Dark matter searches by means of the GAMMA-400 gamma-ray telescope

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Abstract.

GAMMA-400 is a space-based gamma-ray telescope planned for a launch around 2026. Our work briefly outlines the GAMMA-400 performance and quantifies some key goals of its dark matter (DM) search program. The first goal is a deep pointed observation of the Galactic center to search for the narrow lines from DM annihilation. We estimated that the combined analysis of future GAMMA-400 data together with the Fermi-LAT data will increase the sensitivity to diphoton annihilation cross section by 1.7-2.5 times with respect to the current Fermi-LAT limits. This will allow to probe DM particle parameter values predicted by Cline & Toma - 2019. Another very interesting goal is to determine precisely the origin of gamma rays from ω Cen globular cluster – GAMMA-400 will be able potentially to differentiate firmly annihilating DM and millisecond pulsars as possible sources of emission. And finally an observation of nearby supernova explosion (in case it will luckily happen) will allow to probe very large region of axionlike particle (ALP) parameter space.

1. Overview of GAMMA-400 project.

GAMMA-400 [1] is a next-generation pair-converting calorimetric space-based telescope for γ and e± detection planned for a launch around 2026. It will have the working energy range from ≈ 20 MeV to ~ 10 TeV, the main aperture with the total effective area ≈ 4000 cm² at energies ≥ 10 GeV and the field of view ≈ 1 sr. In contrast to the all-sky scanning mode of Fermi-LAT, GAMMA-400 will conduct deep pointed observations of several interesting regions on the sky. Also it will have the lateral aperture (see fig. 1) with poor photon direction reconstruction, but excellent energy reconstruction and large field of view up to 3 sr. Thus, the total field of view will reach ≈ 4 sr or 1/3 of the sky. Such a mode of observations is very valuable for study of transient phenomena like GRBs and supernovae.

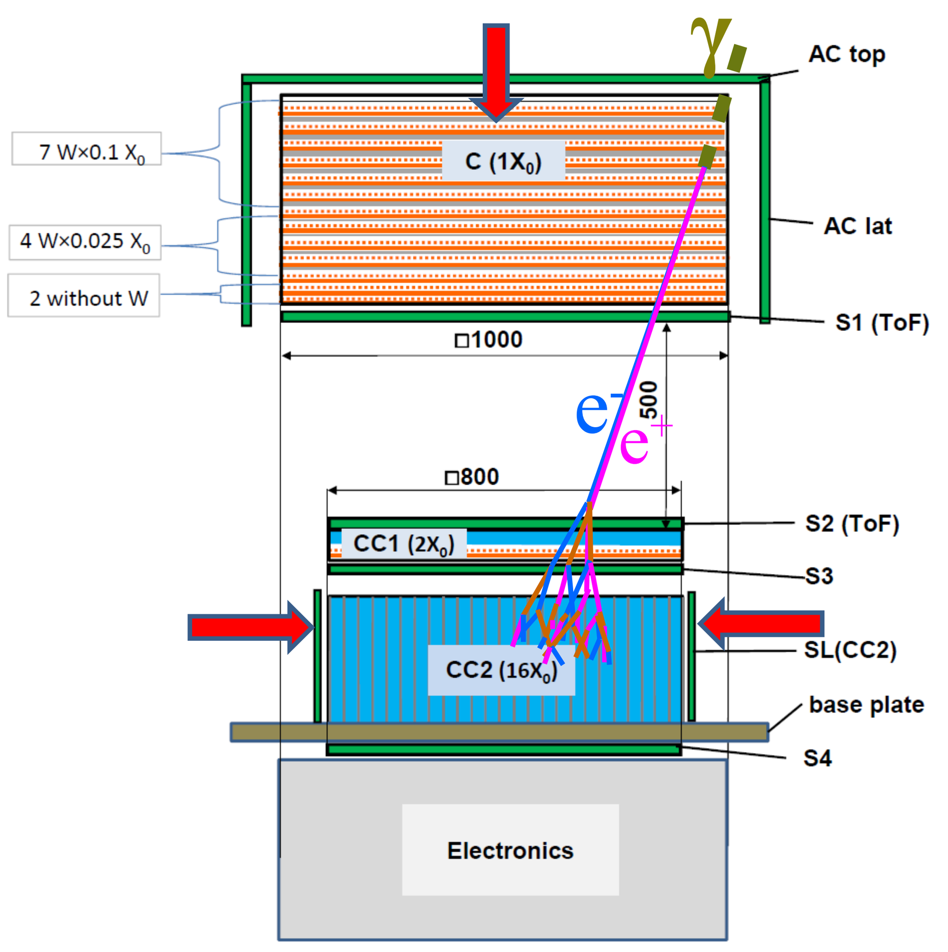


Fig. 1. GAMMA-400 physical scheme.

