Using pulsars to test General Relativity with HAWC

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Introduction

Since 2008, the population of known gamma-ray pulsars has increased from about half a dozen to over 160, thanks to the discoveries by the *Fermi* LAT. A large fraction (~100) of these pulsars are in the HAWC field of view. Roughly half of these pulsars are young and the other half are millisecond pulsars (MSPs). **HAWC** will search for TeV pulsations from all of these pulsars.

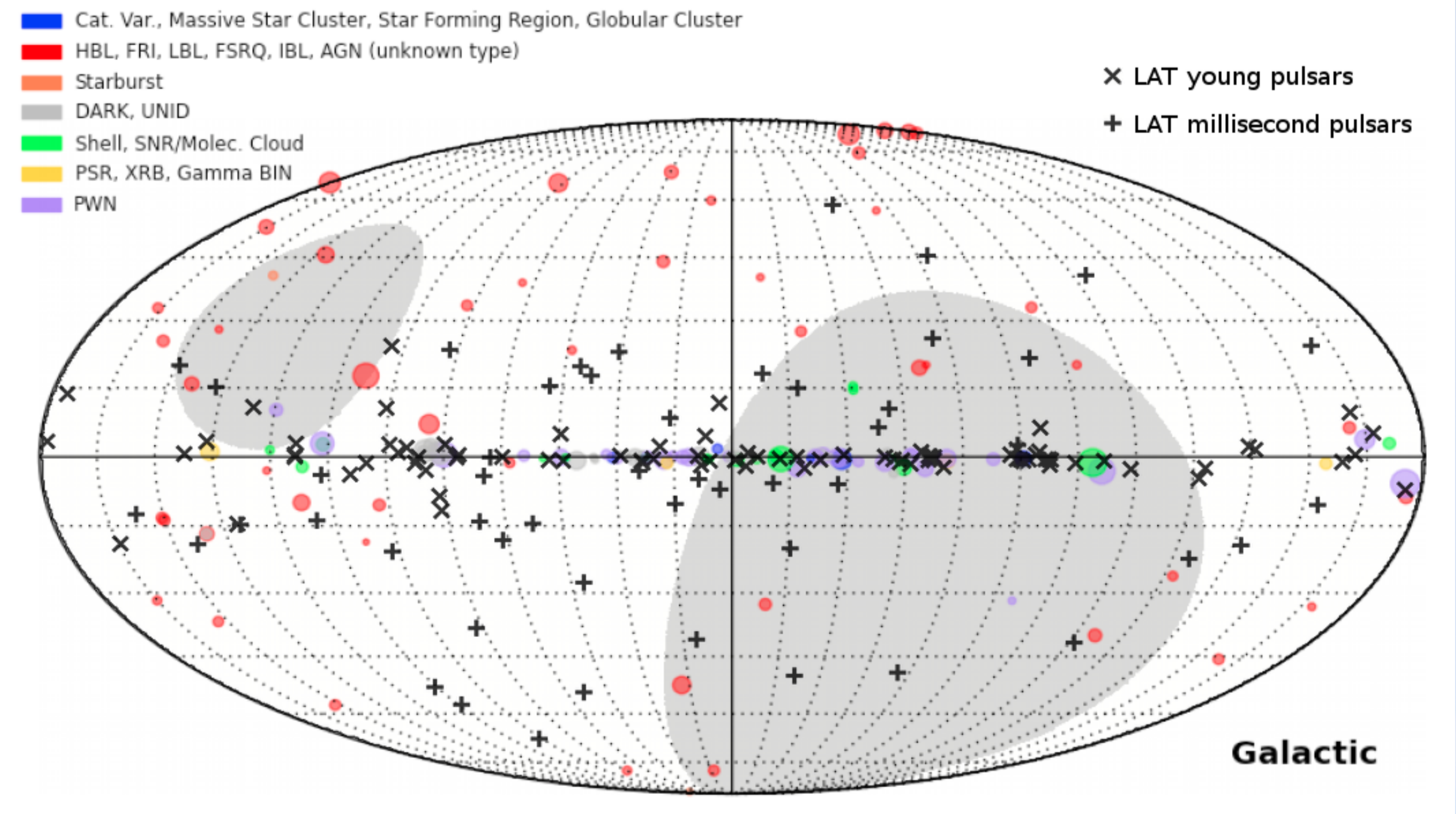


Fig. 1: Map (in Galactic coordinates) illustrating (in white) the part of the sky accessible to HAWC (up to a zenith angle of 45 deg.). The map includes all currently-known TeV sources, plus LAT-detected gamma-ray pulsars (currently there are 99 known in the HAWC field of view - 53 'young' and 46 MSPs).

