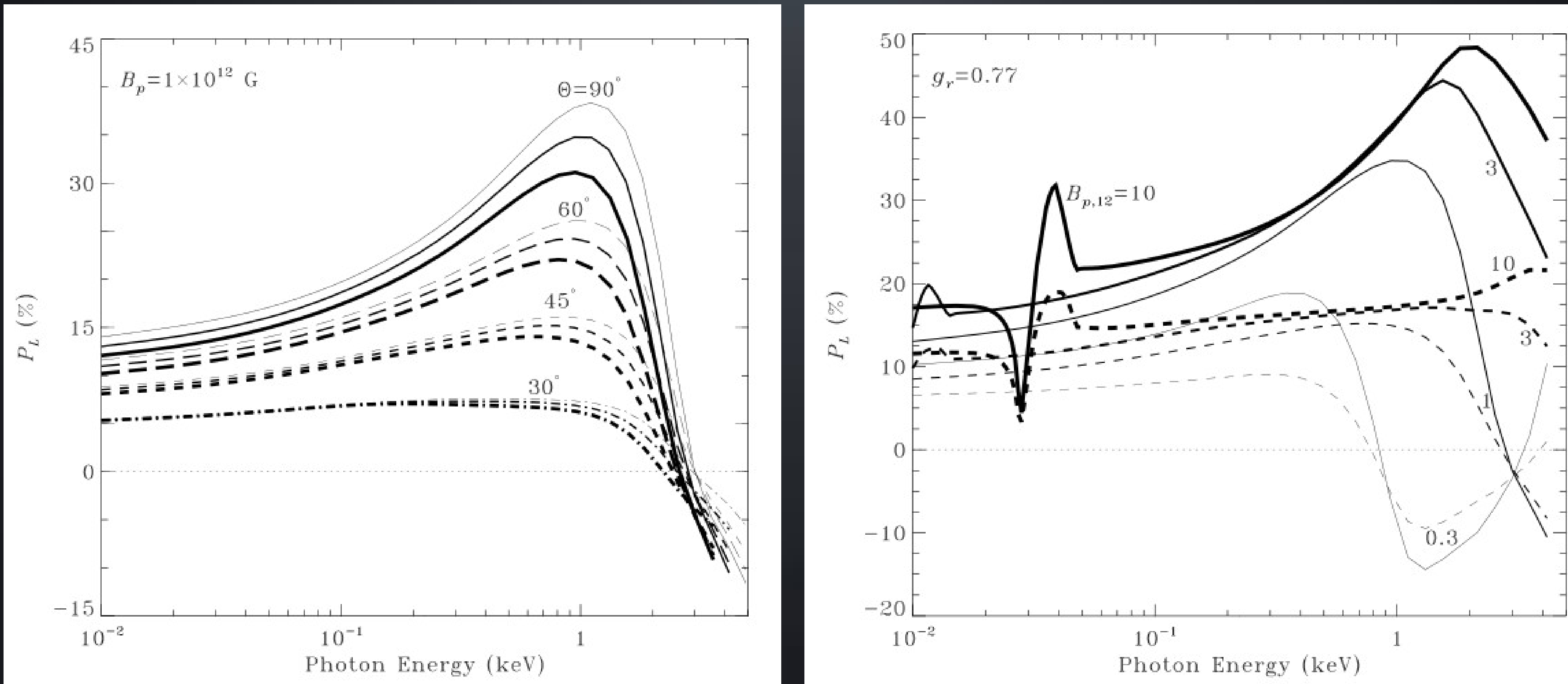
- photon energy

- effective temperature

- magnetic field

Polarimetry is more sensitive than spectroscopy to magnetic fields !

Pulsars and Low-Mass XRB



Pavlov & Zavlin (2000)

Measuring the orientation of the rotational and magnetic axes + mass-to-radius ratio with soft X-ray polarimetry

(magnetic) Cataclysmic Variables

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

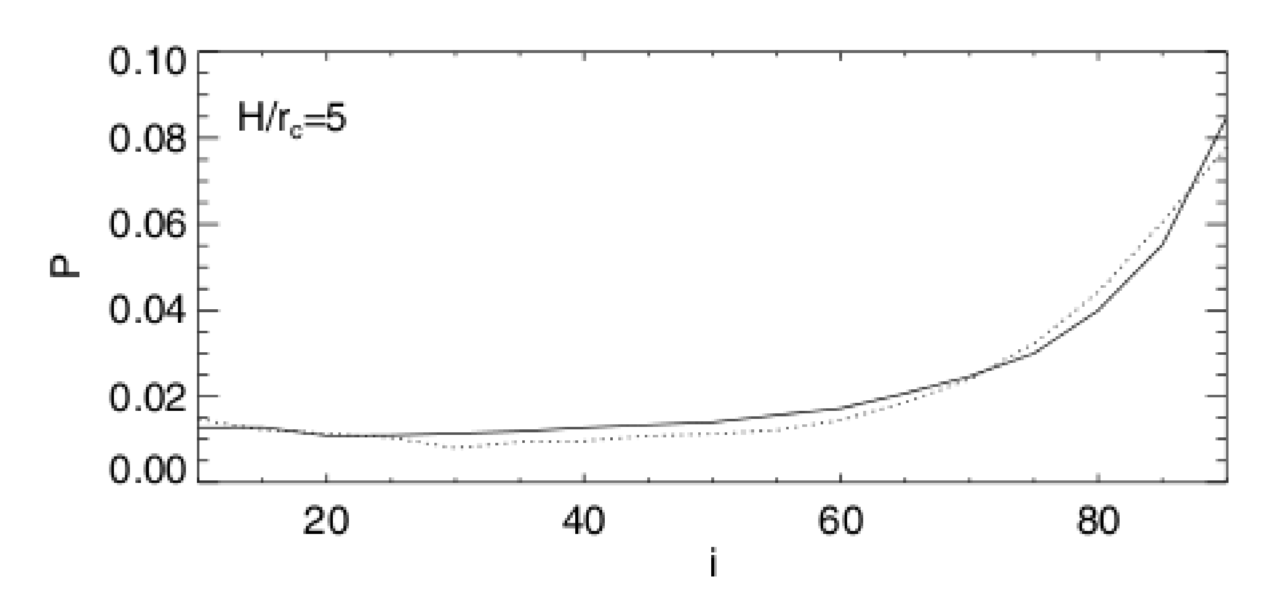
In magnetized systems, the accretion flow is confined by the magnetic fields near the WD (Warner 1995)

