Crab Pulsar: a potential signature of vacuum birefringence?

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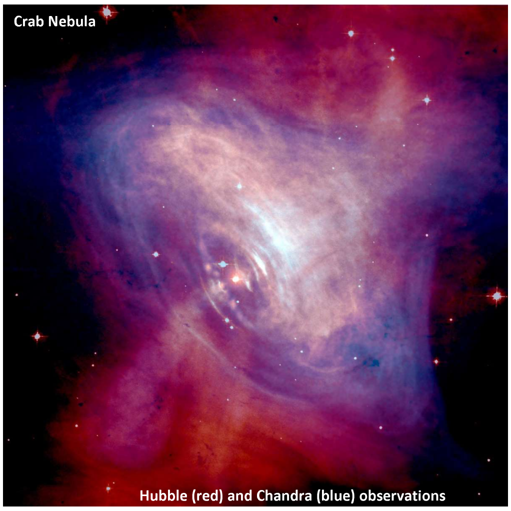
Abstract: Vacuum birefringence is a quantum phenomenon where strong magnetic fields in a vacuum cause it to behave like a birefringent material, making light to propagate into two polarization modes. Detecting this phenomenon requires magnetic fields surpassing $B>10^{10}$ G, unattainable by terrestrial laboratories. Instead, this effect can be observed in extreme environments like the vicinity of neutron stars. Here we use X-ray polarimetric observations of Crab pulsar to search for vacuum birefringence. Our findings include a potential signature of this intriguing phenomenon.

<u>Crab pulsar & Wind nebula:</u> they are the remnant of a supernova observed by Chinese astronomers in 1054 (SN 1054). Crab pulsar is the neutron star located in the central part of the nebula (see image in the right). It has a strong magnetic field of $B\sim10^{13}$ G as well as a short rotation period of P=33.7 milliseconds, which make it and ideal laboratory to study physical processes in extreme astrophysical environments.

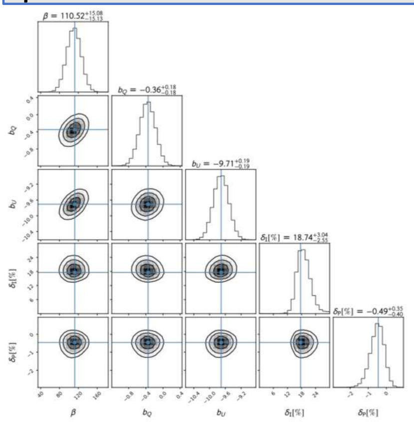
On 2021, NASA launched the Imaging X-ray Polarimetry Explore mission (IXPE), an X-ray observatory that operates in the 2-8 keV range (image on top). One of the main target for IXPE was the observation of Crab pulsar and its nebula.



Hubble (red) and Chandra (blue) observations

<u>Theory:</u> a strong magnetic field can induce the temporary formation of virtual electron-positron pairs, which can modify the properties of the vacuum inducing the so-called vacuum birefringence. This is a QED phenomena that was predicted more than 80 years ago by Heisenberg & Euler but remain experimentally undetected.

Heyl and Shaviv (2002), predicted that the polarization properties of the radiation would be affected by vacuum birefringence. In particular, the measurement of polarization angles at different energy bands would exhibit a phase-shift, whose magnitude depends on the strength of the magnetic field and rotational period of the neutron star.



<u>Method and results:</u> we perform a phase-dependent analysis of the IXPE observation of Crab pulsar. In order to search for phase-shifts in the polarization angle, we build a phenomenological model based on optical polarimetric observations of Crab pulsar. By performing a linear transformation of the Stokes parameters from optical to X-rays, we are able to reproduce for the first time the polarization properties of Crab pulsar in the X-rays (see plots on the right). This imply that similar processes are like powering the emission of Crab pulsar in the optical and X-ray band.

Notably, we also found a large phase-shift in the polarization angle of Crab pulsar, at the secondary pulse peak. This is a strong 8 sigma signature (see corner plot), and it is almost one order-of-magnitude larger that early theoretical expectations for the signature of vacuum birefringence. Further theoretical developments are required to understand this discrepancy.