Gamma-ray Pulsars

Pulsars are rapidly-rotating neutron stars that emit electromagnetic radiation ranging from radio to gamma rays. The radiation is emitted by particles accelerated by the strong magnetic field. This emission is pulsed due to the geometry of the magnetic axis being misaligned with the rotation axis. There are currently more than 2000 known pulsars. At GeV energies the *Fermi* LAT has detected over 160 pulsars, some up to high energies (> 10 GeV) and ground-based detectors have now detected two of them (the Crab and Vela).

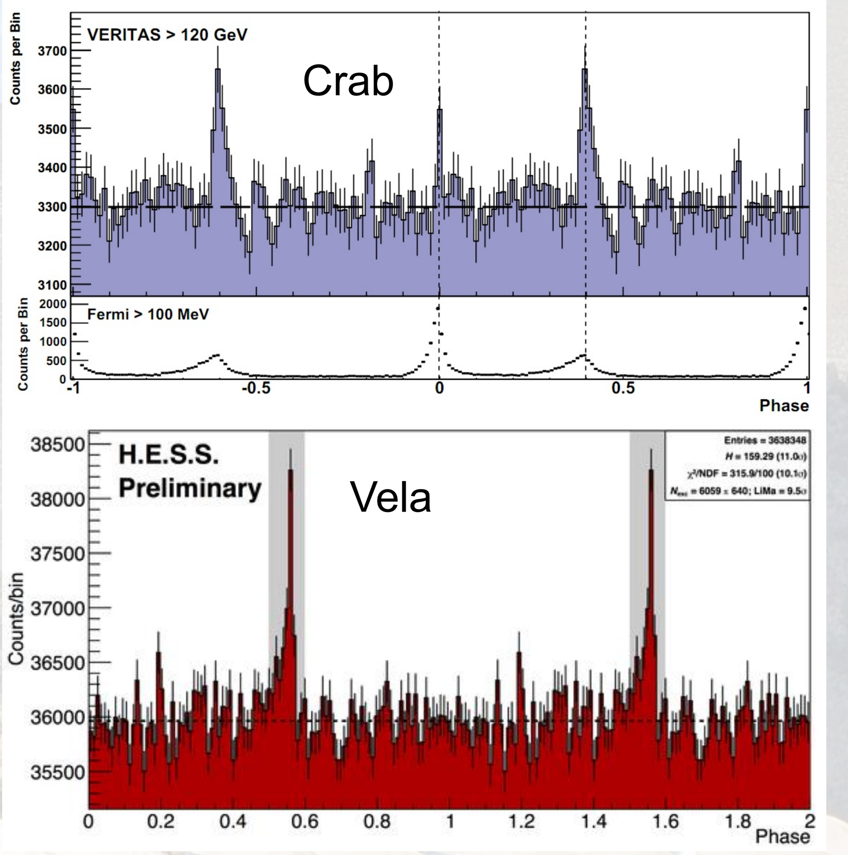


Fig. 3: Two pulsars have been detected with ground-based telescopes: The Crab (by both MAGIC and VERITAS) and the Vela Pulsar (by H.E.S.S.). MAGIC has recently claimed to detect the Crab pulsar up to energies above 1 TeV.