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

If high accretion rate, τ accretion column is high
$\rightarrow$ *Compton scattering (polarization)*

(magnetic) Cataclysmic Variables

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



McNamara et al. (2008)

M_{WD} = 0.5 Msol

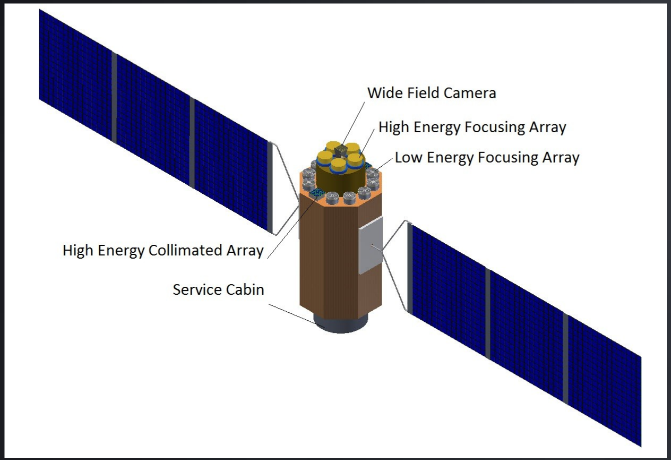
r_{acc} = 10 g/cm²/s

Cycl/Brems cooling rate = 0 and 10

Polarization up to 8% (may vary with rotation phase)

Sensitive to density structure

The future ?



X-ray Timing and Polarization (XTP)

(effective area ~300 cm² (@30 keV), 2000 cm² (@2 keV), 1-10 keV Chinese program)

X-Ray Imaging Light Polarimetry Explorer (XILPE)

(imaging capability, spectral res. 20% @ 6 keV, 2-10 keV, ESA S call)

IXPE-like instrument (Imaging X-ray Polarimetry Explorer)

(SMEX program, no details so far, American-Italian effort)

X-Calibur

(effective area ~50 cm² (@30 keV), FWHM energy res. ~ 5 keV, 2-80 keV balloon tests in October 2014 !)

Conclusions

X-ray polarimetry is a powerful tool to probe virtually *every astronomical source*

Polarization percentages > 1% expected from a large set of sources (CV, NS, XRB, AGN, Blazars ...)

P > 1% is detectable

Future for X-ray polarimetry

→ *Talk: F. Tamborra (Fe Kα line, XRB, AGN ...)*

→ *Posters: M. Dovciak (Non-smooth BH disks)*

F. Marin (Galactic Center)

Supplementary material

Statistics of X-ray polarization

A polarimeter deals with counting rate statistics

→ mainly depend on the modulation factor μ
(response of a polarimeter to a 100% polarized source)

Minimum Detectable Polarization (MDP) at 99% conf. level

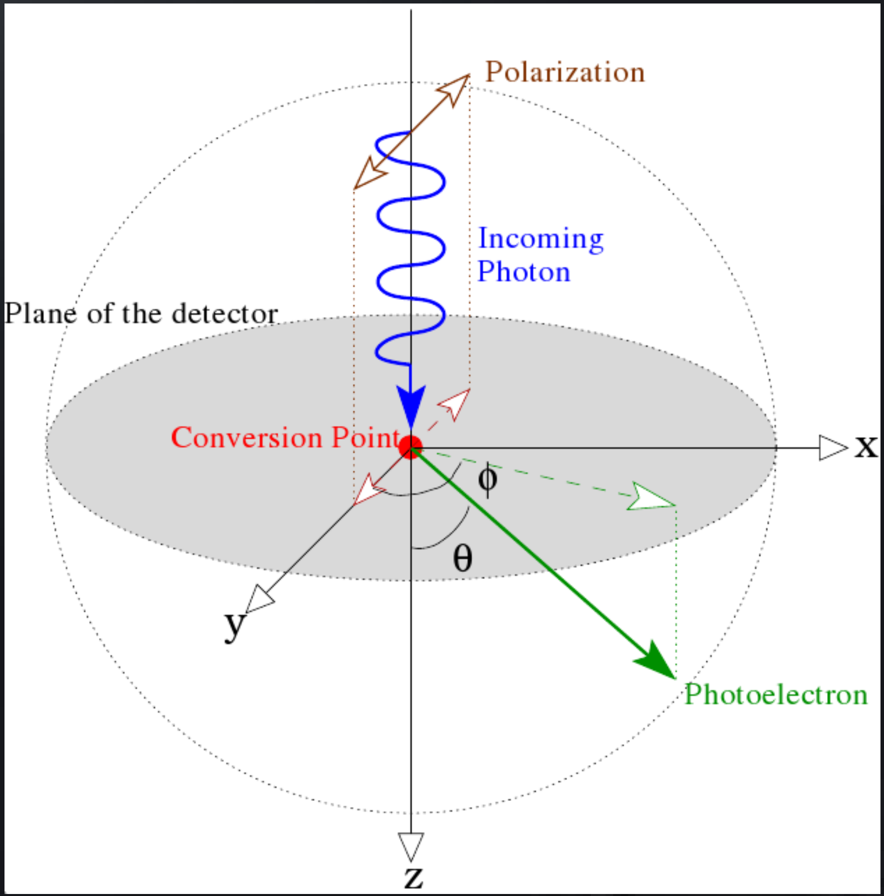
$$MDP = \frac{4.29}{\mu \times S} \times \sqrt{\frac{S+B}{T}}$$

