Deep Neural Networks Hunting Ultralight Dark Matter

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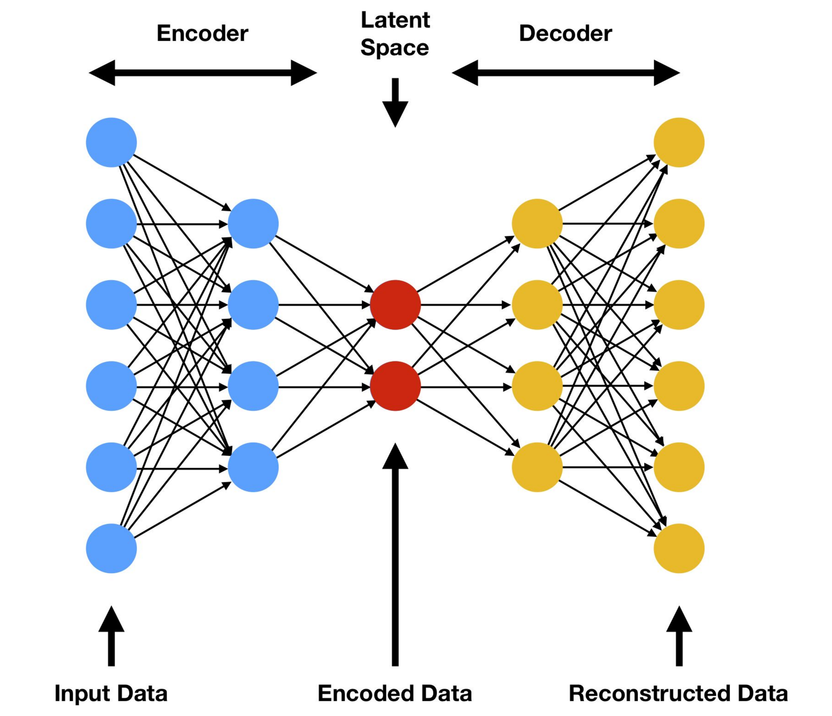
1. Ultralight dark matter scenario

Dark matter constitutes about 27% of the Universe's energy content and is approximately 5x more abundant than baryonic matter, yet its fundamental nature remains elusive. One promising candidate for its origin is ultralight dark matter (ULDM). It is composed of extremely light particles, with masses in the range of $m = 10^{-23}\,\mathrm{eV} \div 1\,\mathrm{eV}$. These particles exhibit wave-like behavior on astrophysical scales, leading to rich phenomenology, yet reproducing the behaviour of cold dark matter (CDM) on cosmological scales.

