# The Breakthrough Listen Search for Intelligent Life in the Universe: Searching for Anomalous Variability in Modern Time-Domain Surveys

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## 1 Introduction

One of the pressing questions in contemporary astronomy is the Search for Extraterrestrial Intelligence (SETI). Highlighted by the Astro 2020 Decadal Survey, SETI

However, SETI has not utilized a new generation of optical wide, fast, and deep time-domain surveys. With the advent of modern ground-based large time-domain surveys, we propose the expansion of frameworks and searches for anomalous variability over a large data volume in real-time.

The Search for Extraterrestrial Intelligence (SETI) is an important one highlighted as a priority from the Astro 2020 Decadal Survey...

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Modern time-domain surveys give us an unprecedented volume of data and parameter space to search for technosignatures in temporal datasets. For example, large sky surveys have been argued to be the ideal springboard advancing the search for technosignatures (Djorgovski, 2000; Davenport, 2019).

Another strange variability such as ASASSN-21qj, a Sun-like star, that exhibits anomalous long-term variability trends.

For example, (Wright et al., 2016) ...

- Some basic SETI technosignature search assumption - and why time series? (need literature i.e Kipping and Teachy 2016, Socas-Navarro et al. 2022)
- Why OSETI in Modern Time-Domain Surveys? For example, large sky surveys have been argued to be the ideal springboard advancing the search for technosignatures (Djorgovski 2000, Davenport 2019)
- What are the challenges, and things that need to be accomplished ahead?

Based on our own evaluation of the 9-axis of merit developed by Sheikh (2020), searches for technosignatures through variable sources are relevant now.

Until most recently, a systematic search for anomalous stellar variably has not been undertaken as rigorously on wide field-of-view modern time-domain surveys as we proposed in this program. For example, Malanchev et al. (2021) performed a search for anomalous events in the ZTF DR3 that contained 2.5 million objects over the span of nearly two years of ZTF observations. Using a series of machine-learning filtering algorithms, their work demonstrates the ability to discover rare variables and transients. Since the work of Malanchev et al. (2021) the current onset of ZTF DR19 contains over 4.8 billion cataloged sources, and more than 5 years of observations begs the opportunity for the thorough investigation of technosignatures. Other hyper-catalogs exist, such as ZTF Ubercalibration[1], that enables even higher photometric precision for the ZTF photometry pipeline that can be utilized in this work.

We present methods here expanding on this work, enabling more robust anomaly detection, while also implementing state-of-the-art algorithms for catalogs of greater volume.

By now, the canonical search for "anomalous variability" is more or less described. Even though converging literature suggests the presence of complex dust behavior. KIC 1233 however remains a mystery, given that no other star exhibits. However, other patterns of odd variability could exist such as asymmetric dimming events, prolonged dimming events,

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[1]http://nessi.cacr.caltech.edu/ZTF/Web/Zuber.html

