Future Steps towards Understanding Pulsars with AGILE

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ABSTRACT. Pulsars are a major topic of investigation of AGILE and, besides studying the small sample of known objects, AGILE will offer the first possibility of detecting several young and energetic radio pulsars that have been discovered since the end of the CGRO mission. We provide an estimate of the expected number of detectable gamma-ray pulsars and present AGILE capabilities for timing analysis with small counting statistics and AGILE pulsars science topics and challenges, based on the analysis of data from simulations, from the EGRET archive, and from radio pulsar catalogs.

1. Introduction

Spin-powered pulsars and possibly their environnements (SNRs, PWNs) are the only firmly identified galactic gamma-ray sources at E$\sim$100 MeV. They represent a major topic of investigation of AGILE.

AGILE will fully exploit the heritage of EGRET with improved performance and favourable boundary conditions for gamma-ray pulsar detection and studies: a very large field of view ($\sim$1/5 of the sky) allowing us uninterrupted, long and simultaneous observations of many sources; an improved point spread function ($\sim 0.5°$, $E\sim1$ GeV) with respect to EGRET to better resolve gamma-ray pulsars in the crowded Galactic Plane; homogeneous coverage of the Galaxy with a 2 year average exposure comparable with the exposure peaks of 9 years of EGRET observations; availability of radio ephemerides of near and young pulsars discovered after the end of the Compton Gamma-Ray Observatory; the smallest deadtime ever obtained for gamma-ray detection (<300 μs) and absolute time tagging with uncertainty near $\sim$1 μs.

We present here a simulation of AGILE all-sky sensitivity for pulsar detection and a consequent ranking list of AGILE pulsars targets, and the most important AGILE pulsars science topics and challenges.

2. How many (and which) pulsars will be observed by AGILE?

Among the $\sim$1500 rotation-powered pulsars, observed mainly in the radio band, only 7 are seen as pulsed gamma-ray sources, and another $\sim$10 have been reported as possible detections (e.g. Kanbach, 2002). The availability of a wider and deeper sample of gamma-ray observations of pulsars could better constrain emission models that predict different beaming angles and directions for the radio and gamma-ray emission. AGILE will improve photon statistics for gamma-ray pulsation searches and will offer the first possibility, before the launch of GLAST (Michelson, 2001), of detecting several young and energetic radio pulsars recently discovered in radio surveys.

Except for the claimed detection of the millisecond pulsar J0218+4232 at high-energy gamma rays (Kuiper et al. 2000, 2002), all other known gamma-ray pulsars discovered by EGRET (including low significance pulsed detections) lie in the region of the $P-\dot{P}$ diagram characterized by $B \geq 2\times10^{11}$ G and $\dot{E}_{rot} \geq 1.3\times10^{33}$ erg s^{-1} (Figure 1). Radio pulsars in this region are natural gamma-ray pulsar candidates to be detected by instruments like AGILE with sensitivity slighly better than EGRET. It is worth noting that tens of them are within the error boxes of selected EGRET unidentified sources