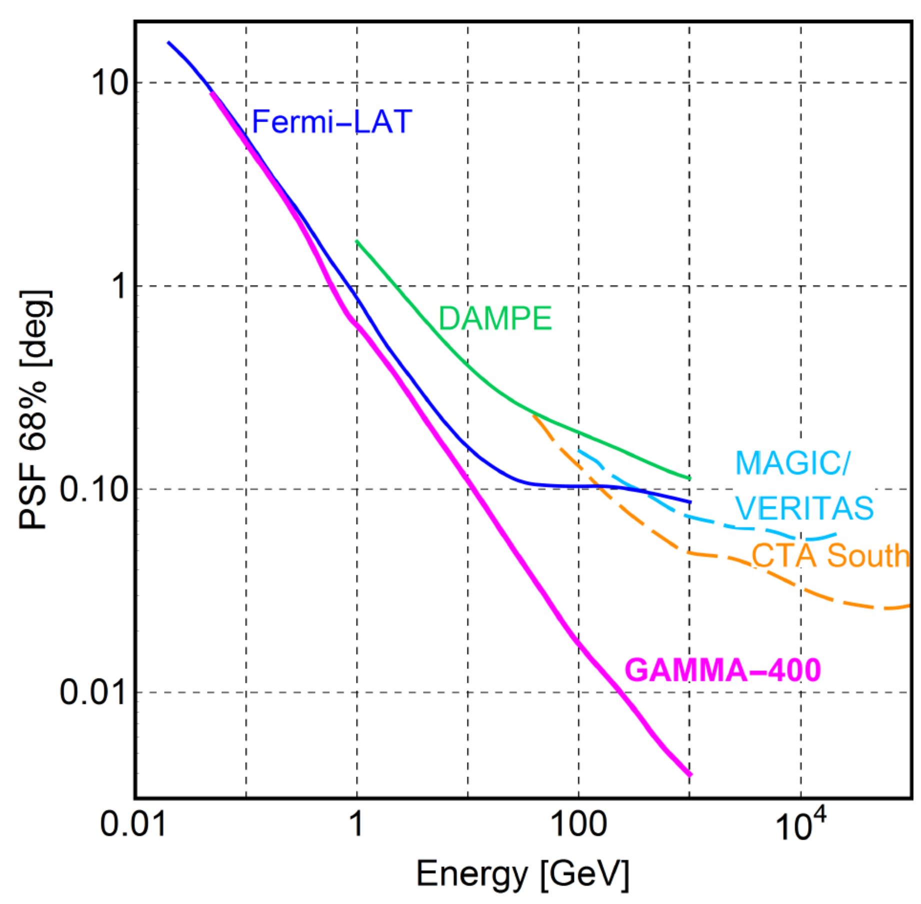


Fig. 2. The angular resolution vs energy in comparison with other telescopes.