Number count required for 1% MDP (μ = 50%, B = 0) is about 7.10^5 counts (spectral slope ~ 100, detection of an X-ray source ~ 10)

Improving the sensitivity

The direction of the emission of a photoelectron carries memory of the polarization of the absorbed photon

P and ψ of a large number (>10^4) of photons can be derived from the modulation of the reconstructed direction of emission

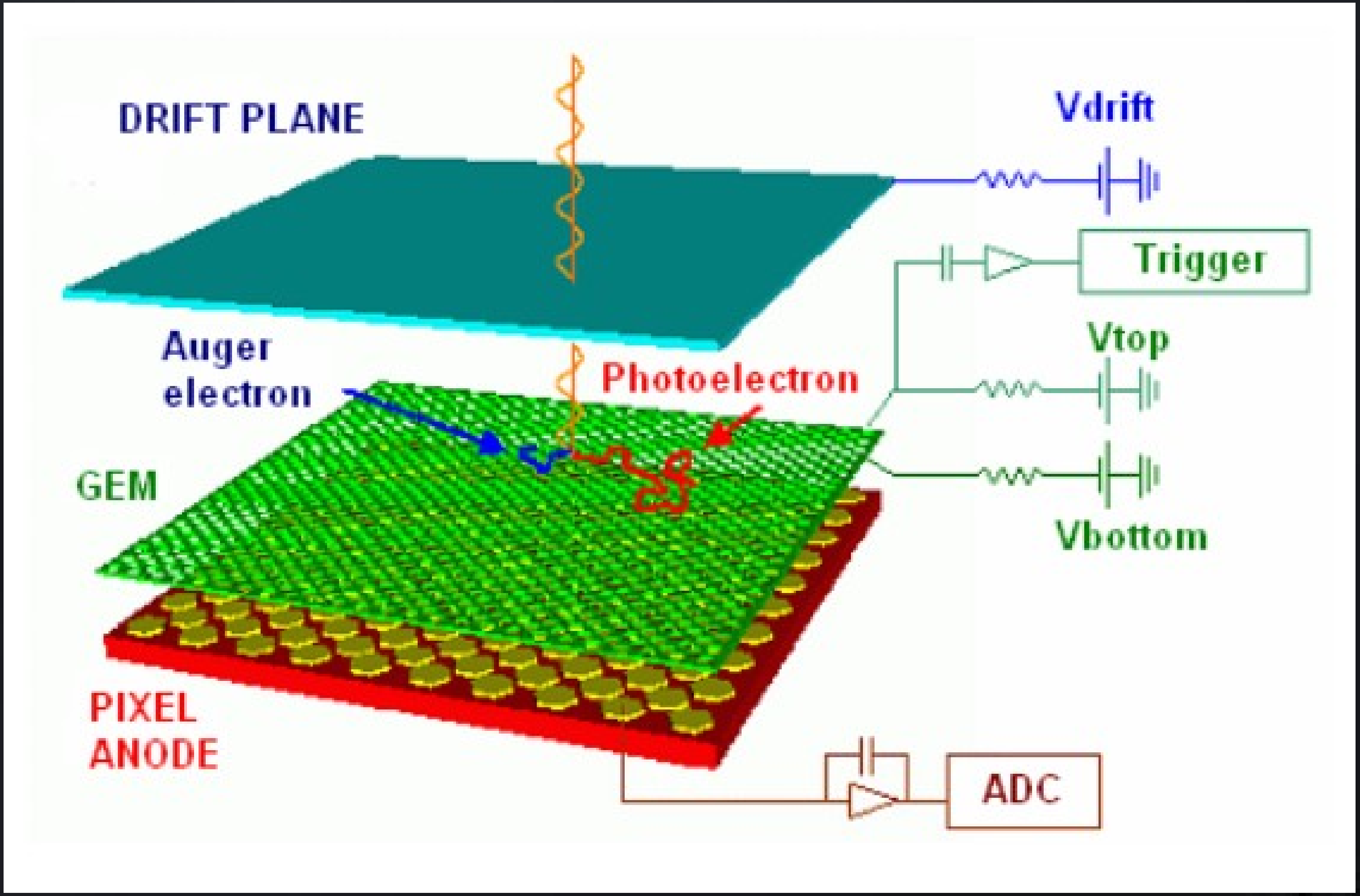


+ wide-band
+ efficient response

Costa et al. (2001);
Bellazzini et al. (2003, 2006,2010)

The Gas Pixel Detector

Photons are absorbed in a high pressure gas detector (Ne-DME or Ar-DME mixtures) → the path of the photoelectrons is traced by the charges generated by ionization.