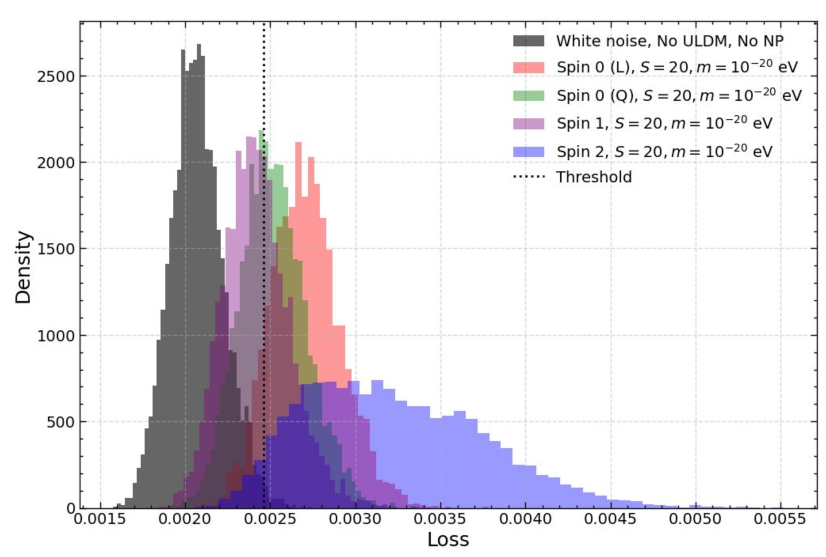
3. Deep neural network



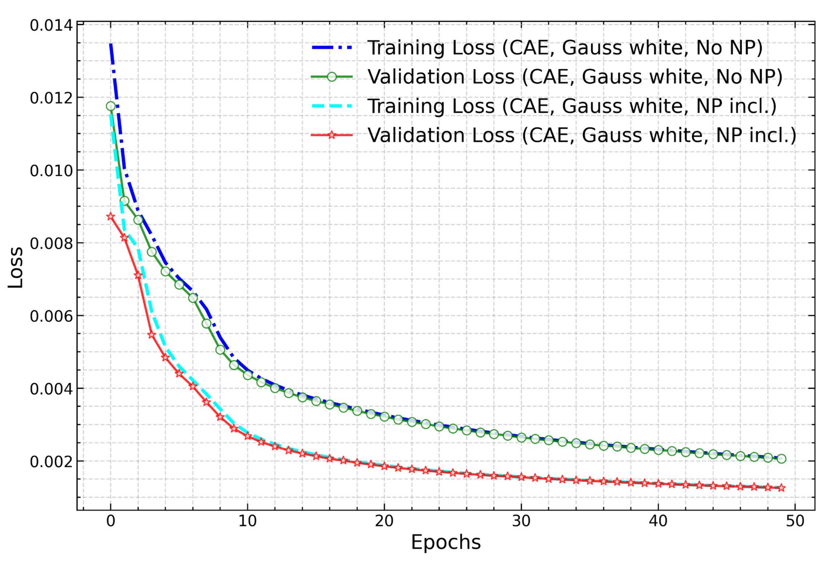
Simplified diagram of the autoencoder

Source: Amor, "Comprehensive introduction to Autoencoders," ML Cheat Sheet, 2021

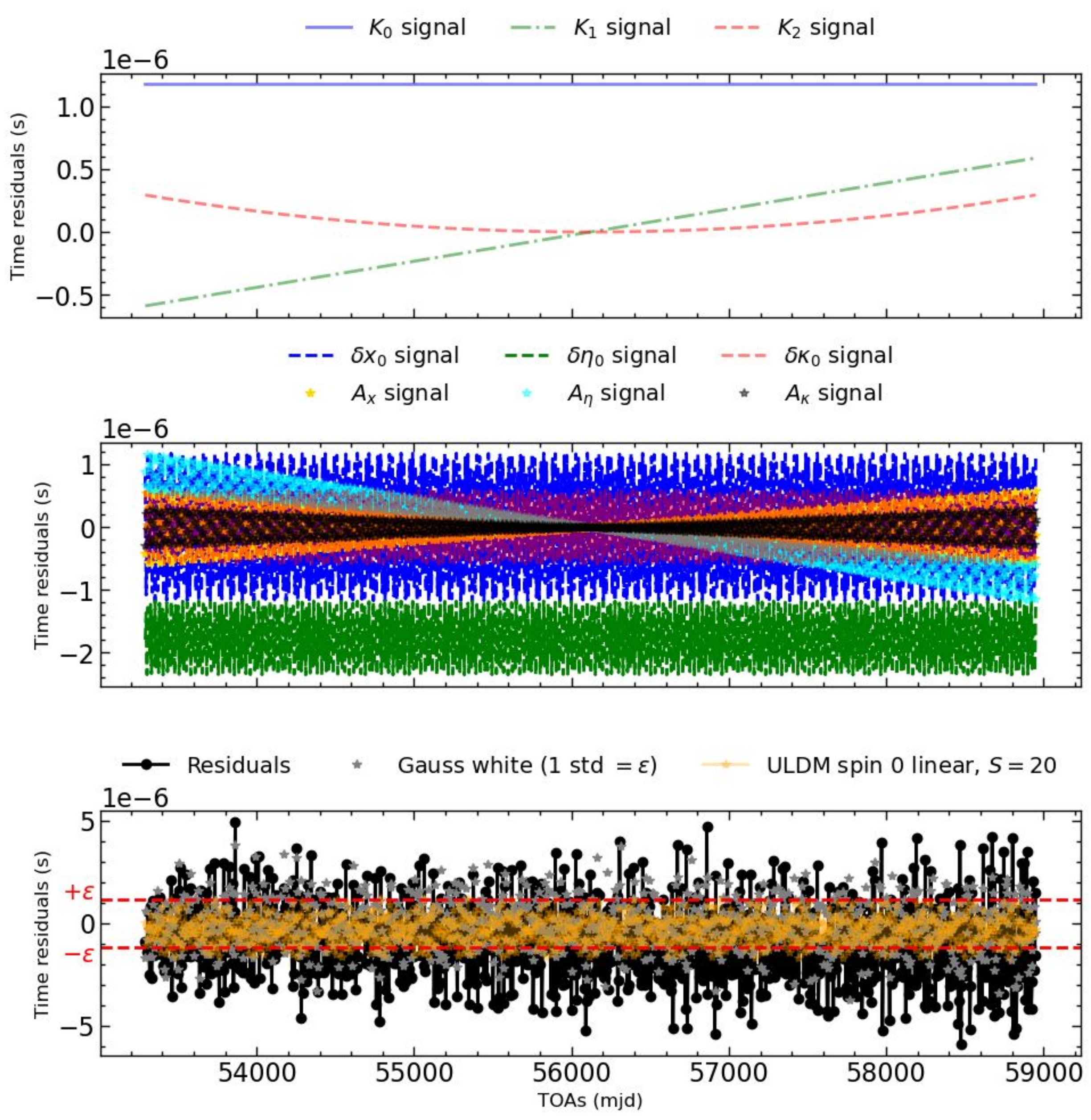
We use a convolutional autoencoder, a type of neural network, as an anomaly detector. It is trained on simulated pulsar timing data with no ULDM signal and then applied to test data containing ULDM signals to detect anomalies. The goal is to estimate the minimum signal strength required for detection.



Distribution of reconstruction errors



Training process



Signal modelling

2. Interaction of ULDM with a binary system

In addition to gravitational effects, ULDM can have direct interactions with ordinary matter, leading to diverse observable consequences specific to a particular ULDM model.

