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Gravitationally Lensed MeV Gamma-ray Blazars

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☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
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1 Abstract

Gravitationally lensed blazars constitute important cosmic beams and rather unexplored laboratories for multi-frequency and multi-messenger astro-particle physics, being also cosmological probes. In those objects of the blazar population distributed at large redshifts (i.e. flat spectrum radio quasars, FSRQs), the high-energy hump of the spectral energy distribution (SED) peaks in the MeV band, and thus the bolometric power is dominated by the radiation emitted at these gamma-ray MeV photon energies. As such, it is at these energies that the largest amplitude changes in brightness and the richest variability patterns occur, making *the MeV regime a pivotal energy band awaiting for exploitation*. Future MeV-sensitive all-sky survey and time-domain monitor facilities like the All-sky Medium Energy Gamma-ray Observatory (AMEGO 18; 19), AdEPT (23), e-ASTROGAM (9) represent the only mean to pursue similar studies. Large brightness variations imply both a potential increase in statistics of new lensed gamma-ray FSRQs observable, and an increase in statistics of strong-lensing and/or microlensing

temporal features observable. Increasing chances also for independent gamma-ray delay measurements, discovery of not yet known lensed systems, and the identification of micro-lensing features are expected. MeV gamma-ray lensing may be a unique way to improve spatial resolution for jet and central engine emission regions, and to have structure insights from micro-/milli-lensing, at the cosmic distances of FSRQ. The possibility for detection of enhanced cosmic neutrinos from the very distant Universe, may be a further exciting topic for lensed gamma-ray FSRQs.

2 Science Background

Blazars, namely BL Lac objects and FSRQs, are a small fraction of the entire population of active galactic nuclei (AGN, e.g. 21) but represent key objects for modern high-energy multi-frequency astrophysics and multi-messenger astro-particle physics researches. For gamma-ray emitting FSRQs, typically distributed at larger distances than BL Lac objects, the sub-GeV and MeV gamma-ray band dominate their electromagnetic radiative bolometric power. For this reason they are the best high-energy probes of the distant and young Universe, along with distant GRBs (16; 14; 2; 15), and they are the best targets for temporal-spatial "tomography" in gamma rays. The sky in the about 0.1-50 MeV energy region is, however, insufficiently explored with only a few tens of steady sources detected since the COMPTEL era, and only the top of the iceberg touched by INTEGRAL IBIS below some MeV.

In parallel to this, strong gravitational lensing of electromagnetic radiation from distant sources (predicted in Einstein's theory of General Relativity 13), has been discovered and studied in hundreds of radio/optical lens systems, since the first detection of multiple images of SBS 0957+561 (24). When the distant source, the lensing galaxy/quasar, and observer lie along a straight line a circle, known as the Einstein ring, may be formed (22).

A gravitational macro lens, often an intervening massive galaxy, magnify the radiation emitted from a distant quasar/FSRQs and produce time delays between the diffraction (mirage) images, with delays depending on the position of the emitting regions in the source plane. Time delays in macro (AGN/galaxy scales) lenses typically range from hours to weeks. The possibility to obtain independent gamma-ray delay measurements from strong macro-lensing, and to derive accurate measurements of the projected size of the gamma-ray emission regions in central engine and the jet, disentangling micro-lensing temporal features, was attested for the BL Lac object S3 0218+35 (6) and PKS 1830−211 (17; 4; 20; 4). S3 0218+35 (lens B0218+357, $z = 0.6847$) is an example of, spatially unresolved, strong-lensing in a GeV blazar detected by *Fermi* and by MAGIC at $E > 100$ GeV (3). S3 0218+35 also represents the smallest-separation lens known and the first gamma-ray delay measurement was possible thanks to continuous *Fermi* LAT temporal monitor. This opened to the possibility of delay measurements for other and more distant lensed gamma-ray FSRQs.

