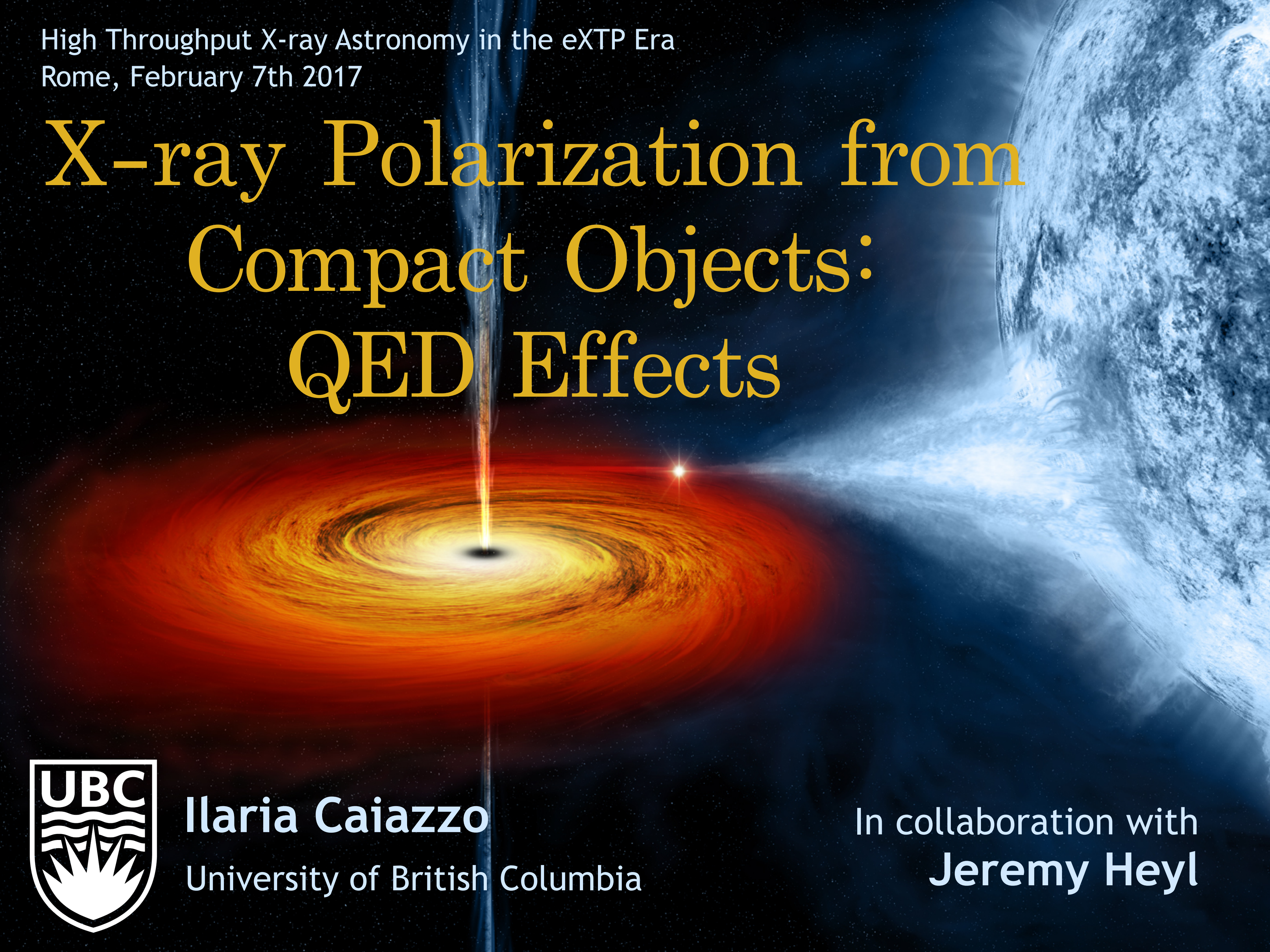
High Throughput X-ray Astronomy in the eXTP Era
Rome, February 7th 2017

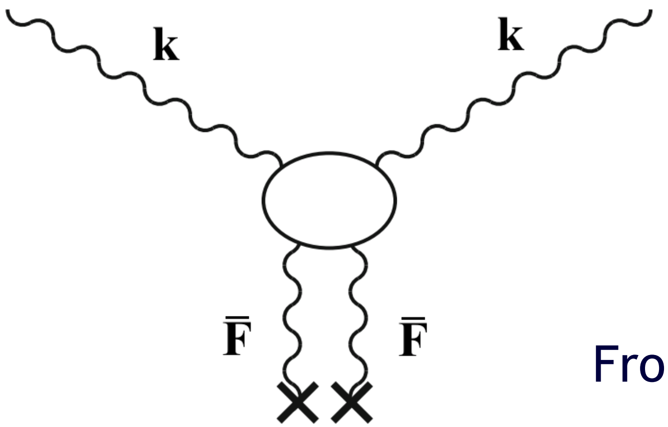
X-ray Polarization from Compact Objects: QED Effects



Ilaria Caiazzo
University of British Columbia

In collaboration with
Jeremy Heyl

Vacuum Birefringence



In **quantum electrodynamics**, photons can couple with each other via the production of virtual electron-positron pairs.

⇨ vacuum in presence of a magnetic field acquires an index of refraction ***n***.