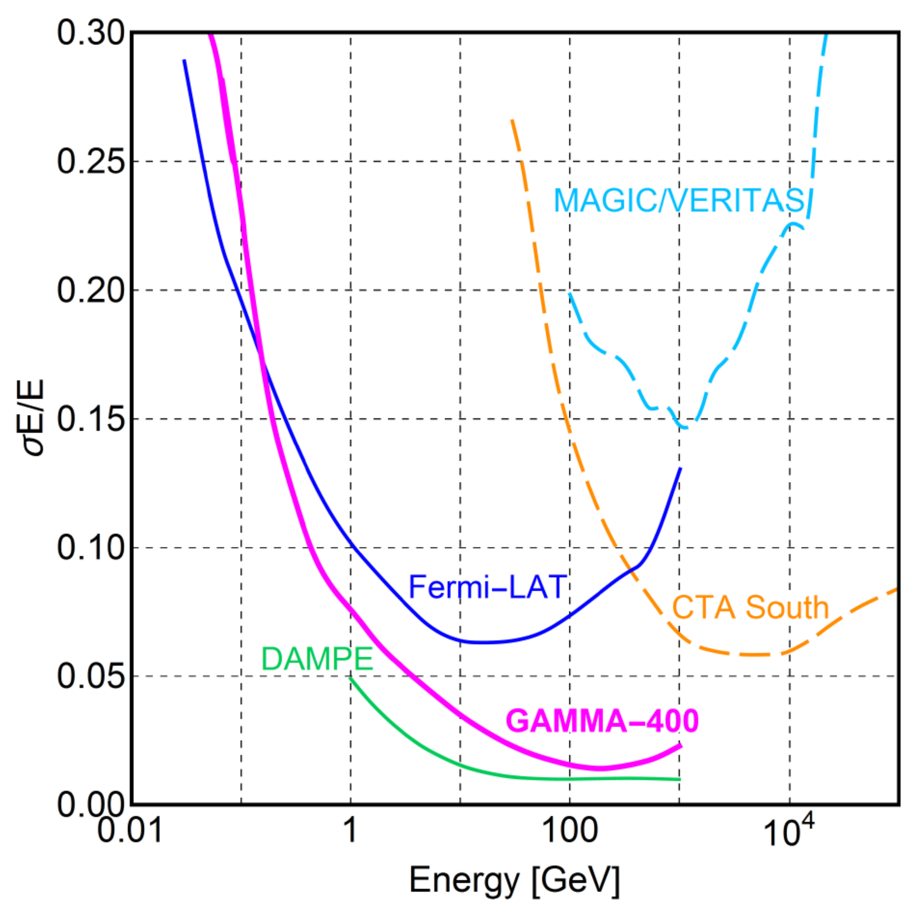
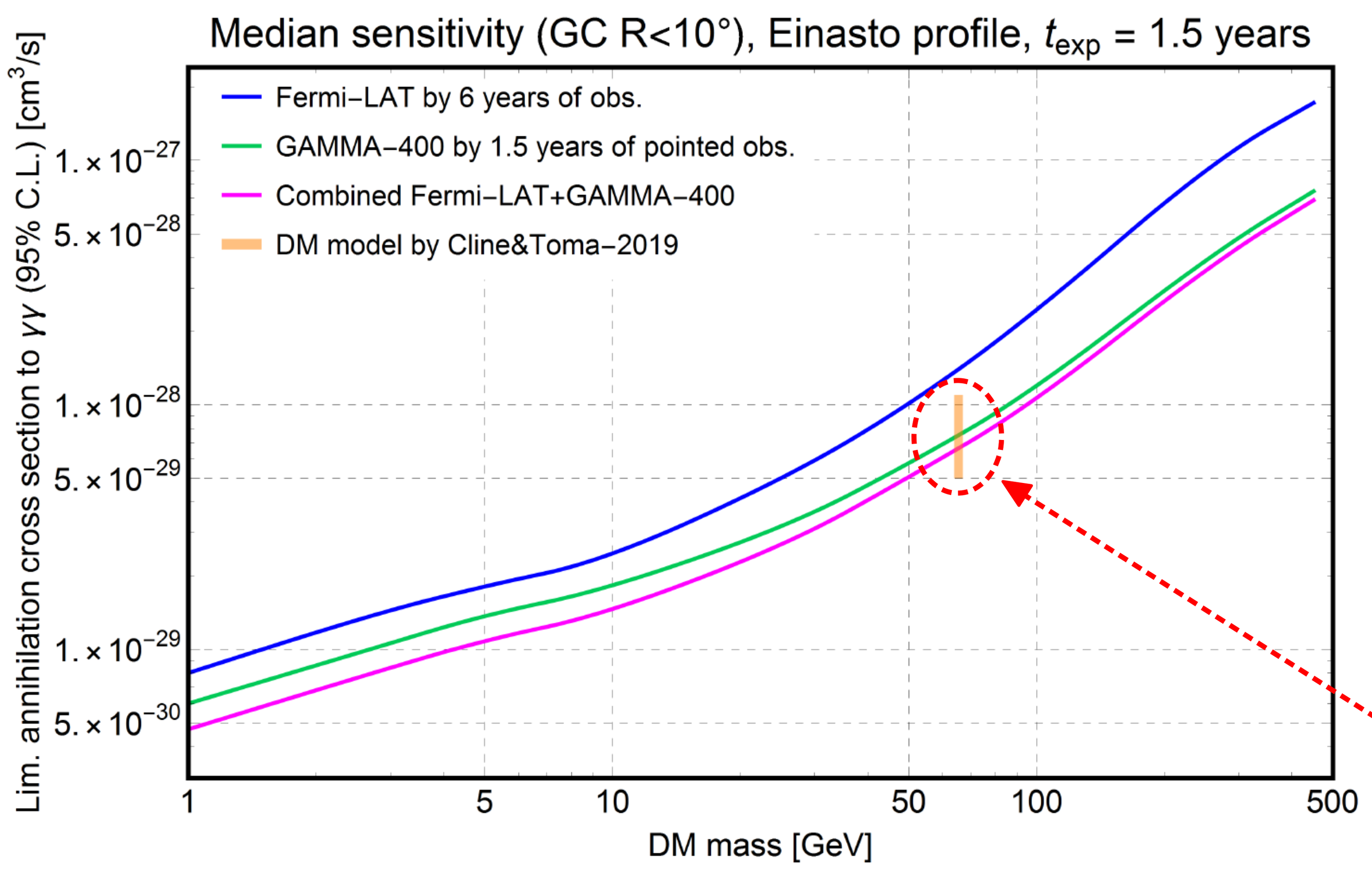