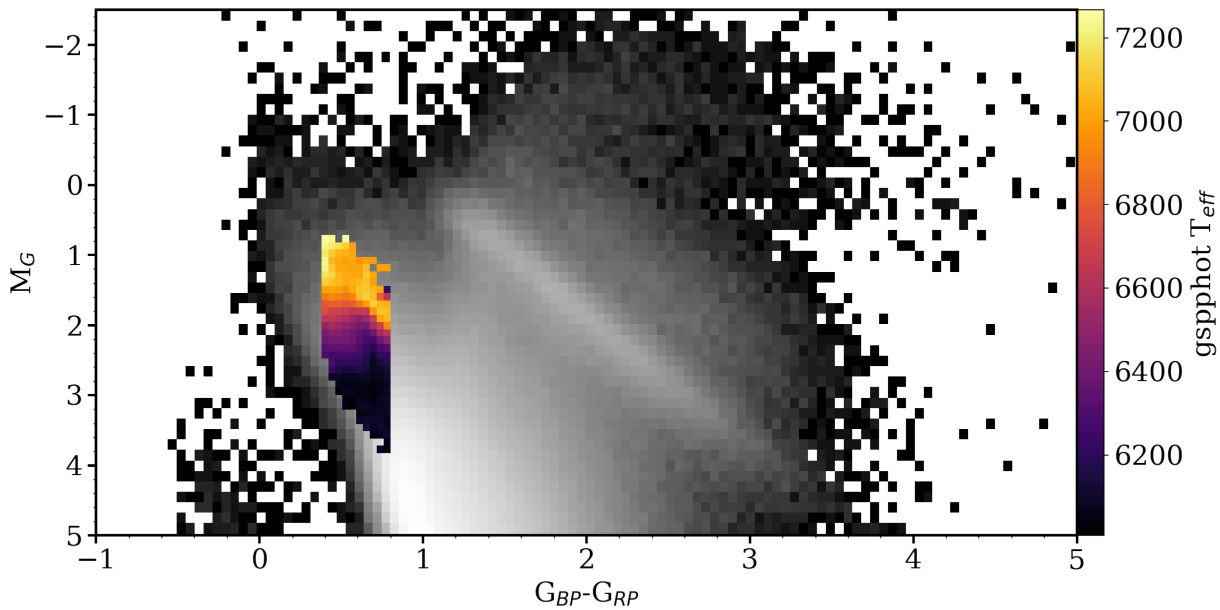


Figure 1: Gaia DR3 observed color-magnitude diagram color-coded by density (in gray). The highlighted region is color-coded by the average gsphot effective temperature, selected as a sub-sample of F0-9 dwarf stars.

complex dimming event profiles, and the overall color-evolution of the variable. **Our program will be the first to place meaningful upper limits to possible detection rates of technosignatures. We will develop a catalog of possible signals in the theme of duration, depth, color, and shape**.

This document is part of the Optical SETI Roadmap document.

In the following sections, we discuss the overall themes and work plan as part of our anomalous variability search using time-domain surveys. The proposed sections will be part of the lead author's Ph.D thesis.

- Build upon the methods for systematically detecting outliers (Giles and Walkowicz, 2019), and using new methods for comparing variability across the color-magnitude diagram, carry out the most comprehensive search for rare or unique stars to date in the ZTF public survey
- Incorporate established methods to search for technosignature candidates, including searching the "SETI Ellipsoid", the "Earth Transit Zone", and for disappearing stars
- Prototype and implement a real-time technosignature alert-based anomaly detection and follow-up strategy for the forthcoming Rubin observatory alerts
- Create an extensible, general-purpose technosignature and outlier software framework, which can be built upon to search for new or novel signal types in future surveys

## 1.1 Pilot Study and Early Preparation

In preparation for the forthcoming LSST, Gaia DR4, and other future releases the opportunity to search for anomalous stellar variability.

The search for anomalous time series can be conducted now with available TD data. We propose to start with a pilot study of $5{\times}10^6$ ZTF light curves selected from F0-F9 possible dwarf candidates using the ZTF & Gaia DR3 synergy.

With the onset of ZTF Data-Release 18[2], the opportunity exists to test extensively.

Our efforts to characterize anomalous stellar variability have already begun with a subset of possible F0-9 dwarf star candidates selected from the Gaia DR3 color-magnitude diagram. Our simple selection criteria alone contain over 1.5 million stars that could be extensively tested for anomalous variability, and perhaps searching for

[2] https://irsa.ipac.caltech.edu/data/ZTF/docs/releases/dr18

### 1.1.1 Access to Modern Time-Domain Surveys

Our home institution provides strong expertise in both algorithms and tools for accessing and processing heaps of time-domain data from large surveys such as Astronomy eXtensions for Spark (AXS) (Zečević et al., 2019).

## 1.2 Open-Source Tools

Upon the successful identification of possible **Anomalous Targets of Opportunity** (ATO), we will require a strong suite of tools to provide a rapid assessment of stellar classification, including the identification of fundamental stellar parameters. Here is a short but not fully complete list of tools: SNAD, AstroARIADNE, VOSA, MESA, STARHorse, IR-excess techniques, spectro-template matching, CLOUDY, batman.