Binary pulsars have proven to be promising ULDM detectors. An interaction between ULDM and the components of a binary pulsar leads to a perturbation in the binary's dynamics, which manifests as a unique signal in pulsar-timing data. Although the gravitational influence of dark matter on the pulsar timing data is too weak to be detectable, the signal from a direct interaction with normal matter could still be observable. If this signal is not detectable, it imposes strong constraints on the coupling constants of a particular dark matter theory [1-4].

Interaction: direct

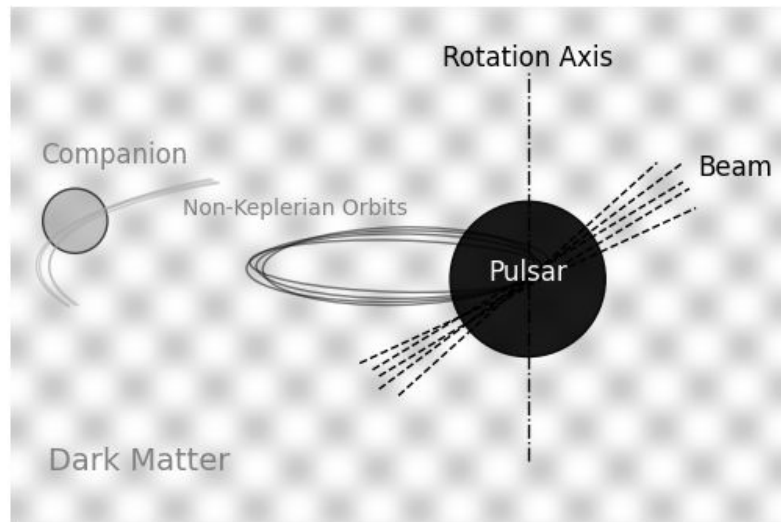
Probed masses: $m = 10^{-23}\,\mathrm{eV} \div 10^{-18}\,\mathrm{eV}$ (back-reaction negligible)