Fig. 3. The energy resolution vs energy in comparison with other telescopes.

2. Search for gamma-ray lines from DM annihilation in the Galactic center.



In order to estimate the expected sensitivity to annihilation cross section we used a typical method of the binned likelihood analysis. We assumed independent energy bins with half-widths = $\sigma_E(E)$ of each telescope (shown in fig. 3). The likelihood function for each telescope and energy bin has the form (index denoting the energy bin number is omitted for simplicity):

$$L(\langle\sigma v\rangle;\mu,n_s|c)\propto\exp\left(\frac{-n_{st}^2}{2\mu}\right)\exp\left(\frac{-n_s^2}{2s^2\mu^2}\right)=\exp\left(\frac{-(n_{DM}(\langle\sigma v\rangle)+n_s)^2}{2\mu}\right)\exp\left(\frac{-n_s^2}{2s^2\mu^2}\right).$$

Here $<\sigma v>$ is the cross section to be constrained, μ is the average number of background photons, $c=\mu+n_{DM}(<\sigma v>)+n_{st}+n_s$ – number of counts assumed to be $=\mu$, $n_{DM}(<\sigma v>)$ is the number of signal photons from DM line, n_{st} is the stat. fluctuation, n_s is the syst. fluctuation and s=0.015 is fractional mean systematics for both telescopes. $L_{Combined} = L_{Fermi\text{-}LAT} \times L_{GAMMA\text{-}400}$

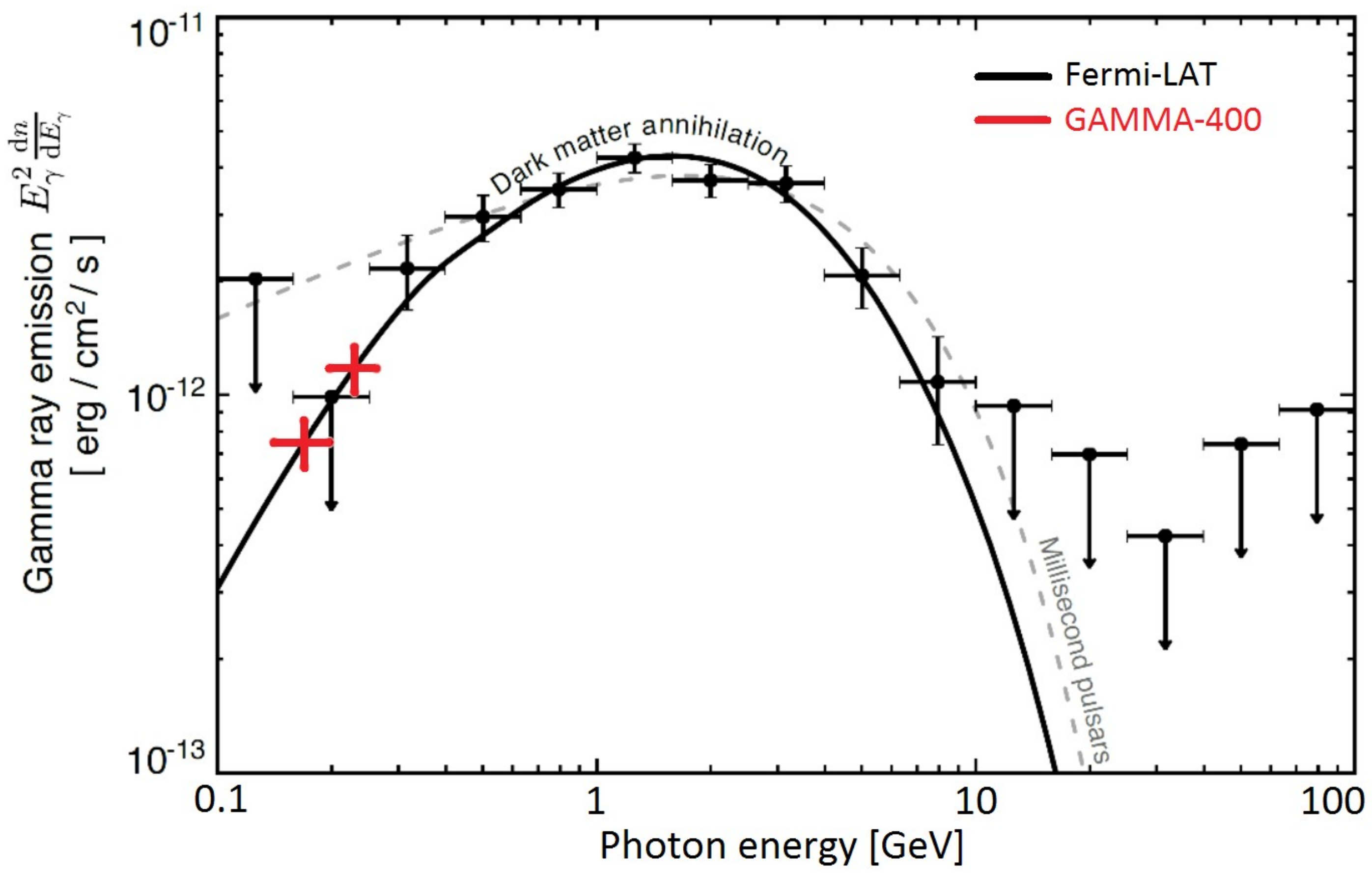
$$\mu(E_1,E_2)=\tau\int_{E_1}^{E_2}dE'\int_{E'-3\sigma_E(E')}^{E'+3\sigma_E(E')}dE\,f_d(E)\,A(E)\frac{1}{\sqrt{2\pi}\,\sigma_E(E)}\exp\left(\frac{-(E'-E)^2}{2\sigma_E^2(E)}\right):$$