### 1.2.1 Observing Programs and Capabilities

Upon the successful identification of possible **Anomalous Targets of Opportunity** (ATO), follow-up capabilities will enable reliable identification, classification, and further examination of identified variable sources. In particular, optical and near-IR medium-resolution spectroscopic follow-up capabilities can be used as a diagnostic tool to differentiate anomalous candidates from other stochastic variables such as Young Stellar Objects (YSO), Cataclysmic Variables (CVS), and R Coronae Borealis (RcB) stars.

As part of our recommended program, both authors will have regular observing programs allocated on the Apache Point Observatory (APO) 3.5m telescope for regular follow-up. We will use pyKOSMOS for rapid spectroscopic assessment. The authors will apply for allocated time in southern-hemisphere-based observatories for...

As a result of our complementary spectroscopic campaign, upon the approval of the Breakthrough Listen project, all spectra can be released publicly either via the Transient Naming Server (TNS), The Astronomer's Telegram (ATel), or other related services that can enable future studies of our targets,

## 1.3 Algorithms and Limits

In this part of our proposed work, we aim to establish a strong understanding of the limit of our algorithms, including simulated data, and the sensitivity of possible technosignature outlier signals we might be capable of finding. The work presenter here will provide a comprehensive examination and detection limit for the most rich time-domain catalogs such as ZTF, LSST,...

Preliminary

- Injection and recovery analysis for sensitivity estimations using emulated technosignature searches via time-domain schedulers such as LSST OPSIMS, ZTF...
- Period synchronization search in the era of LSST, ZTF, TESS (for example; Nillpour + 2023; *Signal Synchronization Strategies and Time Domain SETI with Gaia DR3*)- via Lomb-Scargle Periodogram - we have the sensitivity and algorithms to test this and report limits. For example, Tzanidakis et al. (dmtn-221) Signal Synchronization Strategies and Time Domain SETI with Gaia DR3 have shown the ability to perform an LSST-scalable approach for recovering significant periods for a large volume of data.

  For example, the lead author has already shown in dmtn-221 has shown the ability to do such work.
- Volume sensitivity function enabled through the big surveys.
- we can generate a grid of interesting light curve with (SHADOW IMAGING OF TRANSITING OBJECTS - Sandford and Kipping, Arnord 2015)

## 1.4 `ASTRA-VAR`: A Census for Anomalous Temporal Stellar Variability using Time-Domain Surveys

A complete and robust search for anomalous stellar variability will be performed with our newly developed anomaly detection outlier time series algorithm. There are several surveys we can explore the use of our algorithms: ZTF DR19, Gaia DR4, and unWISE. All work with prepare for the next generation of the truly exceptional volume of data from the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), and Gaia DR4[3] that includes the full astrometric, photometric, and radial-velocity catalogs and all epochs and transit data for all sources

The search fast-slow variability that does not fall within the normal boundaries of stellar variability...

[3]Not before the end of 2025

# 2 Outreach and Community Impact

## 2.1 Undergraduate Research

Undergraduate research opportunities are the pillars for inspiring students to pursue careers in STEM. Our proposal has a plethora of SETI-related research projects aimed at all levels of undergraduate career and experience. The skills acquired from our research projects can drastically vary depending on the interest of our students and their level of involvement. For example, projects with a concentration on algorithms and big-data, observational astronomy, and data reduction, and computational work. We strive to expand the diversity of our projects such that it directly matches the interests of our students. Most importantly, our program is committed to prioritizing students from marginalized communities and first-generation college students. This will be achieved directly in partnership with faculty and staff with a specific focus on Diversity, Equity, Inclusion, and Accessibility (DEIA), and our in-house outreach and DEIA committee.

## 2.2 Public Series *Astrobiology and SETI: Are We Alone in the Universe?*

Both authors lead substantial outreach efforts at the University of Washington in the Department of Astronomy. The primary author, A. Tzanidakis, serves as the director and program coordinator for the University of Washington's Astronomy Planetarium and is a co-leading member of the UW Astronomy outreach initiative. **As part of our Breakthrough Listen program, we aim to complement our work with a series of free public talks, planetarium shows, and public observing sessions with a focus on time-domain astronomy and SETI to the greater Washington community**.