From Heisenberg and Euler effective Lagrangian:

$$n_\perp - n_\parallel = \frac{\alpha_{\rm QED}}{30\pi}\left(\frac{B}{B_{\rm QED}}\right)^2 \sin^2\theta$$

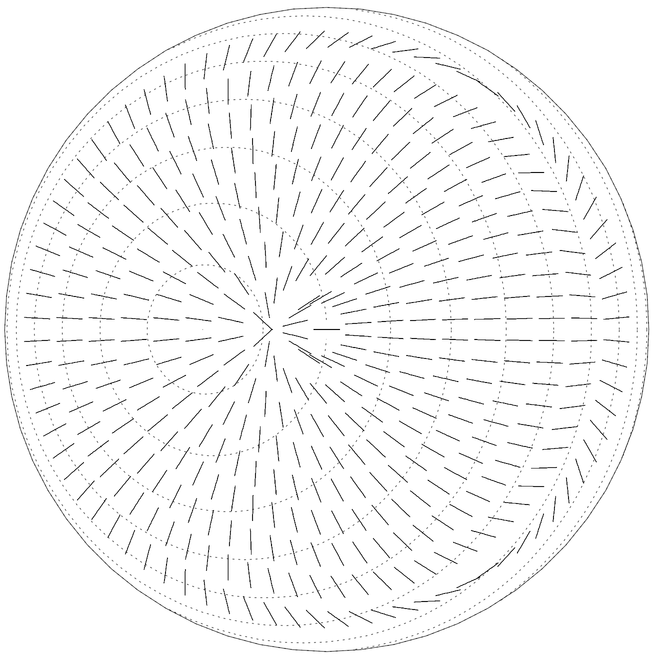
For a strong enough B, the polarization modes are decoupled, and the polarization direction follows the direction of the magnetic field.
The radius at which the polarization stops following the magnetic field is called the polarization-limiting radius

$$r_{\rm pl} \sim 1.2\times 10^7 \left(\frac{\mu}{10^{30}\ {\rm G cm^3}}\right)\left(\frac{\nu}{10^{17}\ {\rm Hz}}\right)^{1/5} (\sin\theta)^{2/5}\ {\rm cm}$$

Heyl & Shaviv 1999

QED effect on X-ray pulsars

Polarization at the surface



$$r_{\rm pl}/R = 0$$

Heyl, Shaviv, Lloyd 2003

QED effect on X-ray pulsars

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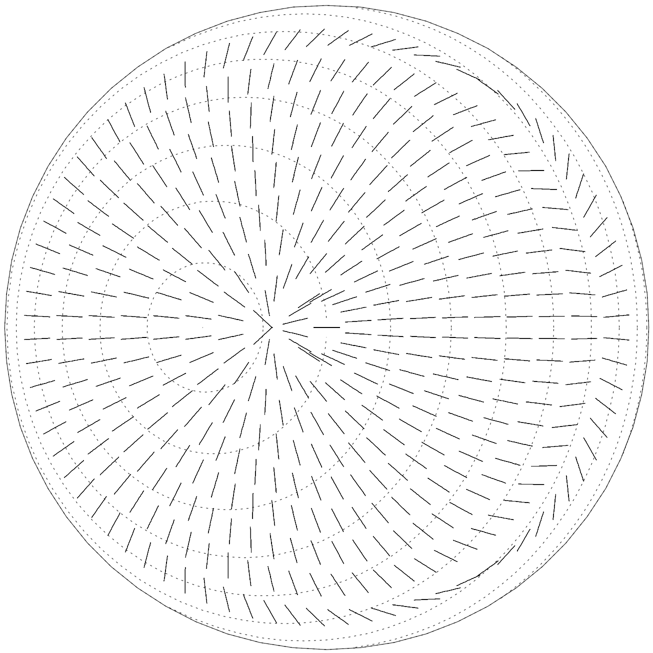
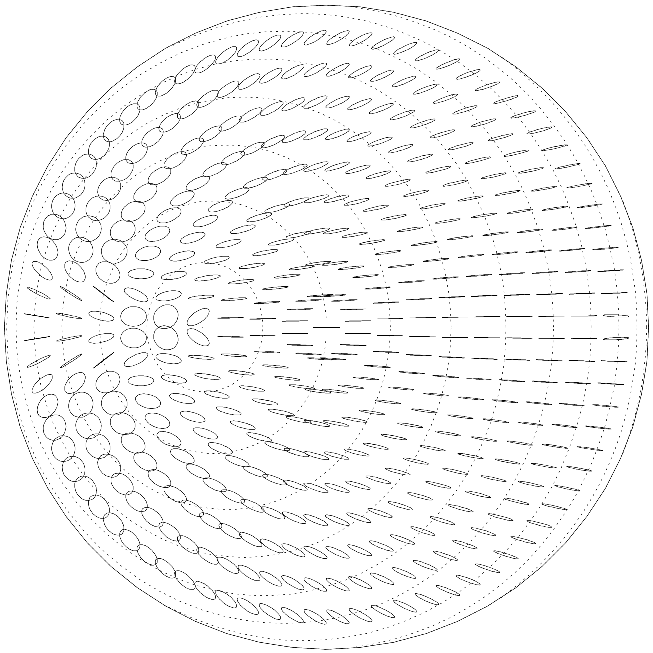