τ – exposure time,
$f_d(E)$ – background flux density,
$A(E)$ – effective area.

GAMMA-400 will be able to test the line predicted in pseudo-Goldstone boson DM model by Cline & Toma - 2019 [3]!

Fig. 4. The median sensitivity to DM diphoton annihilation cross section vs DM particle mass. The blue line is from [2].

3. Refining the origin of gamma rays from ω Cen globular cluster – DM vs pulsras.



ω Cen (or NGC 5193) is the biggest globular cluster in our Galaxy. In [4] it was proposed that in fact ω Cen is the DM-rich remnant of a dwarf satellite. These authors analyzed the gamma-ray emission from ω Cen and concluded that its origin is likely due to WIMP annihilation (see fig. 5) with the following parameters: $m_x \approx 31$ GeV and $<\sigma v> \approx 6.3\times10^{-29}$ cm³/s (bb*-channel). However, as can be seen from fig. 5, the Fermi-LAT data still does not allow to distinguish firmly DM and millisecond pulsars as a source of emission. Their spectra are very similar except at low energies ≲ 300 MeV. Due to optimized performance at low energies GAMMA-400 will potentially refine the spectrum at the low energies significantly: the red crosses on fig. 5 show the modeled data points with 1σ error bars tied to the case of DM annihilation spectrum. Thus we can see that these additional data by GAMMA-400 may provide the crucial and unambiguous discrimination between the two possible emission mechanisms! This may lead to a final DM discovery in this peculiar target. GAMMA-400 statistical error estimates were based on the equation for the number of expected photons $\mu(E_1,E_2)$ above.

Fig. 5. The spectrum of ω Cen. The black crosses represents the data of Fermi-LAT by 10 years. The red crosses reflects the additional data at low energies, which GAMMA-400 will potentially provide by 300 days of pointed observations.

