Gravitational lensing in the time domain

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The primary objective of this PhD project is to develop and apply a novel methodology for the identification of strong gravitational lensing systems in the time domain to probe the "dark Universe". In particular, the proposed research will exploit high-time-resolution data from the Fermi-LAT all-sky survey to detect and characterize low-mass gravitational lenses ($M < 10^8$ $M_\odot$), which are typically inaccessible through standard imaging-based searches. The abundance of low-mass lenses is a **key constraint to the nature of dark matter** (e.g., *cold* versus *warm* dark matter particle models), while their associated time delays provide a one step measurement of H_0, offering an **independent sample to test the *Hubble tension***.

Research Planning

Year 1) The candidate will implement an unresolved light curve method to identify characteristic time delays in unresolved signals. This method, proposed first by Geiger and Schneider (1996), relies on the so-called *autocorrelation function (ACF)*, which consists of finding the correlation of a signal with a delayed copy of itself as a function of delays (like a canon in music). The ACF method will be applied to the latest available catalog.

Year 2) Promising lens candidates will be followed-up using multi-frequency radio observations at milliarcsecond angular resolution, which can directly reveal the lensed images and test the lensing nature. As the extragalactic gamma-ray sky is dominated by *blazars,* we expect the targets to be visible up to the highest frequencies. This property could give the opportunity to learn the data reduction of Very Long Baseline Intereferometric (VLBI) observations at millimeter $\boldsymbol{\lambda}$.

Year 3) With this low-mass lens sample in hand, it will be possible to i) constrain the slope of the sub-halo mass function (hence putting constraints on the warmth of the dark matter particle) and ii) provide an independent joint estimate of the Hubble parameter. The choice of the priority among i) and ii) will depend on the progress and the remaining available time, as in Year 3 part of the time will be allocated to writing the PhD thesis.

This is an ambitious project and it is possible that no new lens will be discovered. However, as a by-product, there will be a new sample of **binary SMBHs candidates** (same ACF method, different time scales). SMBHs binaries are the progenitors of the loudest sources of gravitational waves in the frequency regime of the future NASA/ESA mission LISA. Based on the results of the follow-ups, it will be possible to determine the occurrence of SMBH binaries at different redshifts, providing new important observational constraints to the SMBH formation and evolution models across the cosmic time.

Academic Skills

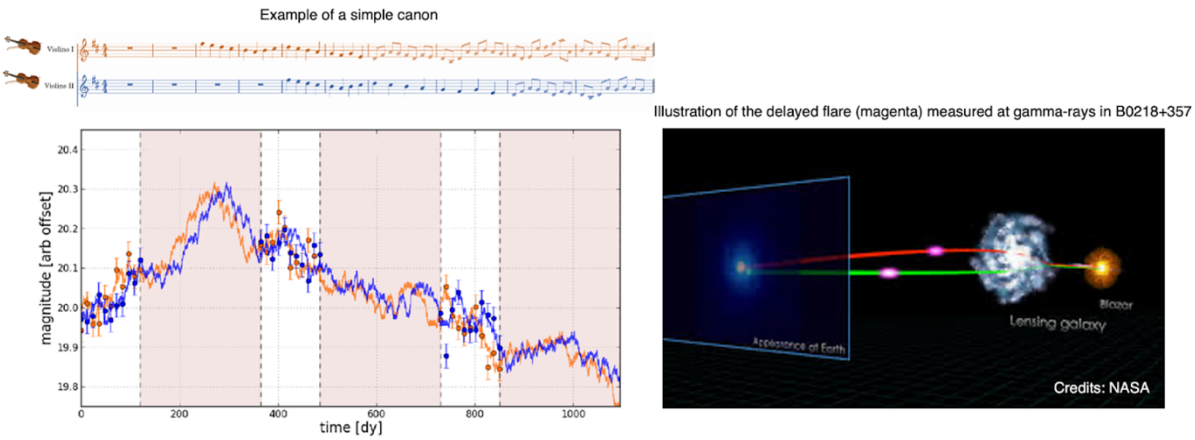
The PhD candidate will develop a strong theoretical and methodological background in strong gravitational lensing, cosmology, and time-domain astrophysics. This includes advanced knowledge of dark matter models, as well as the role of gravitational lensing as a cosmological probe. From a methodological perspective, the candidate will acquire expertise in time-series analysis and statistical analysis techniques. The candidate could also gain practical experience in radio astronomical techniques, in particular VLBI, through schools and direct involvement in observational campaigns. This will include training in the preparation of observing proposals and participation in follow-up observations.

Academic development will be further supported by attendance at international conferences, specific PhD schools, and workshops, where the candidate will present research results and engage with the scientific community. The preparation of peer-reviewed publications will contribute to the development of scientific writing and critical analysis skills.

Transferable Skills

The candidate will develop a broad range of transferable skills relevant to both academic and non-academic career paths. These include scientific writing, effective oral communication, and presentation skills, which will be practiced also through group meetings (once per week) and conference presentations. The project is envisioned to follow open science practices, which will ensure high standards of scientific integrity. Beyond Academia, learning about scientific integrity enables evidence-based decision-making by evaluating data validity and involves an ethical conduct of projects. The candidate will also strengthen collaboration and networking abilities through participation in international conferences and collaborative research environments.

In addition, career development activities such as career counselling and professional development workshops will be pursued, if available. Public engagement and outreach activities may also be undertaken to enhance communication skills and broaden the impact of this PhD research on society (see below).



Example light curves for a simulated double lensed quasar.
The leading image is in orange, while the delayed image is in blue (Dobler et al. 2015)

Public engagement

If the candidate is interested, it could be possible to work on the *sonification* of gravitational time delays (observed and/or simulated, see Zanella et al. 2022), a project with the aim of developing new inclusive methods to perform research and reach a wider audience in terms of outreach (i.e., including people with visual impairment).

Useful readings and links: https://www.youtube.com/watch?v=hAH_0UhRnUo&t=10s ● Geiger & Schneider 1996 ● Shu et al. 2021 ● Bag et al. 2022 ● Cheung et al. 2014 ● Spingola 2023 (Cosmology & VLBI) ● Spingola 2023 (Binary SMBHs at high-z) ● Despali et al. 2025 ● Zanella et al. 2022 (Sonification and sound design for astronomy research, education and public engagement)