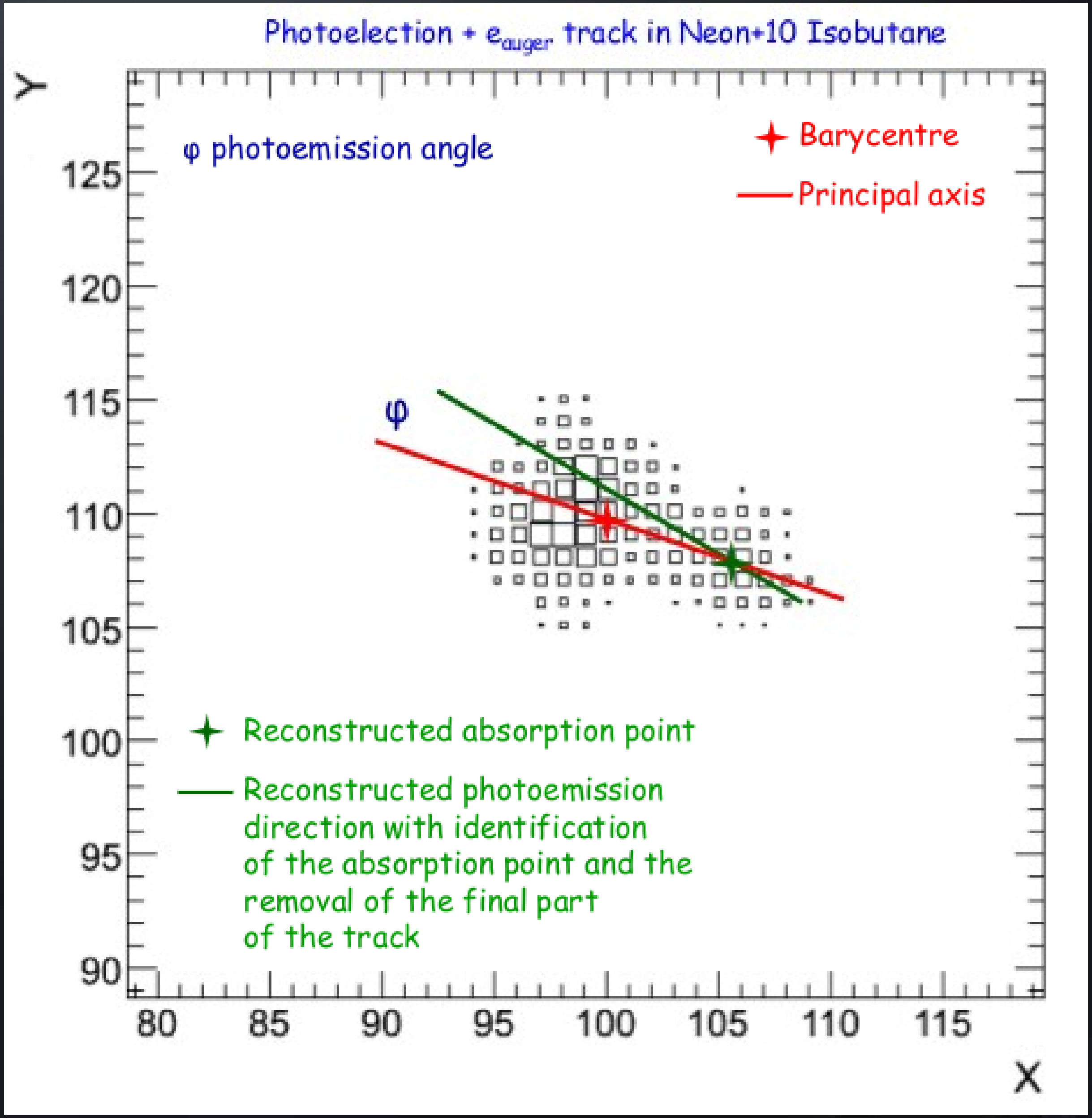
The Gas Pixel Detector

1 - Identify the cluster

2 - Determination of the polarization

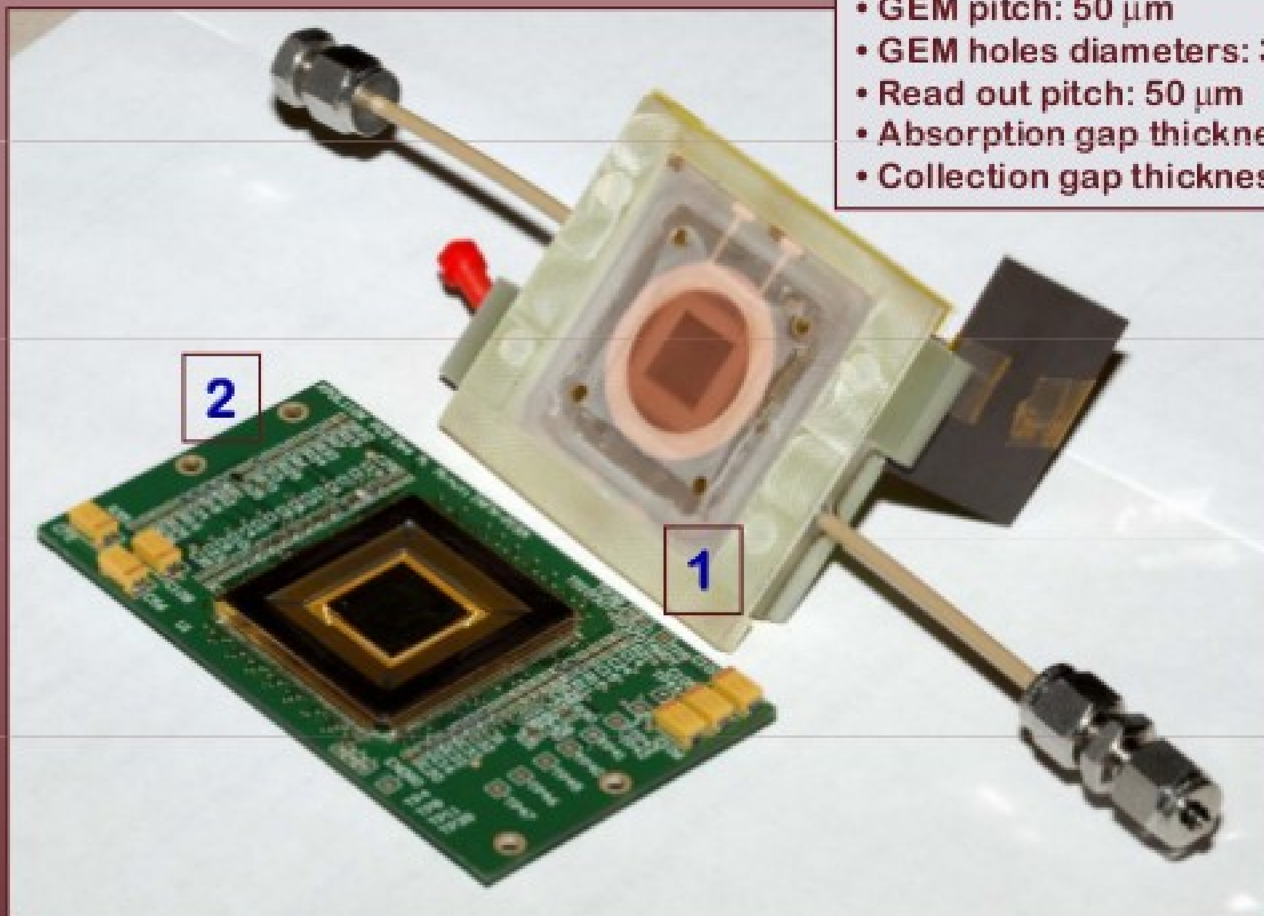
3 - e_{auger} are isotropically emitted with a small fraction of the photon energy

4 - In low Z gas mixture tracks are longer so angular reconstruction is easier