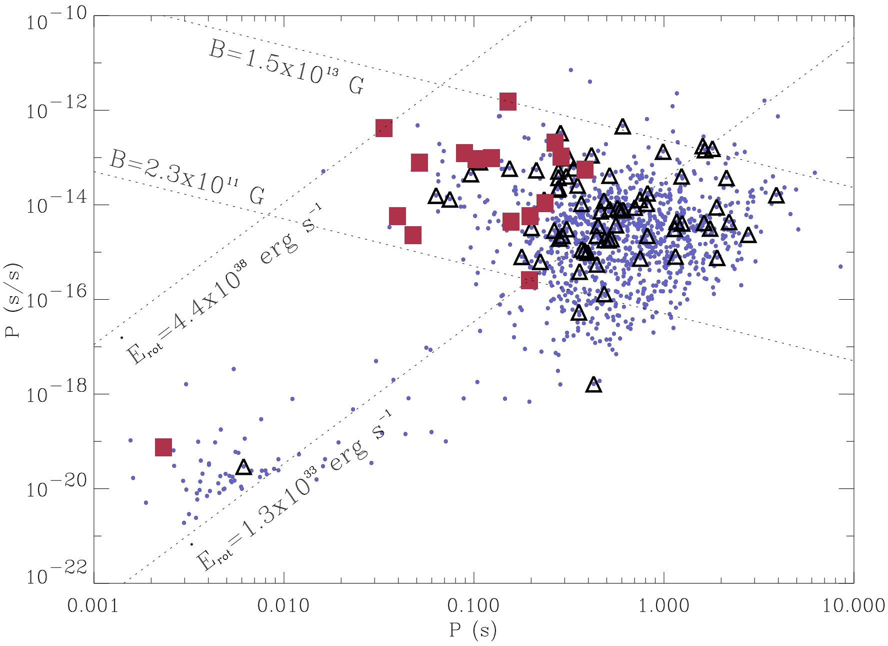

Fig. 1. $P - \dot{P}$ diagram of a set of ~1300 radio pulsars (dots) whose parameters are obtained from public archives. Dotted lines correspond to the extreme values of B and $\dot{E}_{rot}$ (excluding ms pulsars) of the ~15 known and candidate gamma-ray pulsars (filled squares). The "gamma-ray pulsars region" (upper rhomboidal region) includes ~400 radio pulsars likely to be efficient high-energy photons emitters. In this region there are ~20 non-variable EGRET unidentified sources (triangles) coincident with one or more radio pulsars (the total number of radio/gamma coincidences being ~40).

that do not show significant flux variations (compared to blazars) and are therefore good gamma-ray pulsar candidates. Although we estimate that many of these associations are chance coincidences (only < 10 are expected to be real by correlation analysis), they represent top-ranked targets for pulsations searches with AGILE.

The large field of view of AGILE allows simultaneous monitoring of many of these sources, and could cover the whole sky with only 6 pointings (Figure 3). In particular, a single pointing at the Galactic Center region could include tens of nearby radio pulsars belonging to the "gamma-ray pulsar region" described in Figure 1, and ~50 unidentified EGRET sources possibly associated with radio-quiet pulsars, including those within the Gould Belt region (Gehrels et al. 2000).

AGILE will continuously observe pulsars for long periods (~1-2 months) avoiding typical timing analysis problems arising from merging many short observations at different times. On the other hand, long exposures imply that the folding process for younger and active pulsars is strongly sensitive to timing noise; therefore high-order radio ephemerides and accurate period extrapolations must be required in order to avoid smearing effects on light curves and to attain a time resolution below 100 μs.

A typical exposure on the galactic plane after two years of observations is $\sim 2\times10^9$ cm^2 s for E>100 MeV and the expected pulsar counts at these energies (e.g. ~7000 cts from Geminga and ~17000 from the Vela pulsar) are comparable or slighly better than the corresponding values for EGRET. The expected typical sensitivity after folding data at known pulsar periods is $\sim 5\times10^{-8}$ ph/cm$^2 s$ for E>100 MeV (Figure 2). Furthermore,