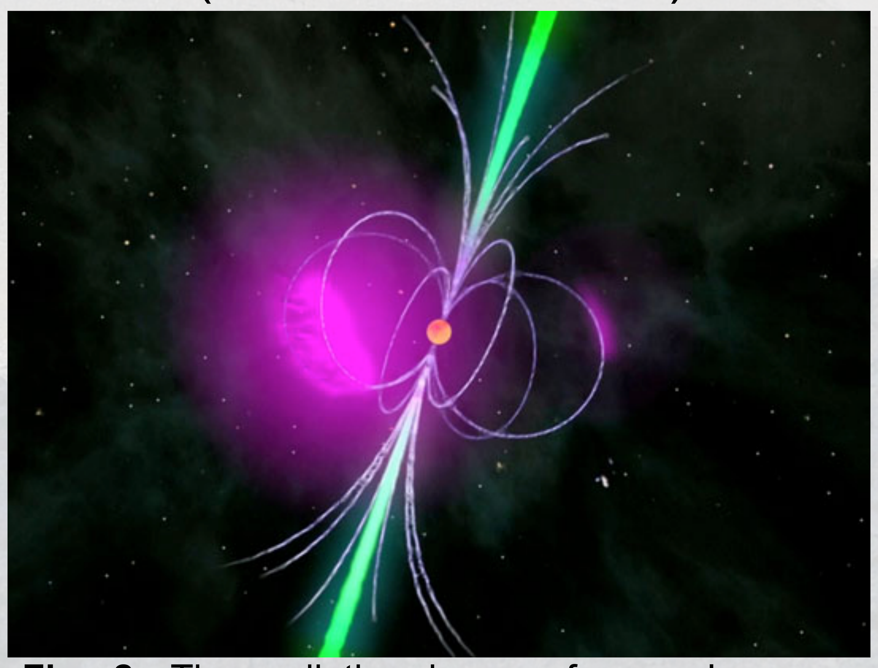


Fig. 2: The radiation beams from pulsars are misaligned with the rotation axis. As they sweep across our field of view, they typically lead to a two-peaked profile (see left). The radio beams (green) are thought to originate above the magnetic poles, while the gamma-ray beams (magenta) likely come from further away, in the outer magnetosphere. *Illustration by NASA/Fermi/ Cruz deWilde NASA/Fermi/Cruz.*