The Gas Pixel Detector

- GEM pitch: 50 μm
- GEM holes diameters: 33 μm, 15 μm
- Read out pitch: 50 μm
- Absorption gap thickness: 10 mm
- Collection gap thickness: 1 mm

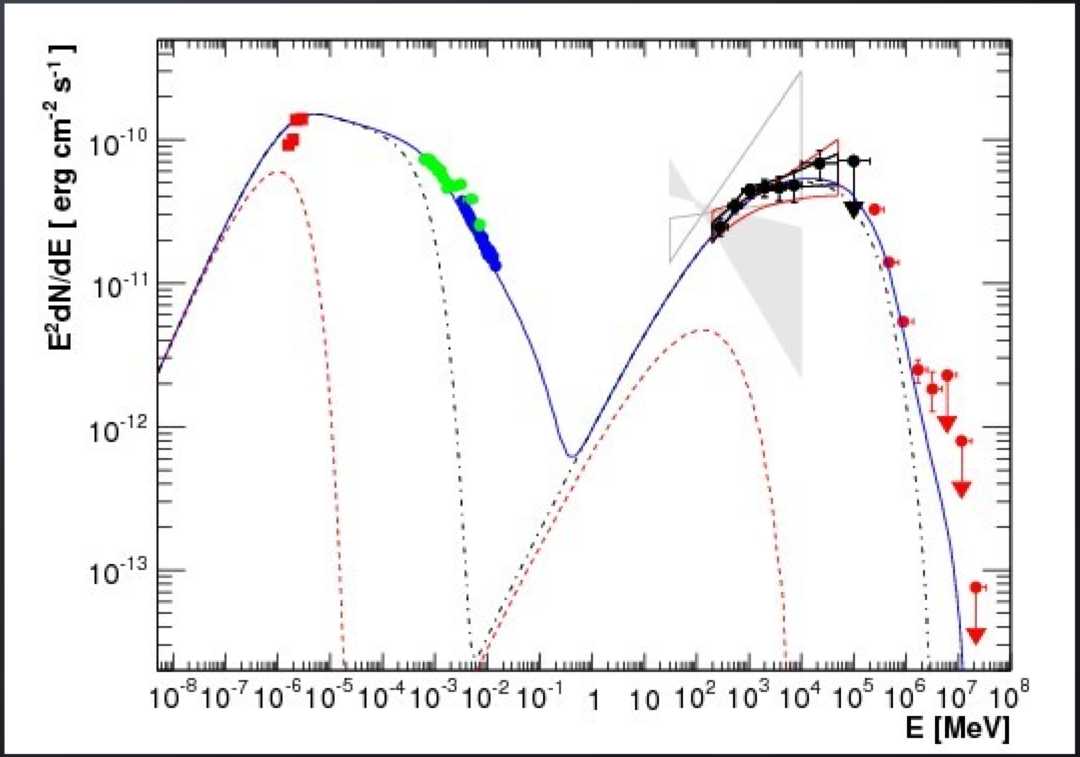


1 - The GEM glued to the bottom of the gas-tight enclosure
2 - The large area ASIC mounted on the control motherboard