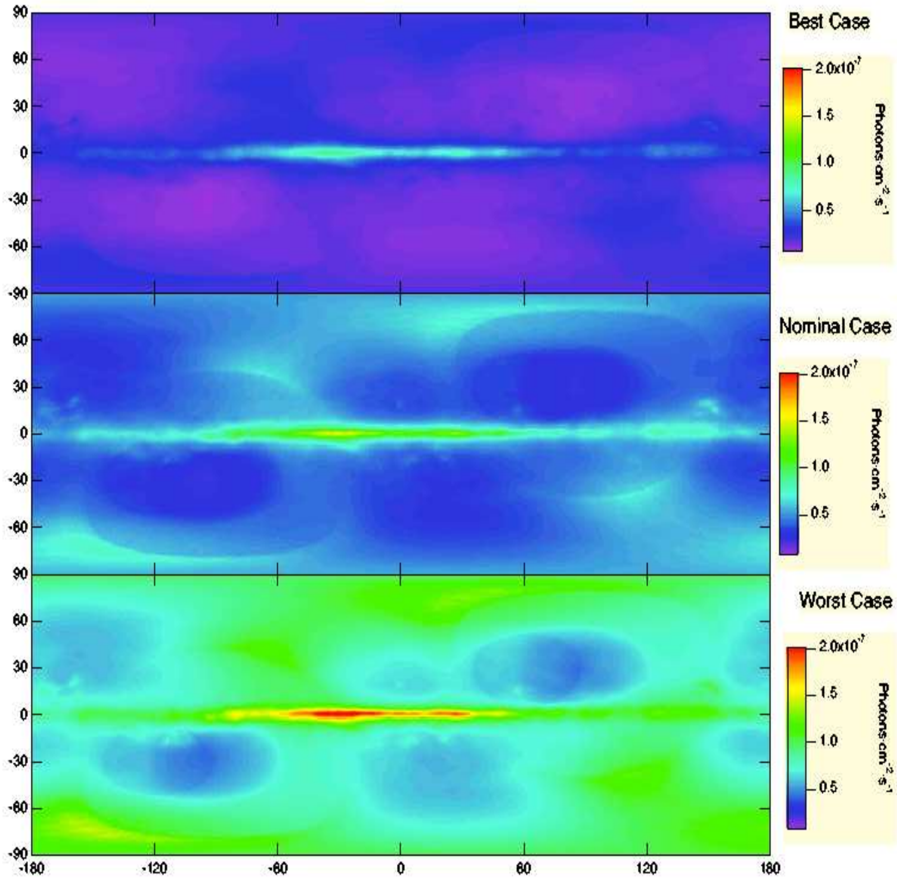

Fig. 2. AGILE sensitivity maps (E>100 MeV) for pulsar detection, corresponding to a two-years all-sky pointing programme taking into account spacecraft/operations constraints and occultation of the AGILE field of view by the Earth. Best/nominal/worst cases were obtained considering possible errors and uncertain parameters on particle background, gamma-ray diffuse emission, AGILE effective area and point spread function, pulsar spectra and light curves. Best and nominal sensitivity maps refer to source detection using a folding process assuming known radio ephemerides.

using accurate radio ephemerides, it is possible to extract pulsar photons also in confused regions and exploit low energy data (20-100 MeV) for which angular resolution is poor but the AGILE effective area is still useful and better than that of EGRET.

In contrast to the relation valid at soft X-ray energies ($F_x \propto \dot{E}d^{-2}$), the expected gamma-ray flux of radio pulsars is directly correlated to the Goldreich-Julian current and can be estimated according to the law $F_\gamma \propto \sqrt{\dot{E}}d^{-2}$ (Kanbach, 2002) fitting EGRET pulsars well. The dispersion of the fit provides the min/max normalization values allowing a worst/best case approach for the gamma-ray flux estimates (F_{min} and F_{max} in Table 1) in the assumption that the gamma-ray beams intersect the line of sight. In this way it is possible to extract a subsample of radio-loud pulsars expected to be above the AGILE sensitivity threshold. Up to ~100 radio pulsars (Figure 3) could provide enough photons to be in principle observable by AGILE, the actual number of detections being dependent on the emission geometry. Assuming, for example, gamma-ray

