

“Dark Matter Is Here - So Why Don’t We See It?”

Astrophysical observations provide compelling and consistent evidence that dark matter exists throughout the Milky Way, including at the location of the Sun and the Earth. Measurements based on stellar kinematics, Galactic rotation curves, and the vertical dynamical equilibrium of stars in the Galactic disk robustly infer a non-baryonic mass component in the solar neighborhood. These independent methods converge on a local dark matter density of order $\rho_{\text{DM},\odot} \sim 0.3 - 0.5 \text{ GeV cm}^{-3}$ as comprehensively reviewed by Lim et al. (2025 @ <https://ui.adsabs.harvard.edu/abs/2025JCAP...01..021L/abstract>). Importantly, these conclusions rely only on the gravitational influence of dark matter and are largely insensitive to its microscopic particle properties.

Despite this strong and long-standing astrophysical evidence, decades of ground-based direct detection experiments - designed to observe the scattering of dark matter particles off nuclei or electrons in terrestrial detectors - have not yet produced a confirmed signal. Modern experiments employing ultra-low-background techniques and large target masses now place increasingly stringent upper limits on the interaction strength between dark matter and Standard Model particles across a wide range of candidate masses (see Section 5 of Cirelli et al. 2024 @ <https://arxiv.org/abs/2406.01705>). These null results have significantly constrained many well-motivated dark matter models, particularly those involving weak-scale interactions.

The only long-standing exception to this experimental landscape is the DAMA/LIBRA experiment, which reports a statistically significant annual modulation in its event rate. This modulation has been interpreted by the collaboration as a potential dark matter signal arising from the Earth’s motion through the Galactic dark matter halo. However, this claim remains controversial and unconfirmed by other experiments, including those using similar NaI(Tl) detector materials, and is therefore not widely accepted as definitive evidence for dark matter (Lee et al. 2025 @ <https://arxiv.org/abs/2409.15748>).

At first glance, this situation may appear contradictory: *if dark matter exists locally with a substantial density, why has it not been detected directly in laboratory experiments on Earth?* This apparent tension motivates the central theme of this project. Students will explore why there is, in fact, no logical inconsistency between strong gravitational evidence for dark matter and the absence of confirmed direct detection signals. More importantly, they will examine what the lack of detection teaches us about the physical nature of dark matter and about the assumptions built into different experimental approaches.

Throughout this project, students will critically examine the assumptions underlying astrophysical inferences of dark matter, particle-physics models of dark matter candidates, and the design and interpretation of direct detection experiments. The goal is not to “solve” the dark matter problem, nor to advocate for a particular model, but rather to develop a precise understanding of what is - and just as importantly, what is not - being tested by different classes of observations. By doing so, students will gain insight into how modern physics confronts fundamental questions using incomplete but complementary evidence.

Project Questions

1. What does “local dark matter density” mean?

Explain how astrophysical observations are used to infer the local dark matter density in the solar neighborhood. What physical and dynamical assumptions are required in these analyses? Why do these measurements rely exclusively on gravitational effects, and not on any non-gravitational interactions of dark matter?

2. From density to detection rate

Estimate the local number density and flux of dark matter particles for a representative dark matter mass. Explain why a large particle flux through the Earth does not necessarily imply a large detection rate in laboratory experiments. Identify and clearly distinguish the astrophysical inputs, particle-physics parameters, and detector-specific properties that enter into the expected event rate.

3. Meaning of null results

Explain what is excluded by current direct detection experiments and how these exclusions are typically presented. Give some examples of dark matter scenarios or models that remain unconstrained by present-day direct detection limits, and explain why they are not detected.

4. The DAMA/LIBRA puzzle

Describe the annual modulation signal reported by the DAMA/LIBRA experiment and the physical reasoning behind its interpretation as a dark matter signature. Why is this signal considered controversial? Why is independent confirmation using the same target material particularly important in assessing this claim?

5. Interpreting the “discrepancy”

Is there a logical contradiction between the astrophysical evidence for local dark matter and the absence of confirmed direct detection signals? Why or why not? What does the current lack of detection imply about the possible mass scale, interaction strength, or particle nature of dark matter?

Lastly, please describe your thoughts on this discrepancy.