Relativistic jets in blazars

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

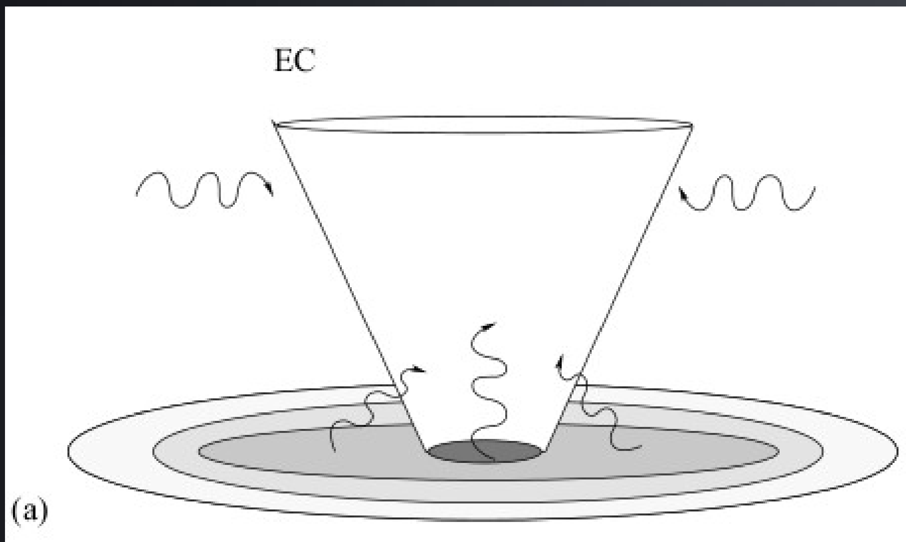
X-ray spectrum steeper than optical spectrum
→ *X-ray produced by accelerated, high energy e^- (base of the jet ? Shocks ?)*



PKS 2155–304 (HESS collaboration)

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

Relativistic jets in blazars

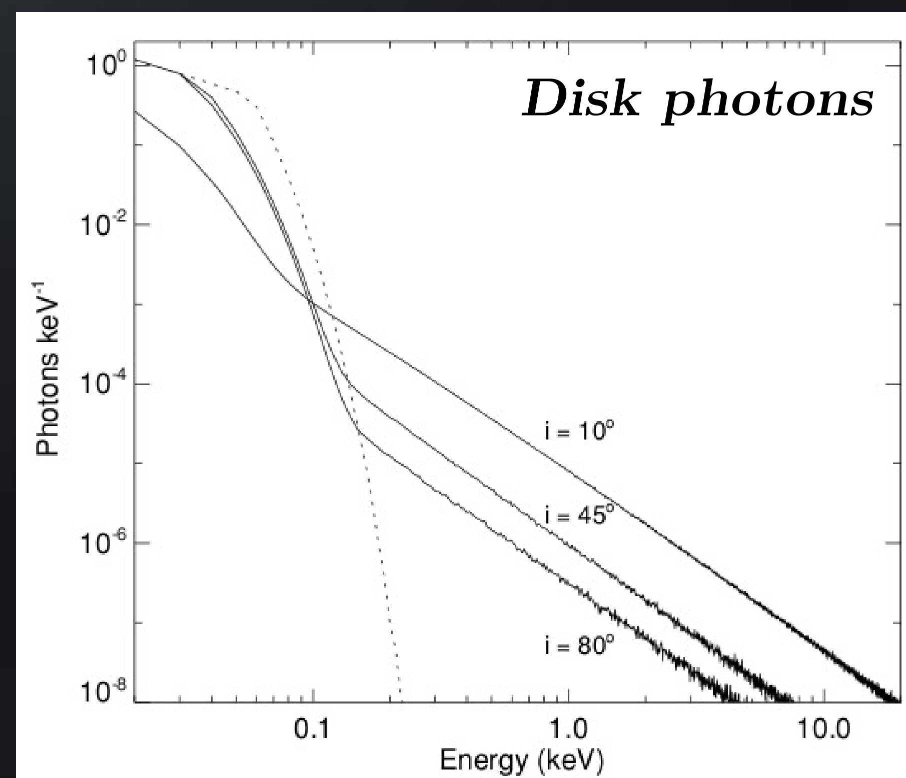


McNamara et al. (2009)