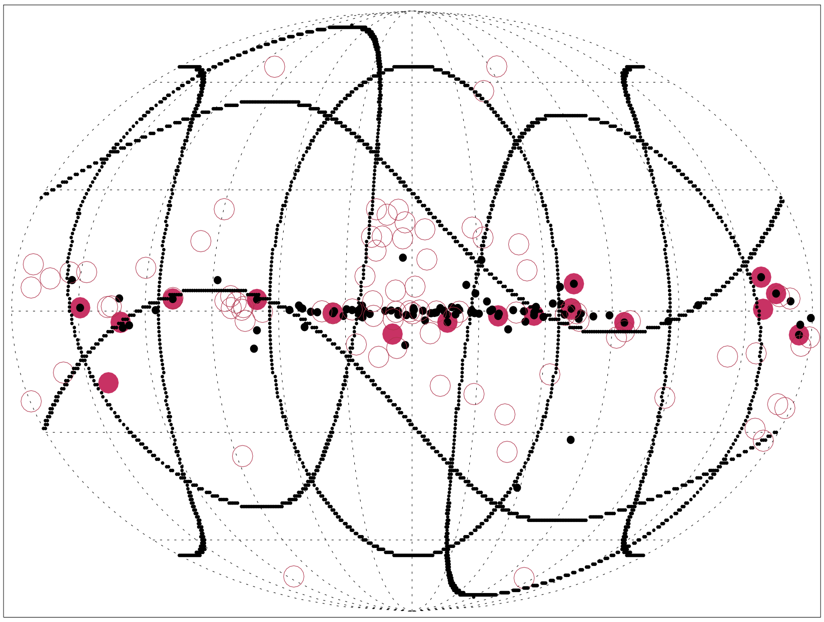

Fig. 3. Map in Galactic coordinates (Galactic Centre in the centre of the figure) of the ∼100 known radio pulsars (dots) belonging to the "gamma-ray pulsar region" described in Figure 1 and with maximum expected gamma-ray flux near AGILE sensitivity (see text). The map also shows claimed gamma-ray pulsars (filled circles) and non-variable unidentified EGRET sources (circles) likely to consist in part of radio-quiet pulsars. Bold contours indicate the fields of view of a set of 6 AGILE pointings covering the whole sky.

emission cones of ∼1 sr with random orientation respect to the radio beam, roughly ∼10 sources of our sample should be detectable with AGILE. Table 1 provides the first 35 top ranked radio-pulsars likely to have detectable fluxes (F_{min}>2×10^{-8} ph/cm^2s) even in the absence of coincidences with EGRET sources. It also includes (lower part) all the other weaker 11 radio-pulsars of the "gamma-ray pulsar region" coincident with EGRET unidentified sources and with expected fluxes near AGILE sensitivity.

Apart from the sources within the "gamma-ray pulsar region", AGILE will have the first opportunity to explore the "millisecond region" of the $P - \dot{P}$ diagram looking for peculiar gamma-ray emission from these objects and to confirm the claimed detection in high-energy gamma rays of PSR J0218+4232 (Kuiper et al. 2000, 2002).

More detailed simulations of the population of gamma-ray pulsars, including deep statistical analysis of the emission geometry and beaming, predict very different numbers of radio-loud and radio-quiet pulsars detectable in gamma rays, strongly depending on the assumed model (see e.g. Gonthier et al. 2001; Mac Laughlin and Cordes, 2001). Extrapolating these results to the AGILE wide-band sensitivity, we expect to discover at least a dozen new objects.

AGILE pulsars science topics and challenges

AGILE will contribute to the study of known and newly discovered gamma-ray pulsars in several ways: 1) detecting possible secular variations of the gamma-ray emission; 2) studying unpulsed gamma-ray emission from plerions in supernova remnants and

TABLE I

Preliminary sample of the ranking list of radio-pulsars expected to have gamma-ray fluxes above or near AGILE sensitivity (see text). This sample includes 14 radio-pulsars coincident with selected unidentified EGRET sources, some of which have marginal pulsed detections. F_{min} and F_{max} represent the expected gamma-ray flux ranges of the sources in the hypothesis that the gamma-ray beams intersect the line of sight.