Spin 0: $M_A^{\alpha}(\Phi) = \bar{M}_A(1+\alpha\Phi)$

$M_A^{\beta}(\Phi) = \bar{M}_A\left(1+\beta\frac{\Phi^2}{2}\right)$

Spin 1: $L_{\rm int} = q_1\dot{\vec{r}}_1\cdot\vec{A} + q_2\dot{\vec{r}}_2\cdot\vec{A}$

Spin 2: $S_{\rm int} = \Lambda\int d^4x\sqrt{-g}M_{\mu\nu}T^{\mu\nu}$



4. Bayesian sensitivity limit

In previous work, we estimated the binary pulsar sensitivity curve in the case of scalar dark matter using Bayesian analysis [5].

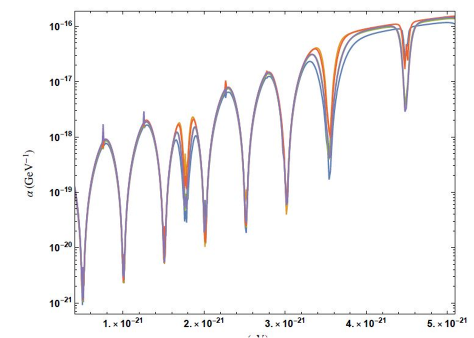
$\mathcal{O}_n = \int \mathcal{L}(\Xi)\,d\vec{\Xi}$ ← nuisance parameters (errors, secular effects)

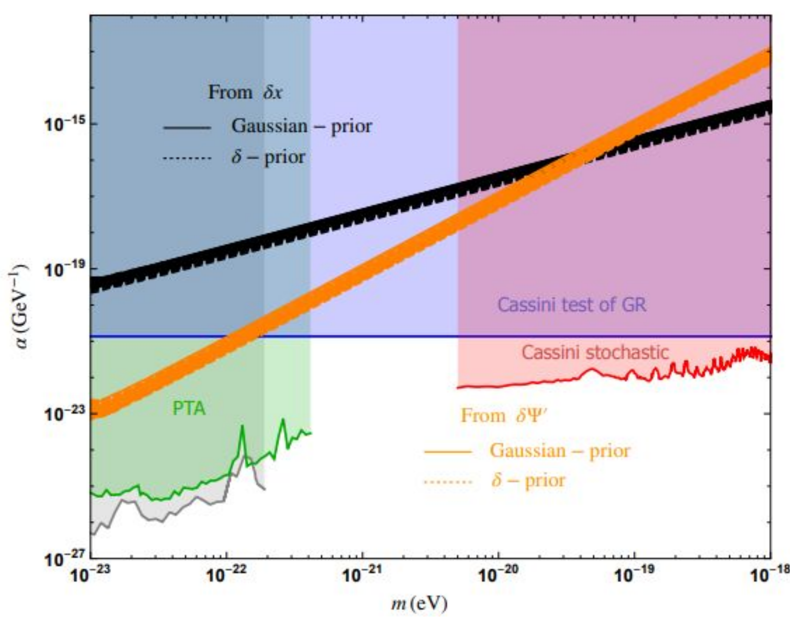
$\mathcal{O}_h = \int P(X,Y)P(\alpha,m)\mathcal{L}(\Xi,X,Y,\alpha,m)\,d\vec{\Xi}\,dX\,dY\,d\alpha\,dm\,,\ P(\alpha,m) = \delta(\alpha-\alpha_f)\delta(m-m_f)$