In the MeV regime (before/around/after the emission peak), the largest amplitude for flares and variability patterns occurs, enriching the statistics in strong-lensing/microlensing gamma-ray temporal features. This is a very specific and limited topic where the key scientific questions can be enunciated as following. How we can substantially improve the spatial resolution of the central engine and identify the sizes and locations of gamma-ray emission regions from distant sources ? How independent gamma-ray delay measurements and radio-delays are related in strong macro

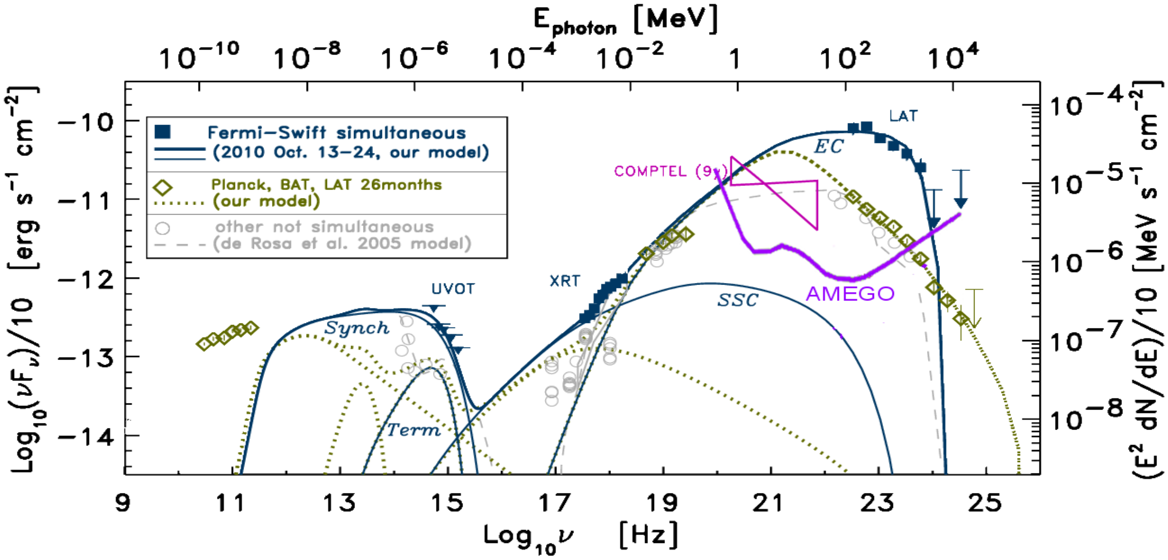

Figure 1: Observed SED of the gravitationally lensed flat spectrum radio quasar PKS 1830−211 ($z = 2.507$), built with simultaneous LAT and *Swift* XRT and UVOT data, averaged over the Oct. 13-24, 2010 period of the multi-frequency campaign led by *Fermi*. Past 26-month LAT, 58-month BAT, *Planck* ERCSC, Gemini-N, *Hubble*-ST, *Chandra* and INTEGRAL IBIS (11), COMPTEL and EGRET data are also reported (corrected for lensing by a factor of 10×). Adapted from (1). The approximated AMEGO gamma-ray continuum sensitivity with a 10^6 s integrated exposure is reported.

lensing ? What is the role of micro/milli lensing, for example a view into astrophysical emission regions only or also a probe for dark-matter substructure and subhalos intrinsic of the source ? Can high-redshift, lensed MeV blazars, help us in the detection of cosmic neutrinos from the very distant Universe, enhancing the fluence and possibly inducing oscillations in the traveling cosmic very high energy neutrinos ? Are distant gravitationally lensed MeV blazars a potential and unexplored tool for gamma-ray/neutrino multi-messenger and fundamental physics ?

3 Importance of MeV gamma-ray observations

A strong-lensing object that is also a very powerful, MeV-peaked gamma-ray FSRQ, is PKS 1830−211. Located at $z = 2.507$, it is routinely detected in the GeV band by *Fermi* and AGILE (see Fig. 1 and ref: 1; 12). PKS 1830−211 is the brightest strong lens in the sky at cm, hard X-ray, MeV gamma-ray energies, and detected already by COMPTEL (7) in 0.75−30 MeV band. Its bolometric SED is largely dominated by the radiation emitted at MeV energies. The two lines of sight to this object have been used in the past also as a cosmological probe (5).
As observational facilities become more sensitive, the presence of micro/milli-lensing effects in strong lensed quasars is increasingly supported. Micro/milli-lensing effects can introduce a variability in the flux ratio of the two images, in addition to an intrinsic energy-dependent source structure and the different region sizes, resulting in a “chromatic” spectral variability (1; 12; 17). The study of variability of gravitationally MeV-peaked and lensed FSRQs in the about 0.1MeV−1GeV band, can open interesting perspectives:
• More, small separation, lenses that can not be spatially resolved by the current generation of observatories, can be discovered in the MeV band measuring time delays of the lens images,