PSR Name	Gal. Long. deg	Gal. Lat. deg	P s	$\dot{P}$ 10^{-15} s/s	D kpc	$\dot{E}$ log erg/s	$F_{\rm min}$*	$F_{\rm max}$*	3EG coinc.
J1932+1059	47.38	-3.88	0.227	1.16	0.17	33.59	109	986	
J0659+1414#	201.11	8.26	0.385	55.01	0.76	34.58	16	151	
J2043+2740	70.61	-9.15	0.096	1.26	1.13	34.75	9	83	
J1908+0734	41.58	-0.27	0.212	0.82	0.58	33.53	8	76	
J1048-5832#	287.42	0.58	0.124	96.32	2.98	36.30	8	71	3EG J1048-5840
J1524-5625	323.00	0.35	0.078	38.95	3.84	36.51	6	54	
J0742-2822	243.77	-2.44	0.167	16.81	1.89	35.16	5	47	
J0117+5914	126.28	-3.46	0.101	5.85	2.14	35.34	5	46	
J1826-1334	18.00	-0.69	0.101	75.49	4.12	36.46	4	44	
J1531-5610	323.90	0.03	0.084	13.74	3.10	35.96	4	44	
J1809-1917	11.09	0.08	0.083	25.54	3.71	36.25	4	43	
J1617-5055	332.50	-0.27	0.069	137.20	6.46	37.21	4	43	
J1803-2137	8.40	0.15	0.134	134.43	3.94	36.35	4	43	
J1918+1541	49.89	1.36	0.371	2.54	0.68	33.29	4	42	
J0205+6449	130.72	3.08	0.066	193.93	7.54	37.43	4	41	
J1856+0113#	34.56	-0.50	0.267	208.41	2.78	35.63	4	38	3EG J1856+0114
J1913+1011	44.48	-0.17	0.036	3.37	4.48	36.46	4	37	
J0454+5543	152.62	7.55	0.341	2.37	0.79	33.37	3	34	
J0940-5428	277.51	-1.29	0.088	32.87	4.27	36.29	3	34	
J1801-2451	5.25	-0.88	0.125	127.98	4.61	36.41	3	34	
J0538+2817	179.72	-1.69	0.143	3.66	1.77	34.69	3	31	
J1825-0935	21.45	1.32	0.769	52.36	1.01	33.66	3	29	
J1549-4848	330.49	4.30	0.288	14.11	1.54	34.37	3	28	
J1718-3825	348.95	-0.43	0.075	13.22	4.24	36.10	3	27	3EG J1714-3857
J1730-3350	354.13	0.09	0.139	85.10	4.24	36.09	3	27	
J1705-1906	3.19	13.03	0.299	4.14	1.18	33.79	2	25	
J1420-6048	313.54	0.23	0.068	83.17	7.69	37.02	2	24	
J0358+5413#	148.19	0.81	0.156	4.40	2.07	34.66	2	22	
J1509-5850	319.97	-0.62	0.089	9.17	3.81	35.71	2	22	
J1739-3023	358.09	0.34	0.114	11.40	3.41	35.48	2	21	
J1835-1106	21.22	-1.51	0.166	20.61	3.09	35.25	2	19	
J1530-5327	325.33	2.35	0.279	4.68	1.46	33.93	2	19	
J1302-6350#	304.18	-0.99	0.048	2.28	4.60	35.92	2	19	
J2337+6151	114.28	0.23	0.495	191.81	2.47	34.79	2	18	
J1453-6413	315.73	-4.43	0.179	2.75	1.84	34.27	2	18	
J1837-0604	25.96	0.26	0.096	45.17	6.19	36.30	1	16	3EG J1837-0606
J2229+6114#	106.65	2.95	0.052	78.27	12.00	37.35	1	14	3EG J2227+6122
J1105-6107	290.49	-0.85	0.063	15.83	7.07	36.39	1	14	3EG J1102-6103
J1740-3015	358.29	0.24	0.607	465.87	3.28	34.92	1	11	3EG J1744-3011
J1637-4642	337.79	0.31	0.154	59.20	5.77	35.81	1	10	3EG J1639-4702
J1745-3040	358.55	-0.96	0.367	10.66	2.08	33.93	1	9	3EG J1744-3011
J1016-5857	284.08	-1.88	0.107	80.62	9.31	36.41	0	8	3EG J1013-5915
J1757-2421	5.31	0.02	0.234	13.00	3.50	34.60	0	7	3EG J1800-2338
J1853+0056	34.02	-0.04	0.276	21.39	3.82	34.61	0	6	3EG J1856+0114
J1715-3903	348.10	-0.32	0.278	37.69	4.80	34.84	0	5	3EG J1714-3857
J0614+2229	188.79	2.39	0.335	59.63	4.72	34.80	0	5	3EG J0617+2238