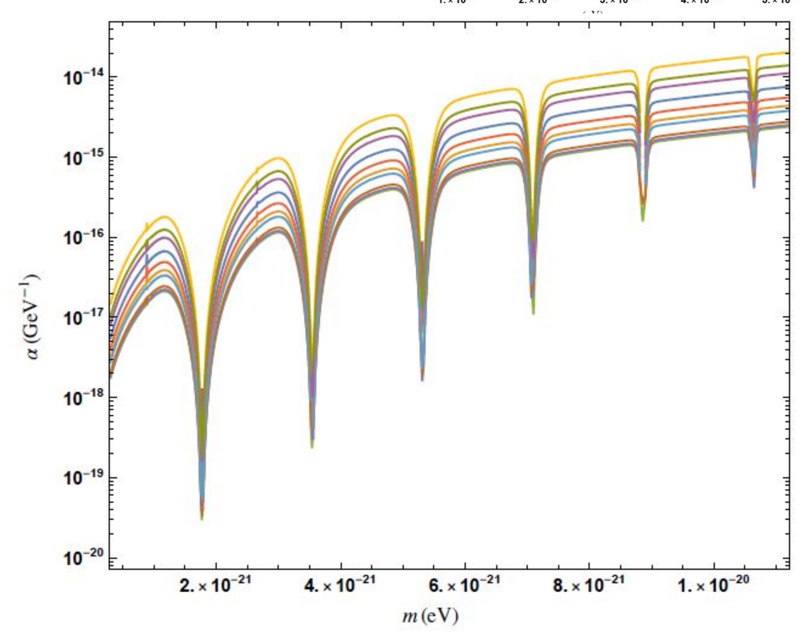
$\mathcal{B} \equiv \frac{\mathcal{O}_h}{\mathcal{O}_n}$ ← evidence for signal hypothesis / ← evidence for null hypothesis

$\bar{\mathcal{B}} \equiv \int d\mathbf{n}P(\mathbf{n})\mathcal{B}$ — averaging over noise

$\bar{\mathcal{B}}^C = \prod_{p=1}^{N_p}\bar{\mathcal{B}}_p = 1000$ — combination of all pulsars