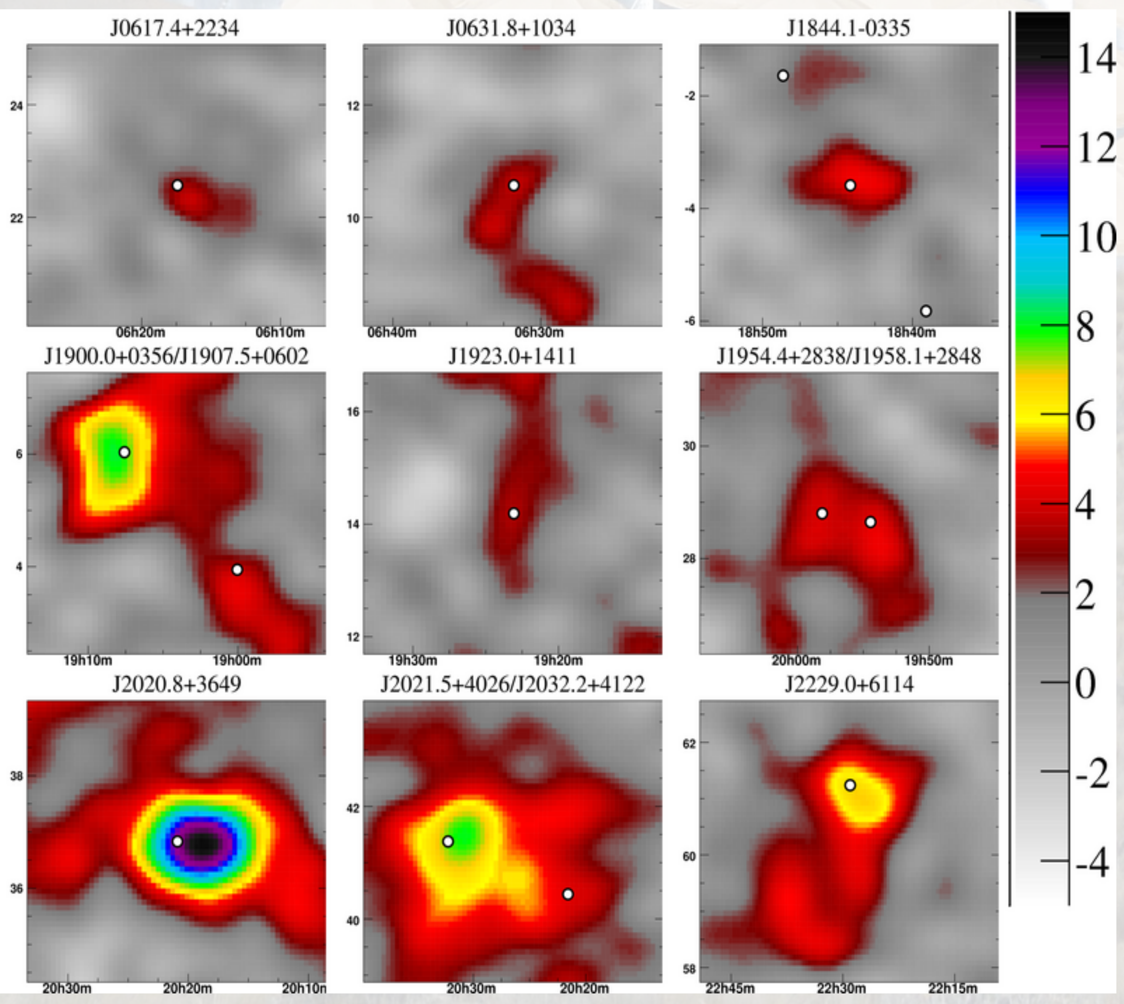


Fig. 4: Milagro TeV gamma-ray sources coincident with bright *Fermi* LAT GeV sources (white dots), most of which are associated with known *Fermi* gamma-ray pulsars [Abdo et al., ApJL, **700**, 127 (2009)].

TeV emission coincident with pulsars has been detected by many ground-based instruments, including MILAGRO (2000-2008), the predecessor of HAWC. Much of this emission may come from the pulsar wind nebulae, rather than the pulsars, but **HAWC**, with a 30x improvement over Milagro should help us clarify the picture.

Testing General Relativity with pulsars

Despite its many successes, General Relativity (GR) is incompatible with Quantum Mechanics. The search for a theory of quantum gravity (QG) to replace GR has been a major goal in physics and astronomy for decades. Pulsars, with their extreme properties (e.g. densities, spin periods) are one of the best tools in this quest. Gamma-ray bursts (GRBs) are another astrophysical source class that can be exploited for these purposes (cf. poster by Harding, Nellen, and Pérez). Although no quantum theory of gravity currently exists, we can search for signatures of such a theory by testing GR to the point where it no longer holds. One such test involves looking for a violation of one of the central tenets of GR, which is the constancy of the speed of light. Such a violation would result in high-energy photons being delayed, with respect to low-energy ones (see Fig. 5).