*) 10^{-8} ph/cm^2 s (E>100 MeV)
#) Low significance pulsed detection with EGRET

searching for time variability of pulsar/wind nebula interactions (e.g. in Crab); 3) looking for possible cut-off and breaks in pulsar spectra; 4) obtaining high time resolution of known gamma-ray pulsars; 5) exploration of gamma-ray emission from millisecond PSRs In particular, AGILE will have the first opportunity to observe the most luminous pulsars with better time resolution than EGRET, looking for possible microstructures in folded gamma-ray light curves such as those clearly seen in single radio pulses from Vela (Johnston et al. 2001). We simulated a $\sim 5\times10^6$ s AGILE observation of the Vela pulsar including different microstructure templates in the light curve. A preliminary analysis shows that we can achieve an effective resolution better than $\sim$50 μs with a good signal-to-noise ratio allowing us to discover hypothetical microstructures not resolved with lower resolution (Figure 4).

The analysis of a larger sample of pulsar spectral breaks could provide a powerful tool to constrain the production processes and sites in the magnetosphere (e.g. the height of the emission region from the neutron star surface). Pulsar spectra are generally curved

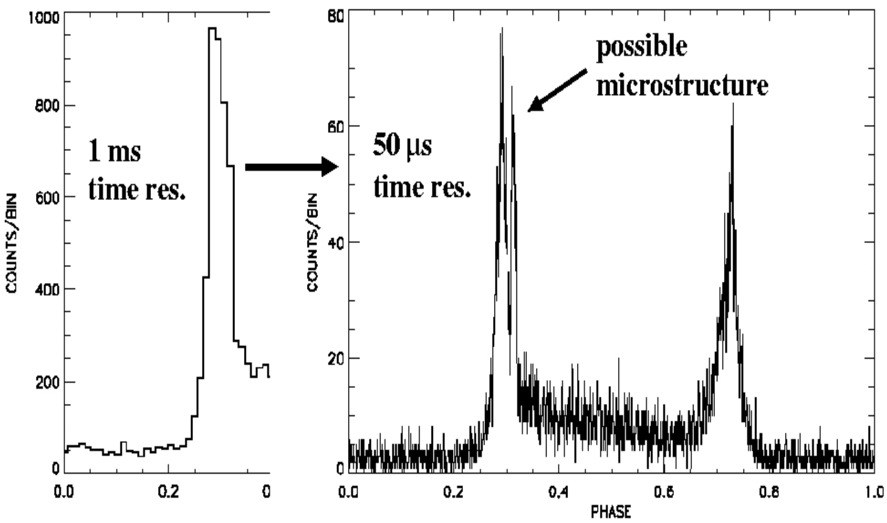

Fig. 4. Simulation of an AGILE observation of the Vela pulsar. Timing analysis with resolution 10-50 μs could reveal possible microstructures within the peaks of the light curve.