$r_{\rm pl}/R = 0$

Polarization at the polarization limiting radius



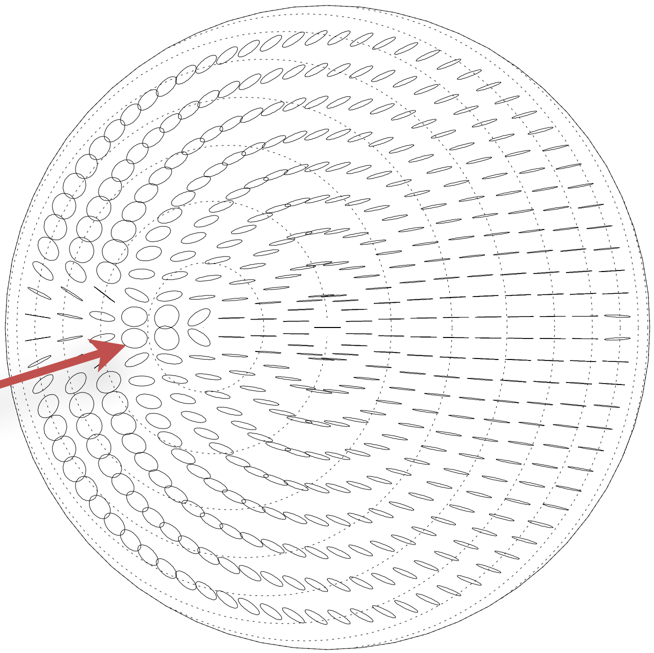
$r_{\rm pl}/R = 12\ (\rm XRP)$

Heyl, Shaviv, Lloyd 2003

QED effect on X-ray pulsars

Polarization at the
polarization limiting radius

Quasi-tangential region
Wang & Lai, 2009

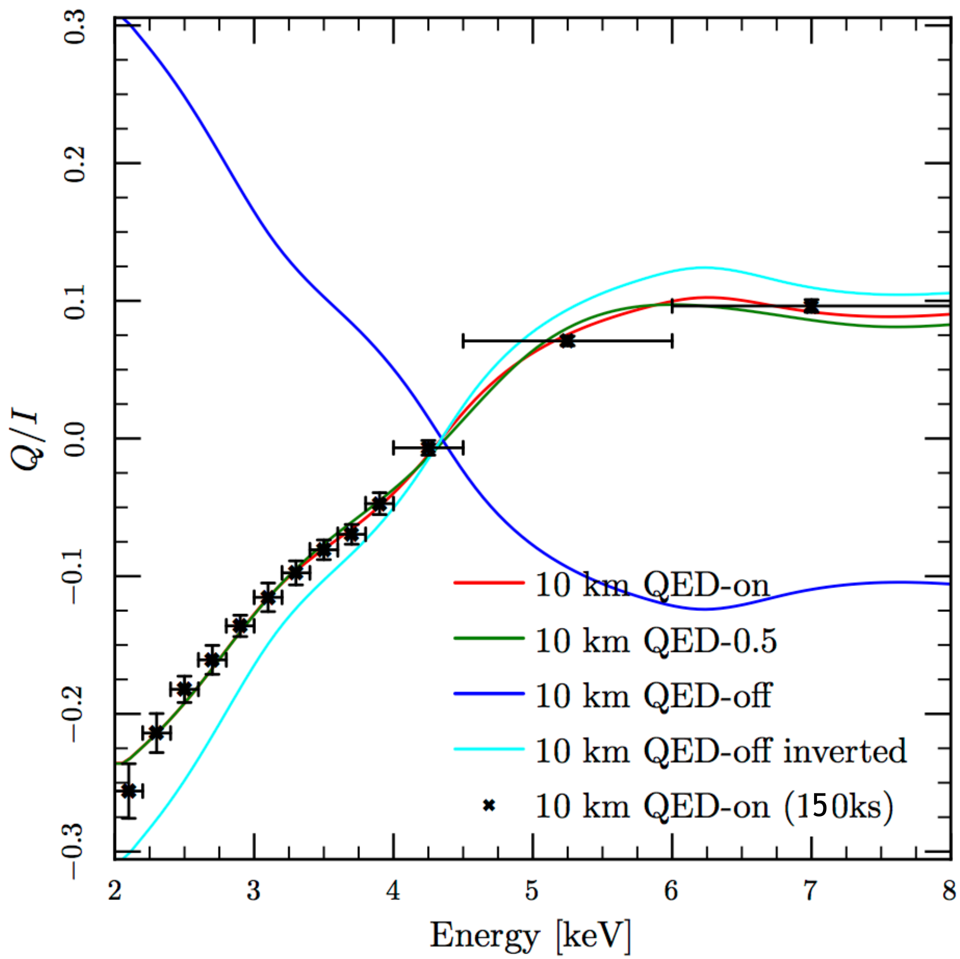


$$r_{\rm pl}/R = 12\ (\mathrm{XRP})$$

Heyl, Shaviv, Lloyd 2003

QED effect on X-ray pulsars

Polarization degree from Her-X1. Black dots are a 150ks simulation with eXTP
Atmospheres models: Mészáros 1988