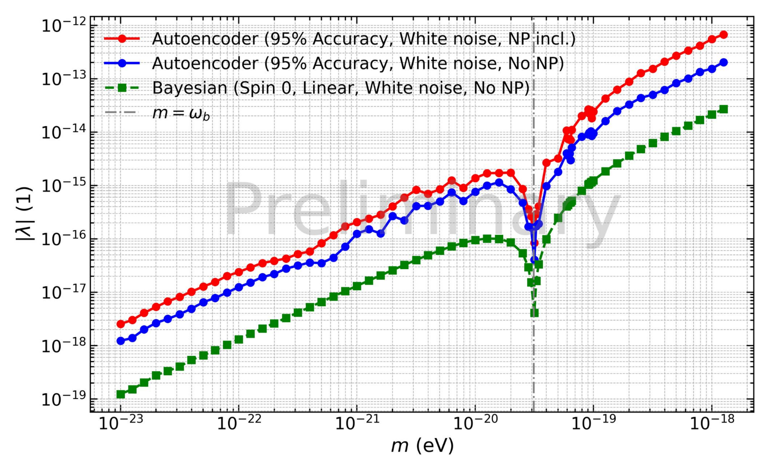


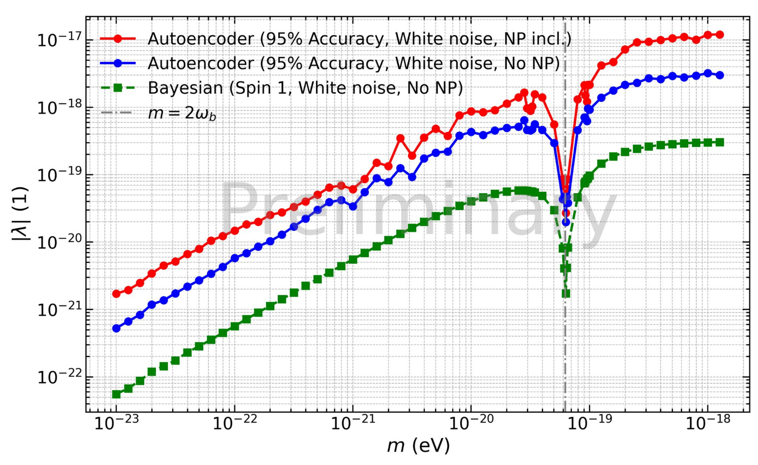


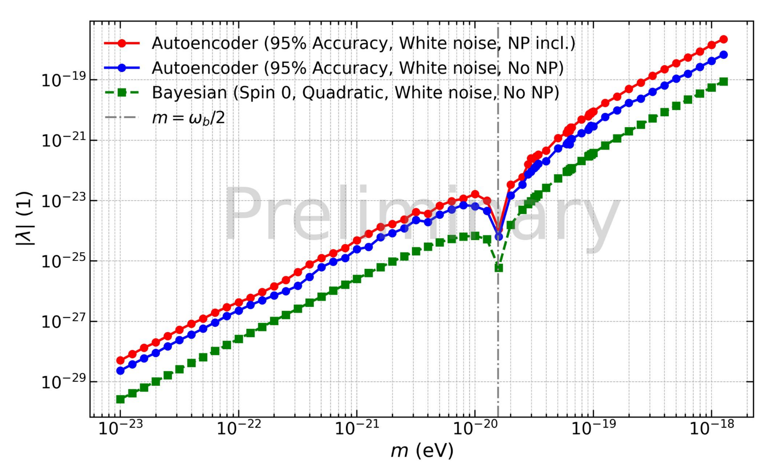


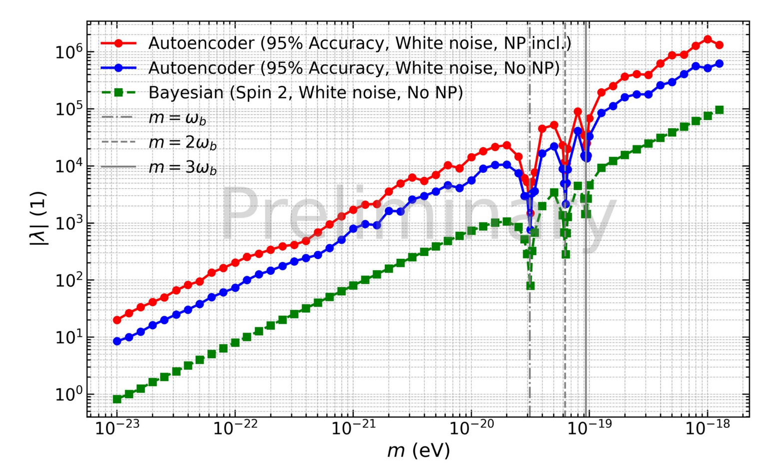
5. Preliminary results and future

All 4 figures show the sensitivity curve obtained by the autoencoder, compared with a simplified Bayesian analysis. The λ depends directly proportional to the coupling constants of the respective theories.









Our goal is to develop the most effective machine learning models for detecting ULDM signals in pulsar timing data. In addition to detection, we are working on ML-based parameter estimation.

References

[1] Diego Blas, Diana López Nacir, and Sergey Sibiryakov. Ultralight Dark Matter Resonates with Binary Pulsars. Phys. Rev. Lett., 118(26):261102, 2017.

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[3] Diana López Nacir and Federico R. Urban. Vector Fuzzy Dark Matter, Fifth Forces, and Binary Pulsars. JCAP, 1810(10):044, 2018.

[4] Juan Manuel Armaleo, Diana López Nacir, and Federico R. Urban. Pulsar timing array constraints on Spin-2 ULDM. JCAP, 09:031, 2020.

[5] Pavel Kůs, Diana López Nacir, and Federico R. Urban. Bayesian sensitivity of binary pulsars to ultra-light dark matter. A&A, 690, A51 (2024).

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