in the gamma-ray band leading to a cut-off at a few GeV and therefore very difficult to investigate with reasonable energy resolution ($\Delta E/E\sim 1$) due to the poor photon statistics available at these energies. However, PSR B1509-58, a pulsar with a very strong magnetic field ($>10^{13}$ G), shows a spectral turnover in the 10 MeV range (Kuiper et al. 1999) which can be explained with photon absorption by photon splitting in the scenario of polar cap models (Harding et al. 1997) (Figure 5). For the competing scenario with outer gaps, Zhang and Cheng (2000) offer an alternative explanation. There are now more than $\sim$30 pulsars known with $B > 10^{13}G$. These highly-magnetized pulsars represent a good opportunity for AGILE to perform a set of gamma-ray observations providing spectral break measurements in a more accessible energy range, possibly providing conclusive evidence for the signature of this exotic photon splitting process in the strongest magnetic fields of pulsars.

The chance to detect unpulsed gamma-ray radiation from wind nebulae and supernova remnants surrounding pulsars could represent an interesting challenge for AGILE. For example, AGILE could detect PWN variability ($> 10\%$) of the Crab nebula as expeted in ion-doped wind interaction models (e.g. Amato, 2003). Futhermore, by deep observations, AGILE could resolve pulsed point-like emission from diffuse unpulsed emission in the brightest SNR/NS systems.

Multi-wavelength observations are crucial to discover both new gamma-ray radio-loud pulsars and radio-quiet objects hidden among the presently unidentified gamma-ray sources. SuperAGILE will provide X-ray observations of the strongest sources. Furthermore, a wide field instrument such as AGILE can perform coordinated observations with other space- and ground-based observatories. In particular, the availability of simultaneous radio observations is essential to perform accurate gamma-ray timing analysis of young and energetic radio-loud pulsars. They usually present a significant amount of timing noise that could strongly affect the folding process of AGILE long exposures and smear gamma light curves. Therefore, the scientific collaboration between the AGILE Team and radio observers is crucial to fully exploit the AGILE potentialities.

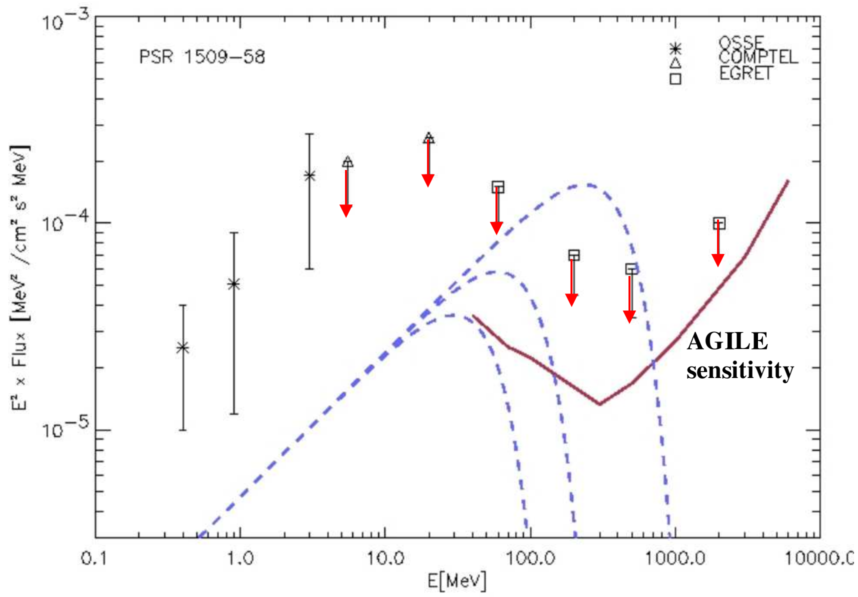

Fig. 5. CGRO spectrum of PSR 1509-58. COMPTEL and EGRET upper limits imply a spectral cut-off at $E \sim 10 MeV$. AGILE sensitivity (solid line) could improve CGRO upper limits and possibly detect spectral cut-off in highly magnitized pulsars (also weaker than 1509-58) expected accoding to current models (dashed lines) for these objects (see e.g. Harding, 1997).

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