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

Relativistic jet

- *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*



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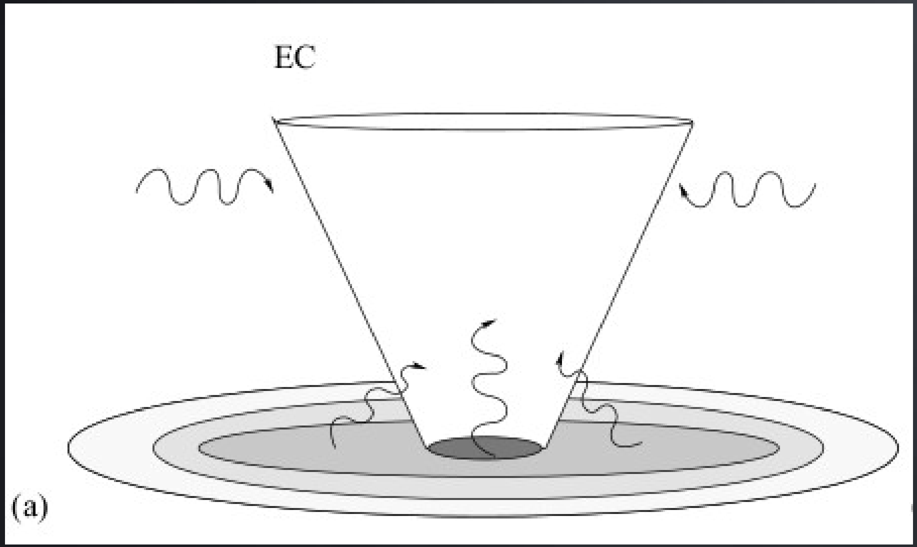
McNamara et al. (2009)



i	P (per cent) (E = 1–10 keV)	Average number of scatterings per photon
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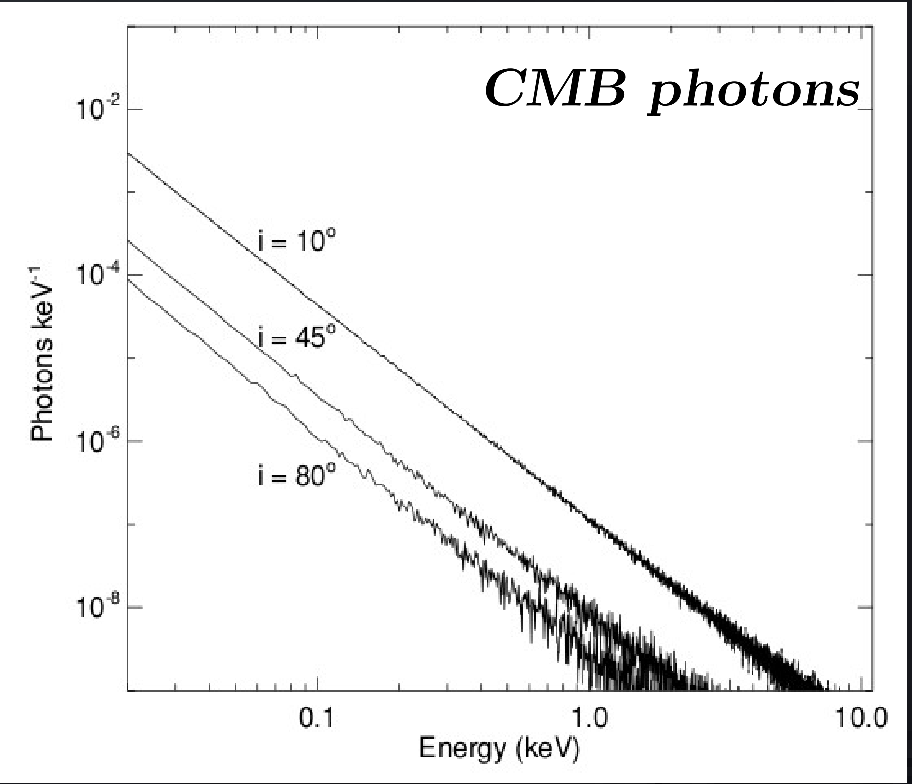

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Relativistic jets in blazars

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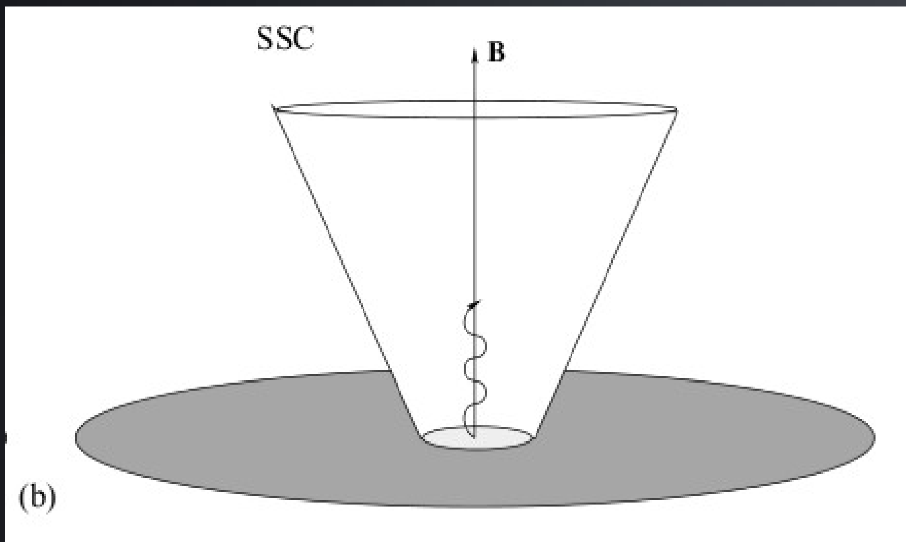