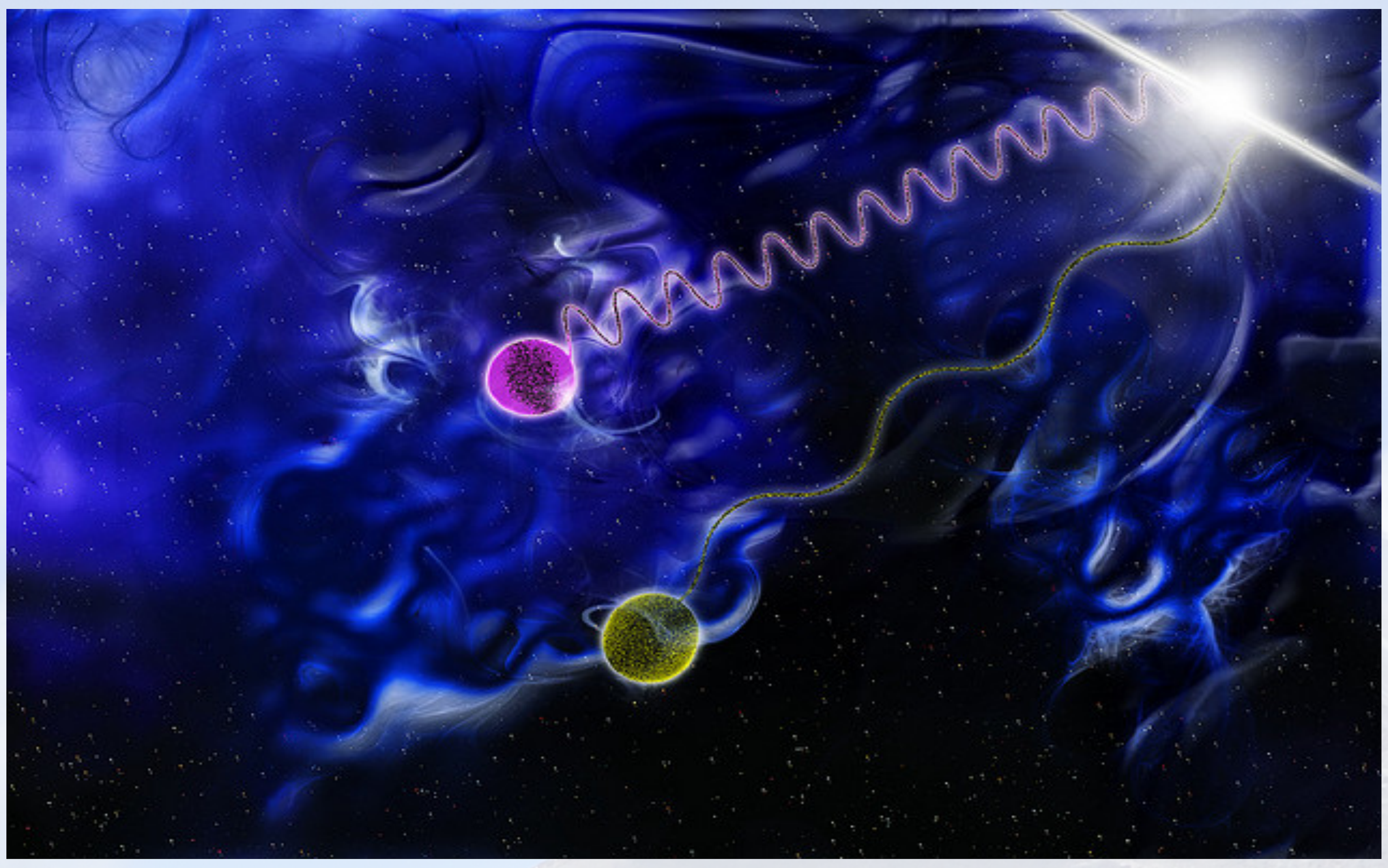
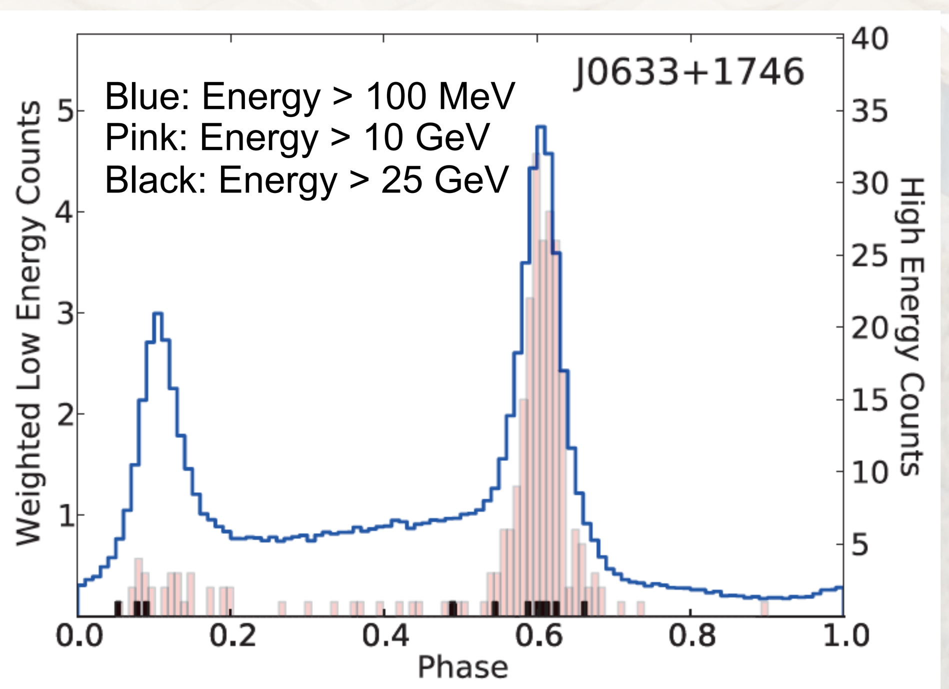