Our home institution currently has all the tools and programs in place for such specialized programs. For example, In 2020, our program was successfully awarded over \$70,000 grant from the University of Washington Student Technology Fund (STF), updated with the state-of-the-art 4k projectors system[4]. Our planetarium currently operates on the World Wide Telescope (WWT) (Goodman et al., 2012) platform that enables data-driven astronomical 3D visualizations to create stunning planetarium programs. Other data-driven outreach media include the sonification time-series data (Zanella et al., 2022) by expanding the accessibility of media during our shows. Our suggest program can also be expanded to reach beyond the local Seattle vicinity with the UW Mobile Planetarium[5].

Similarly, A. Tzanidakis was a co-investigator in collaboration with the undergraduate Astronomy club (League of Astronomers[6]; LOA) for the successful application of another STF proposal over \$18,000 for an H-$\alpha$ solar telescope that can be used as part of this program for daytime solar observations with the public. This will also be reinforced with our in-house telescope gear in partnership with the on-campus Jacobsen Observatory [7].

## 2.3 Enabling Broad Interdisciplinary Collaborations

The Search for Extraterrestrial Intelligence in the context of our program is inherently interdisciplinary. The temporal evolution of astrophysical sources is complex that requires a suite of tools and understanding spanning from data science, statistics, and overall expertise in many domains of astrophysics such as transients, AGN, and various other sub-fields of TDA. The authors propose a journal-club equivalent meeting that will focus on the search for technosignatures. The focus of the meetings will successfully allow all academically staged students and faculty to engage with the SETI literature, but most importantly facilitate collaboration with others. The meetings will be advertised beyond the Astronomy department such as the Astrobiology (AB) division, Earth and Atmospheric Sciences (EAS), and statistics.

# 3 Summary Timeline

The corresponding lead author, A. Tzanidakis, will be entering his 3$^{\text{rd}}$ year of graduate studies at the University of Washington (UW). Here we summarize a rough timeline of the proposed research:

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| Phase | Timeline | Goals and Milestones |
| --- | --- | --- |
| Pilot Study | Year 1 | • Assemble tools and data products used for the program<br>• ApJL paper submission for *Search for F-Type Main Sequence KIC 8462852 Analogs with the Zwicky Transient Facility and Gaia DR3* (**Tzanidakis** et al. in-prep)<br>• Target of Opportunity (ToO) proposals with APO/Gemini S (for later), ATA radio observatory follow-up ...<br>• Compile a census of **anomalous** stellar variability patterns: *duration*, *depth*, *light curve shape*, *color* with ground based data<br>• Applying to NSF for the Search Anomalous Stellar Variability in the Rubin Era<br>• Can we establish an upper limit with ZTF a boundary condition/limits we can use the alert framework to find anomalous events in *gri*. Needs to be deployed on the alert brokers in $\sim 2$ years. |
| Algorithms & Limits | Year 2 | • Collaboration with Rubin/LSST `OpSims` simulations to place meaningful upper limits on the search for optical technosignatures through stellar variability<br>• Estimate upper limit of detectability of megastructures induced variability with most modern surveys: ZTF, SDSS, LSST, and Gaia<br>• How would our detection rates change if we wanted to work with alerts? Can we enable the first real-time search for technosignatures through alert-based classifiers?<br>• Signal synchronization upper limits with LSST and other surveys. *Spatio-Temporal Signal Synchronization for the Search of Technosignatures using Time-Domain Surveys. Deploying the ellipsoid at scale for Rubin. ElaSTICC technosignature for Andy Nilipour et al. (including Davenport, Tzanidakis, Croft)*<br>• Development of open-source tool `Astra-Var` extensive time series tools for enabling robust anomaly searches with sparse multi-band data<br>• Student project ideas for undergraduate researchers & post-bacc., explore some of the exotic ideas for spatiotemporal ideas, look for VASCO's... |
| Systematic Search | Year 3-4 | • **The big search**. Using our pilot program, limits, and newly developed algorithms let's search for technosignatures: ZTF DR19, SDSS, Gaia DR4, and LSST<br>• Enable auxiliary stellar variability estimates. After the completion of this project, our study will have the largest temporal characterization of stellar variability with a sampling cadence of 3-7 days. Could be also used for future studies to enable robust classification and for more anomaly searching in alerts. |