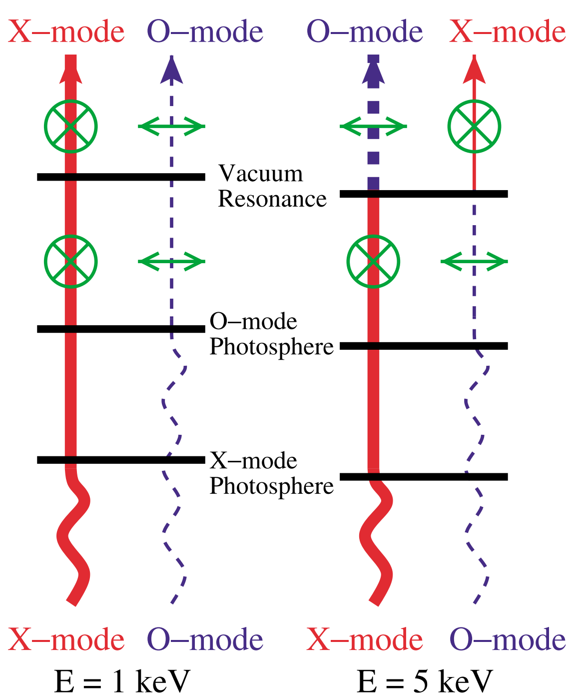
Caiazzo & Heyl, in preparation

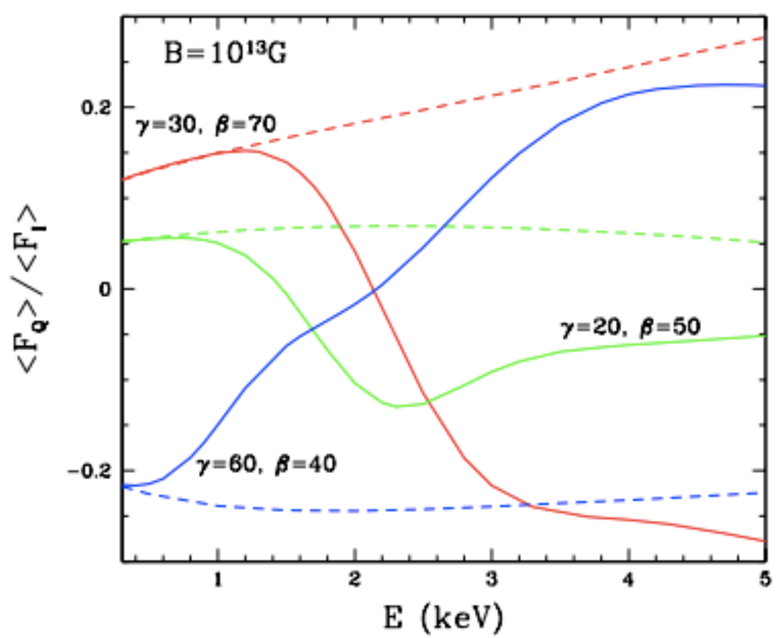
Vacuum resonance

Deep in the atmosphere of the neutron star the plasma dominates, while outside the vacuum dominates.

$$E \gtrsim E_{\rm ad} = 2.52(f \tan\theta|1-u_i|)^{2/3} \left(\frac{1\ \rm cm}{H_\rho}\right)^{1/3} \ \rm keV$$

$$H_\rho = 1.65 \frac{T_6}{g_{14}\cos\theta}\ \rm cm \qquad\qquad u_i = \left(\frac{E_{\rm cycl}}{E}\right)^2$$



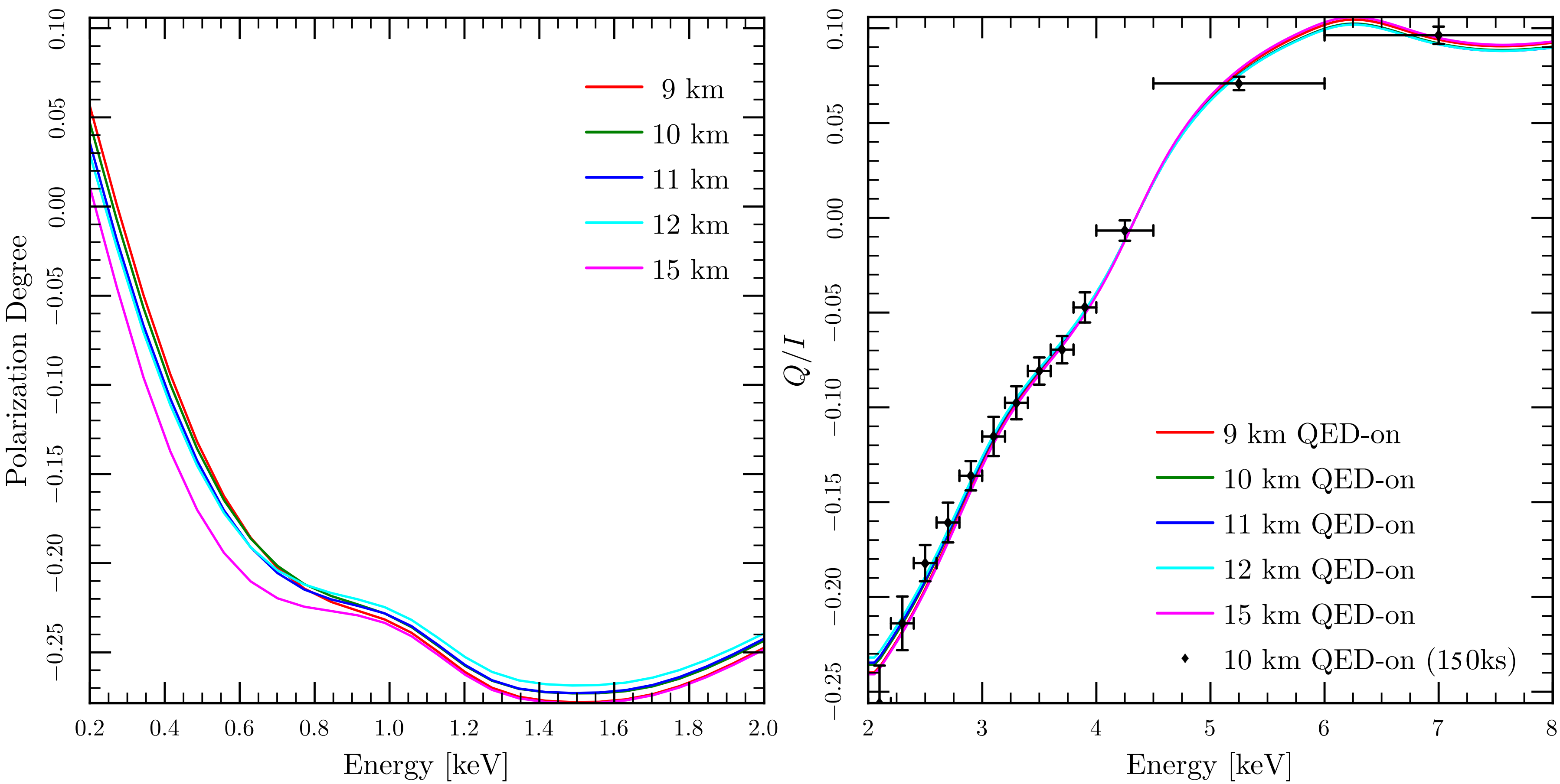


Lai & Ho, 2003

QED effect on X-ray pulsars

Polarization degree from Her-X1. Black dots are a 150ks simulation with eXTP

$$P_{\text{con}} = 1 - \exp\left[-\frac{\pi}{2}\left(\frac{E}{E_{\text{ad}}}\right)^3\right]$$