Fig. 5: In this illustration, a high-energy (short-wavelength) photon (in purple) travels at slower speed than the low-energy (long-wavelength) photon. By measuring the time difference in the arrival of photons, we can probe the quantum nature of gravity. So far, no such delay has been found (e.g. in the top panel of Figure 3, we can see that the location of the Crab pulsar peaks at 100 MeV is exactly the same as at > 120 GeV). *Credit: NASA/Sonoma State University/Aurore Simonnet.*

While no precise predictions for the magnitude of the *quantum-gravitational* time delay exist, it is expected to be small and start to manifest itself only at very high energies (the *quantum-gravity energy scale*). The sensitivity of our tests for quantum gravity depends on the distance to the pulsar, the difference in the energy of photons, and the period of the pulsar. Previous searches using observations of the Crab pulsar (P ~ 30 ms, distance ~ 2 kpc) can be greatly improved by using faster-spinning pulsars that are more distant and detecting them up to higher energies.

Candidate pulsars for HAWC

The detection of the Crab pulsar at energies above 25 GeV by MAGIC [Aliu et al., Science 322, 1221 (2008)] was a major breakthrough. Since then, both VERITAS and MAGIC have shown that its emission extends up to at least 400 GeV, and possibly up to 1.7 TeV [*Fermi Symposium 2014*].



Fermi observations have shown that 12 more pulsars, besides the Crab, emit at >25 GeV. Continued observations (and timing) by *Fermi* will provide good candidates for HAWC to study at very high energies (> 100 GeV), where *Fermi* runs out of statistics.

Fig. 6: *Fermi* LAT 3-year observation of *Geminga,* one of the brightest gamma-ray pulsars [Ackermann et al., ApJS **209**, 34 (2013]. Note the small number of photons collected at >25 GeV (due partly to the small size of the LAT). While Milagro detected an extended excess coincident with Geminga [Abdo et al., ApJL, **700**, 127 (2009)], HAWC should enable us to carry out sensitive searches for pulsations at TeV energies.

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