enabled by continuous flux monitoring. This is also relevant for unidentified *Fermi* LAT point sources.
• MeV data are important to understand blazar particle acceleration and emission processes, the combination and interplay of different leptonic inverse-Compton mechanisms (SSC, BLR, torus, diffuse dust photon fields) or hadronic emission processes (photopion, e.m. cascades, proton synchrotron, Bethe-Heitler).
• MeV temporal/spectral variability produced by unresolved lensing of distant FSRQs is able to probe the central engine and jet structures and the origin of the HE emission, this also in synergy with facilities still operating in the second half of 2020s like CTA, SKA, ALMA, e.g., dedicated observations of PKS 1830−211 performed already in the very early project phase (17), LSST and the heritage of Euclid and Spektr-RG e-ROSITA.
• MeV data pinpoint the high-energy emission peak of distant FSRQs where more pronounced variability and flares are observable, and thus enhance the detection of temporally delayed events and micro-lensing signals. *Fermi* LAT already observed common 1-day GeV flares of factors 3-10$\times$ compared to few-10% increases in mm/radio bands.
• Gravitational lensing might help to enhance the sensitivity to cosmic neutrinos emitted by hadronic-dominated gamma-ray FSRQs that are typically placed at much larger distances with respect to other expected neutrino sources. The neutrino signal magnification by astrophysical lenses is of much interest for the future of large-scale neutrino detectors. Lens multiple paths might induce also neutrino quantum interference and oscillations (8) based on some theoretical hypotheses.
• Pseudoscalar axion-like particles (ALPs) generically couple to two photons, giving rise to possible oscillations with gamma-ray photons emitted by a FSRQ in the intergalactic/intervening-galaxy magnetic fields. Strong lensing of a background MeV FSRQ has some, speculative, possibility to enhance the flux of non-isotropic/streaming ALPs. Anomalies in the flux ratios of lensed images are foreseen by some DM theories. Time-variable lenses are also probes on the behavior of DM substructure in the intervening galaxy halo.
• Depending on the particle properties, cosmological parameters, masses and separations of elements in the lensing system, differential arrival times of multi-messenger particles (gamma-ray photons, massive-neutrinos, gravitational waves, even massive axions and gravitons) are expected. Multi-messenger detections of different time delays from a lensed MeV FSRQ would be an unexplored fundamental physics phenomenon.

4 Expected results

A sensitive MeV gamma-ray space telescope like AMEGO (18; 19), AdEPT (23), or e-ASTROGAM (9) is able to obtain independent gamma-ray delay measurements from unresolved strong macro-lensing, and to identify variability features related to micro-lensing, in the case of MeV gamma-ray-dominated blazars. AMEGO and similar facilities are expected to discover several new high-redshift FSRQs undetected by the *Fermi* LAT because of GeV spectral cutoffs, and to see many MeV gamma-ray flares, including those from lensed FSRQs. These are interestingly expected to host the heaviest supermassive black holes of the Universe and the primordial relativistic jets (see e.g., sect. 2.5 of 10) at high redshifts ($z \gtrsim 2$). In addition, space-borne wide field imaging observatories, such as ESA's Euclid space telescope, would soon produce hundreds of new useful strong lenses to be searched for a MeV detection. At the end of 2020s time-series and spectral analysis of gamma-ray variability, combined with the properties of the lens from radio observations (SKA, ALMA, etc.) or IR/optical observations (LSST, and heritages from Spektr-RG e-ROSITA, Euclid, JWST and other) can yield an improvement in spatial resolution at gamma-ray energies by a factor of 10^4 (4; 20). Multi-frequency and multi-messenger studies using powerful gamma-ray FSRQ sources with candidate hadronic processes, will also be potentially opened in conjunction with the, foreseen, large scale neutrino array experiments (IceCube, KM3NeT and other). The lens magnification of the neutrino flux is expected to be equal to that of MeV gamma-ray photon flux, and this could drive to measure the intrinsic neutrino luminosity of powerful MeV-GeV FSRQs. MeV gamma-ray lensed FSRQs might also be of interest for, speculative, hypotheses in multi-messenger and fundamental physics.

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