Caiazzo & Heyl, in preparation

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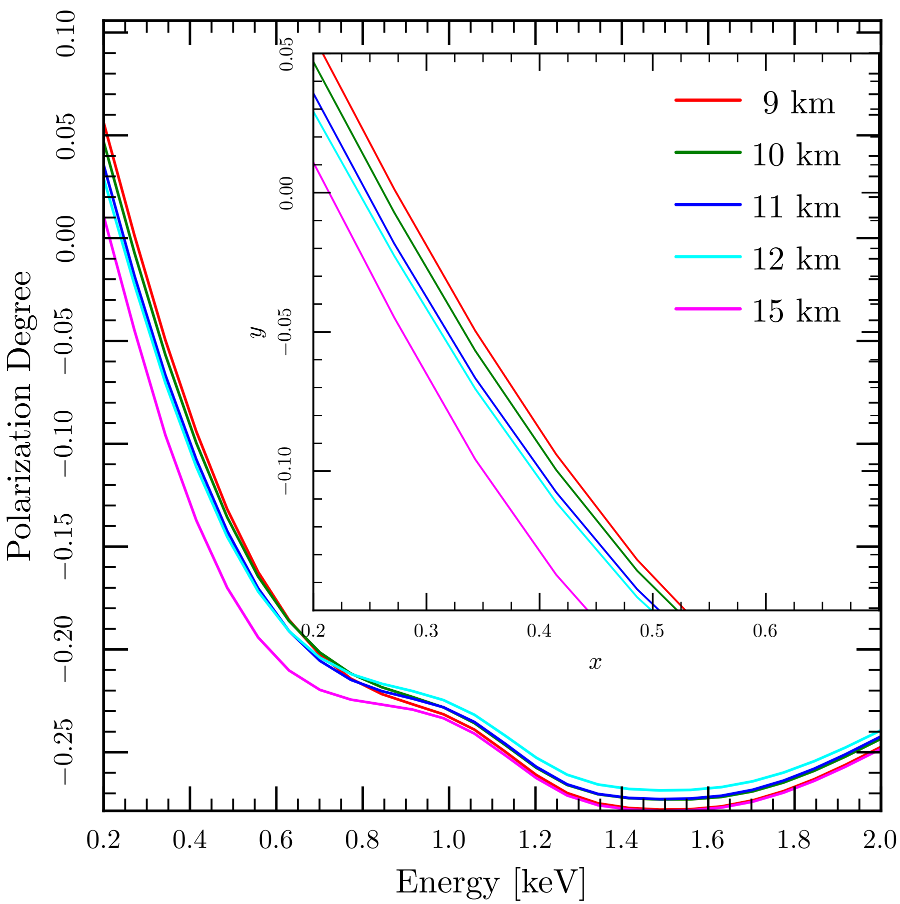
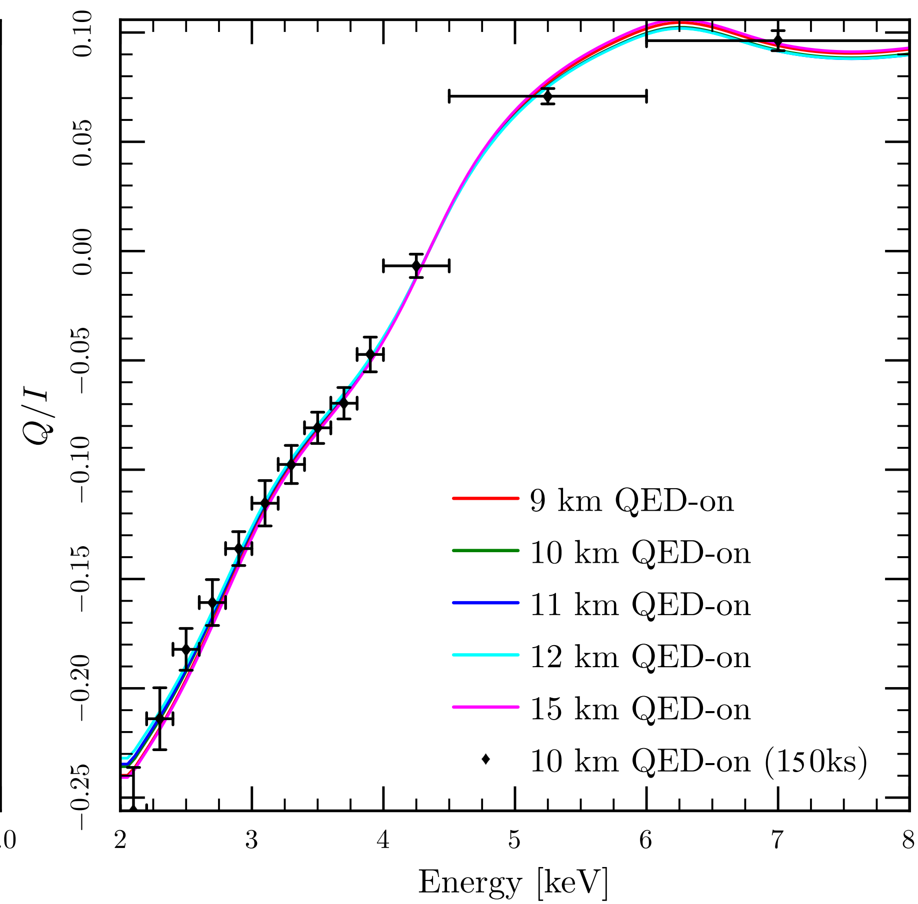