4. Search for ALPs by an observation of supernova explosion in the Local group.

According to [5], supernova (SN) explosion may generate a huge amount of ALPs with energies ~(10-100) MeV. Then propagating through the Galaxy these ALPs may partially convert to gamma-ray photons in the Galactic magnetic field due to Primakoff process. Thus, it will be very valuable to catch a nearby SN in the field of view of the telescope, which has not been done so far. The estimated sensitivity to ALP parameters is shown at fig. 6. Both telescopes – Fermi-LAT and GAMMA-400 – have comparable sensitivities due to very weak dependence of the ALP-photon coupling constant on the detector area [6]:

$$\textit{gamma-ray fluence} \propto g_{a\gamma}^{\ 4} \rightarrow g_{a\gamma} \propto A^{1/4}.$$

As was mentioned in section 1, GAMMA-400 lateral aperture is very useful for transient detection. It will provide the total field of view ≈1/3 of the whole sky. The effective areas at 100 MeV of the main and one-side lateral apertures are approx. the same - ≈ 2000 cm². The ratio of this area to that of Fermi-LAT in ¼ power ≈ 10%. This provides an estimate of sensitivity difference to $g_{a\gamma}$ between two instruments. Clearly, it's almost indistinguishable at fig. 6. As for the probability for GAMMA-400 to catch the SN in the Local group, it may reach ~50% for 10 years of observations, taking into account the average SN rate of 2-3 per century per galaxy and absence of SNs during Fermi-LAT period of operation.

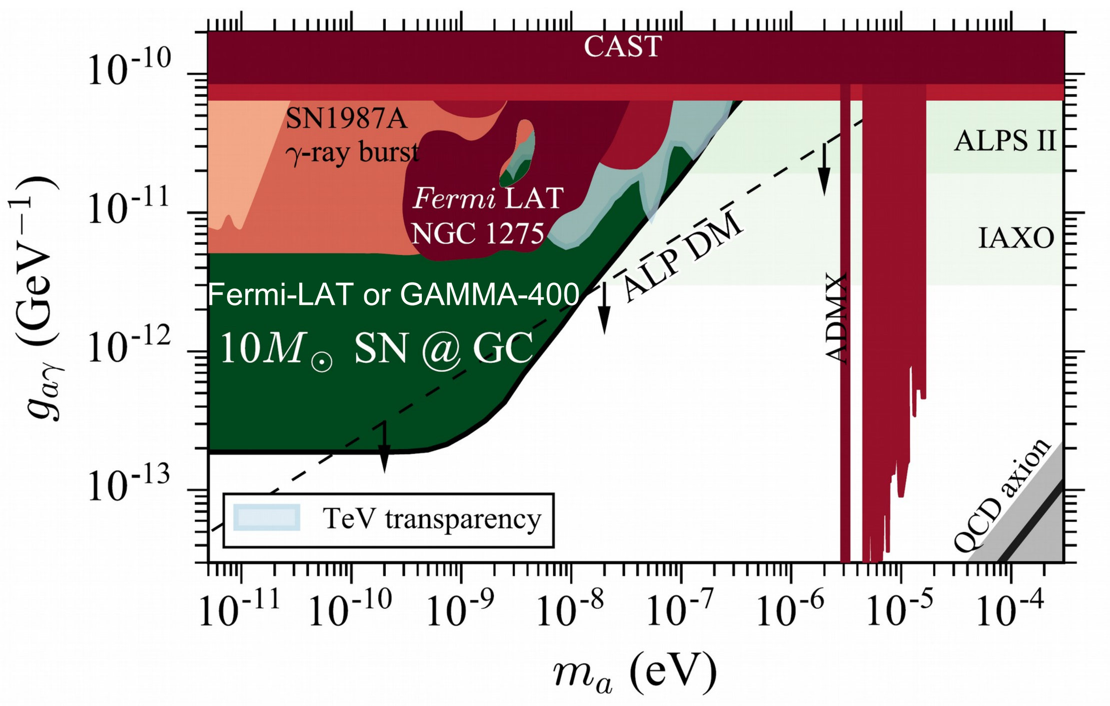


Fig. 6. The sensitivity to ALP parameters in comparison with other probes (from [5]).

5. Conclusions.

- The planned GAMMA-400 mission will have a significant potential to discover DM particle astrophysically.
- Combined analysis of the future GAMMA-400 data on the Galactic center together with the Fermi-LAT data will increase the sensitivity to DM diphoton annihilation cross section by 1.7-2.5 times, allowing at the same time to test the predicted line at ≈ 64 GeV by the recent and interesting pseudo-Goldstone boson DM model by Cline & Toma.
- Deep pointed observations of ω Cen globular cluster may ultimately confirm WIMP annihilation as a dominant source of gamma-ray emssion from this object.
- An observation of SN explosion in the Local group will probe very large and important part of ALP parameter space, which includes the parameter region, where ALPs can explain all DM.
- **Collaborators from any countries are very welcome! The project website is http://gamma400.lebedev.ru/**

References.

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