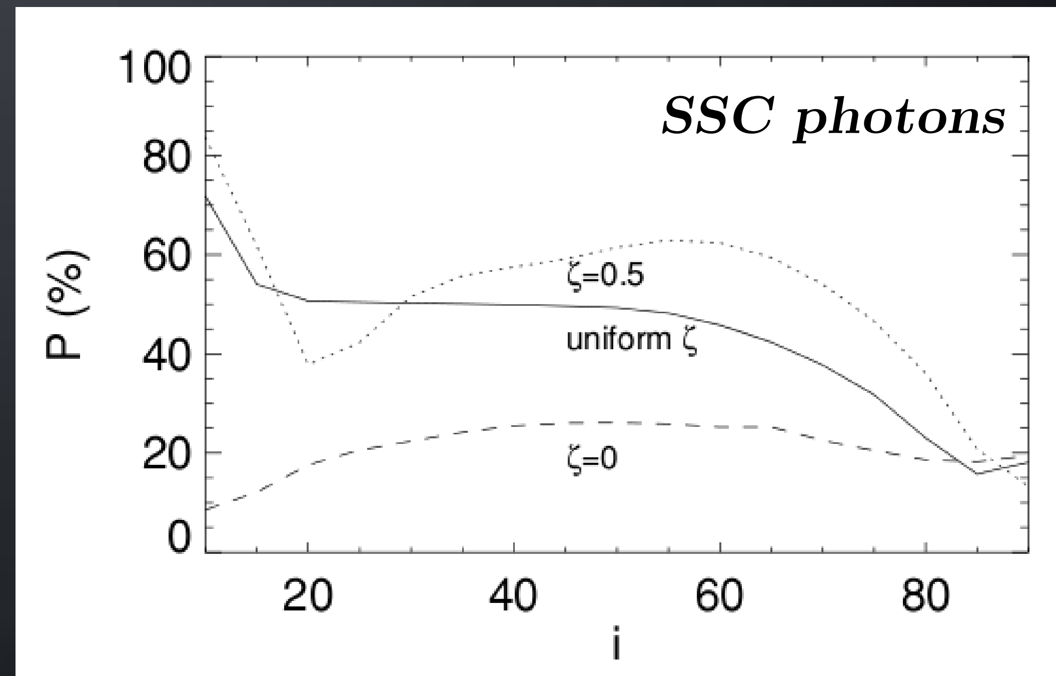
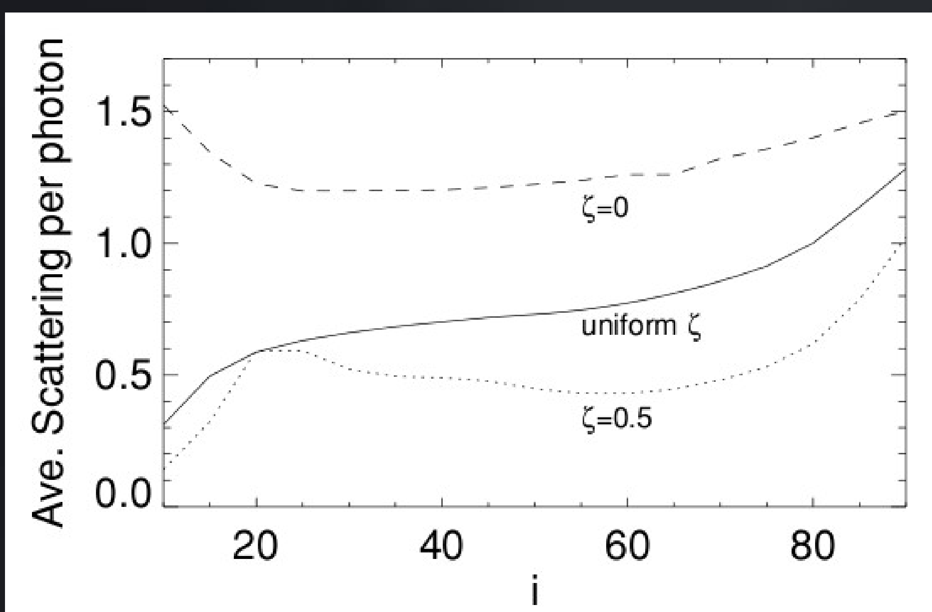


Figure 6. Polarization degree P of SSC photons with energies between 1 and 10 keV plotted as a function of the inclination angle i. The solid line is for the case where the seed photons are emitted uniformly throughout the jet (uniform ζ). The dashed and dotted lines are for the cases where the seed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



Synchrotron seed photons are intrinsically polarized (depolarization ?)

Jets in AGN & XRB

X-ray emission from accretion onto BH may arise from

- Comptonization in a hot corona
- Synchrotron or Comptonization in a jet

Transients with stellar-mass BH (e.g. XTE J1118+480) can be very soft $\rightarrow$ jets may contribute most of the X-rays

Intrinsic polarization !

Origin of jets not resolved in the X-ray band

$\rightarrow$ determining the presence and orientation of jets at $< 1000\ r_g$ with X-ray polarimetry

Other putative instruments

Solar Energetic Emission and Particle Explorer (SEEPE)
(10-35 keV, solar physics only, 16 kg, 25 W)

??
(Next ESA Cubesat call, nano-satellite composed by 3 cubes 10 cm of side, solar polarimetry)

??
(SMEX program, a Compton polarimeter by Mark McConnell)