Caiazzo & Heyl, in preparation

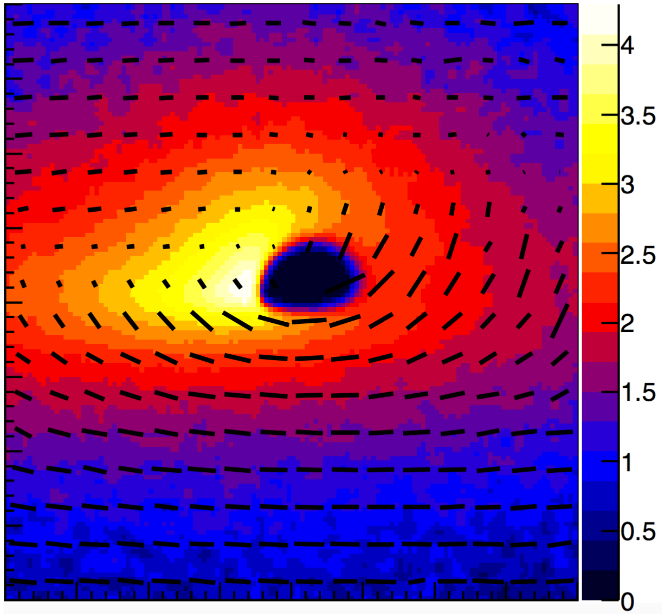
BH accretion disk

Novikov & Thorne (1973) accretion disk: spinning black hole in a Kerr metric

spinning parameter: $$a = \frac{cJ}{GM^2}$$

viscosity:

$$t_{\hat{\phi}\hat{r}} = \underbrace{\rho c_s v_t}_{\text{turbulence}} + \underbrace{\frac{B^2}{4\pi}}_{\text{magnetic field}} = \alpha P$$



Krawczynski, 2012

Minimum magnetic field needed for accretion:

$$B^2 \sim 4\pi \underbrace{\alpha}_{\text{Shakura \& Sunyaev parameter}} P \sim \frac{8\pi c}{3\kappa_R}\sqrt{\frac{GM}{r^3}}\,\frac{\mathcal{B}^2\mathcal{E}}{\underbrace{\mathcal{A}^2}_{\text{GR functions of a and r}}}$$

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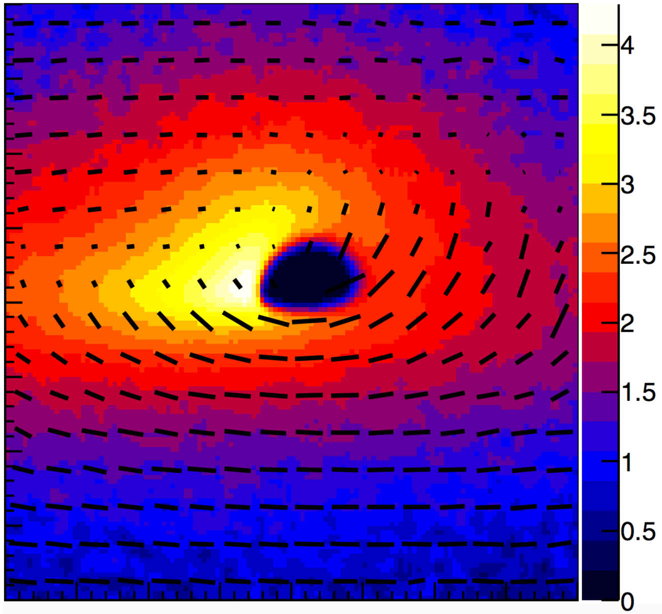
turbulence **magnetic field**



Krawczynski, 2012

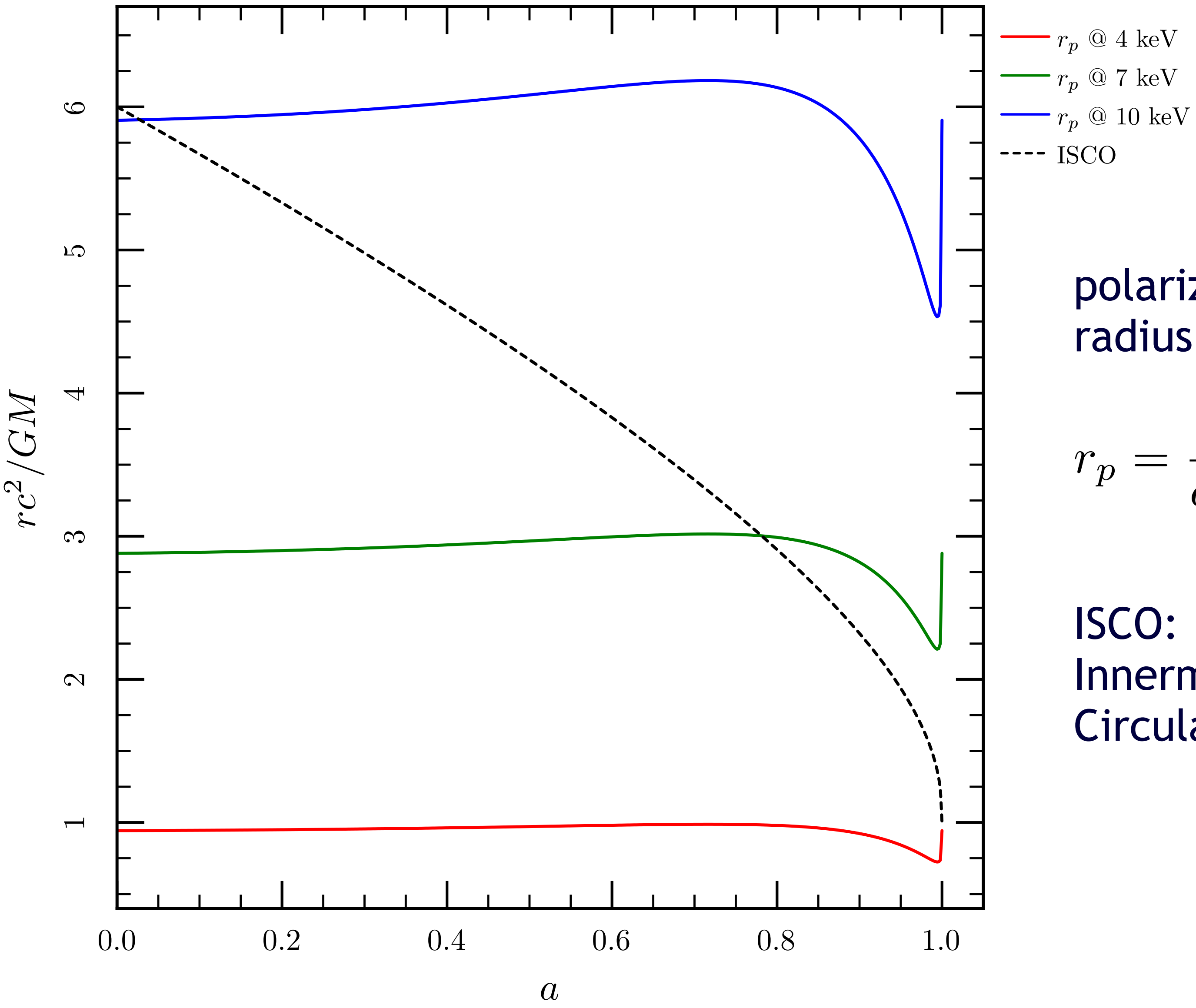
Minimum magnetic field needed for accretion:

(at ISCO)

$$B^2 = (0.29 - 1.13 \times 10^8 \text{ G})^2 \left(\frac{10 M_\odot}{M}\right)\left(\frac{2}{1+X}\right)$$

a = 0 **a = 1**

QED effect on BH accretion disks



polarization limiting radius:

$$r_p = \frac{15\pi}{\alpha_{\rm QED}} \frac{c\hbar}{E_p} \left(\frac{B_{\rm QED}}{B(r_p)} \right)^2$$

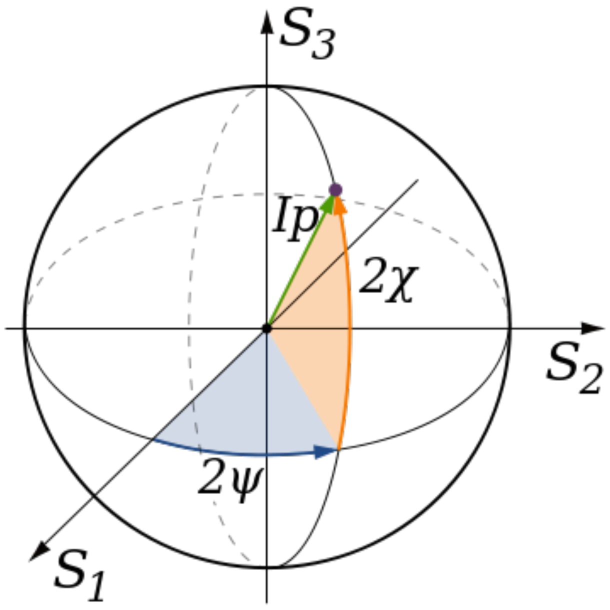
ISCO:
Innermost Stable Circular Orbit

Caiazzo & Heyl, in preparation

QED effect for a chaotic magnetic field

As a first step, we considered a chaotic magnetic field in the plane of the disk. We evolved the polarization of a photon coming along a geodesic from the ISCO to the observer, near the accretion disk plane.

Results are shown on the Poincaré sphere:

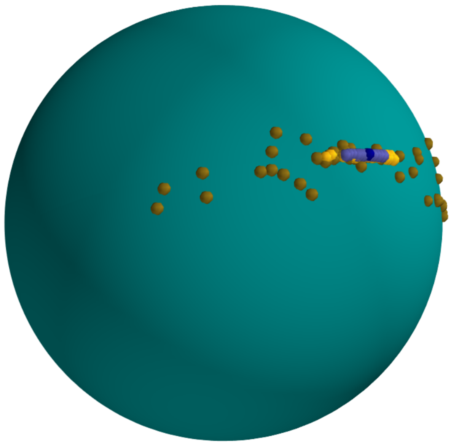


$$\mathbf{s} = \frac{1}{S_0}(S_1, S_2, S_3) = \frac{1}{I}(Q, U, V)$$

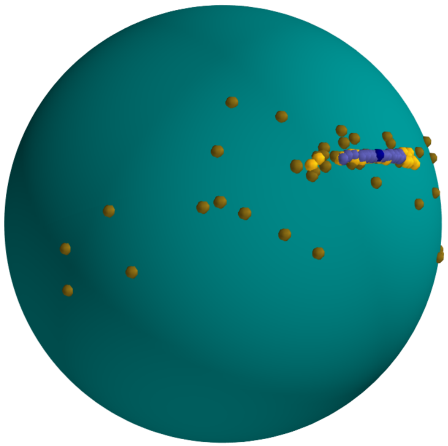
$$p = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

QED effect for a chaotic magnetic field

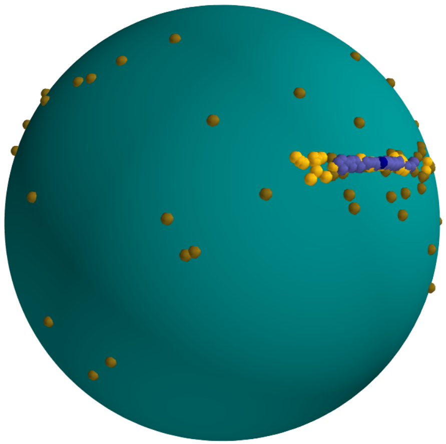
Monte-Carlo simulation of the depolarization of radiation from a black hole with $a = 0.84$ (as NGC 1365) for three photon energies:



3 keV



5 keV



8 keV

Polarization is represented on the Poicaré sphere: the dots represent the end-point of the polarization vector.

- dark blue dot: initial polarization
- violet dots: final polarization of photons that receive a large blue shift
- gold dots: final polarization of photons with zero-angular-momentum
- copper dots: final polarization of photons that receive a large red shift on their way from the ISCO to us.

Caiazzo & Heyl, in preparation

Summary

QED effects are not negligible at the energy range of eXTP. On the contrary, 1-10 keV is the energy range in which QED becomes important.

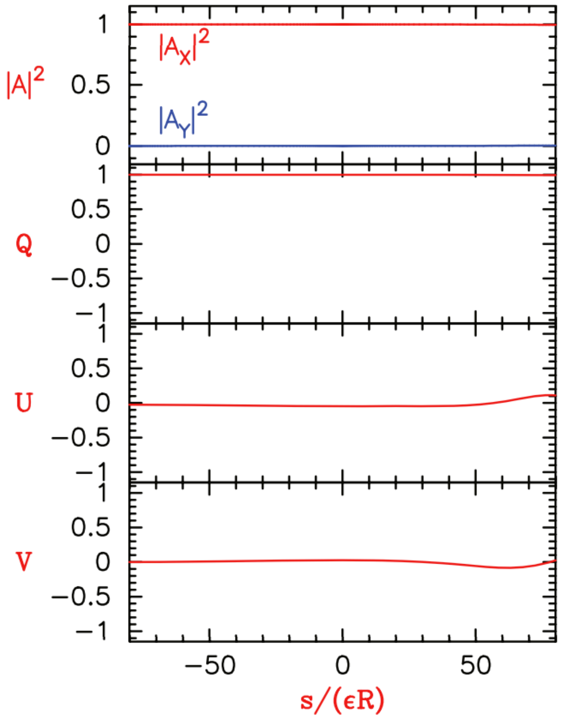
X-ray pulsars:

- the strength of the QED effect can be tested in the eXTP energy range
- an indication on the surface gravity can be inferred from the low energy polarization

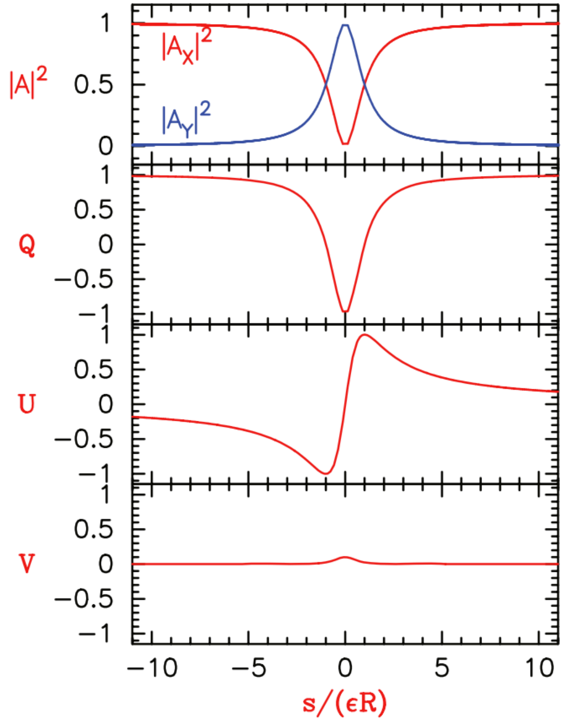
Accreting black holes:

- QED effects becomes important in the eXTP energy range independently of the mass of the black hole
- the presence of a chaotic magnetic field in the disc results in a noise in the polarization that depends on the energy and angular momentum of the photons
- Polarization from accreting BHs probes the role of the magnetic field in the physics of accretion

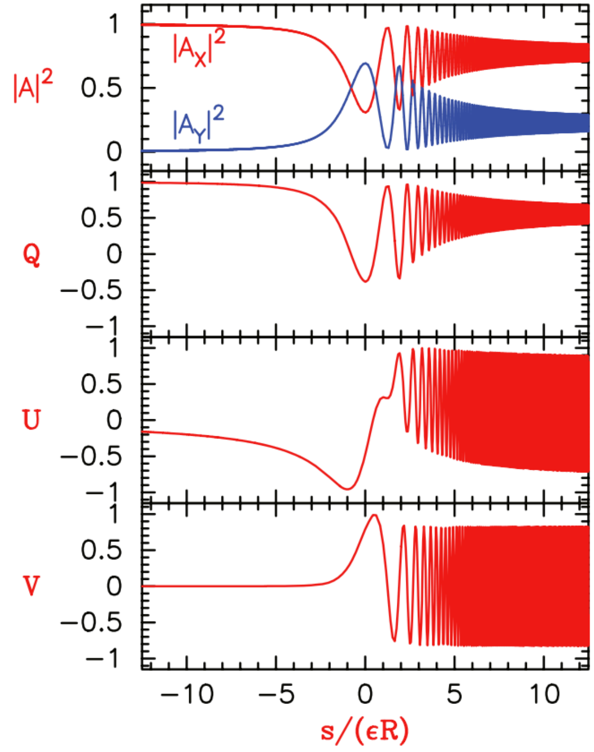
Quasi-Tangential Region



Adiabatic



Non adiabatic



Intermediate