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# Roman CCS White Paper

## Asteroseismology with the Roman Galactic Bulge Time-Domain Survey

**Scientific Categories:** Stellar physics and stellar types; Stellar populations and the interstellar medium

**Principal Authors:**
Daniel Huber, University of Hawai'i (huberd@hawaii.edu) & University of Sydney
Marc Pinsonneault, Ohio State University (pinsonneault.1@osu.edu)

**List of contributing authors :**
Paul Beck, Universidad de La Laguna & Instituto de Astrofisica de Canarias
Timothy R. Bedding, University of Sydney
Joss Bland-Hawthorn, University of Sydney
Sylvain N. Breton, INAF, Osservatorio Astrofisico di Catania
Lisa Bugnet, Institute of Science and Technology Austria ISTA
William J. Chaplin, University of Birmingham
Rafael A. García, Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM
Samuel K. Grunblatt, Johns Hopkins University
Joyce A. Guzik, Los Alamos National Laboratory
Saskia Hekker, Heidelberg University & Heidelberg Institute for Theoretical Studies (HITS)
Steven D. Kawaler, Iowa State University
Stéphane Mathis, Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM
Savita Mathur, Instituto de Astrofísica de Canarias & Universidad de La Laguna
Travis Metcalfe, White Dwarf Research Corporation
Benoit Mosser, LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris
Melissa K. Ness, Columbia University & Center for Computational Astrophysics
Anthony L. Piro, Carnegie Observatories
Aldo Serenelli, Instituto de Ciencias del Espacio (ICE, CSIC)
Sanjib Sharma, Space Telescope Science Institute
David R. Soderblom, Space Telescope Science Institute
Keivan G. Stassun, Vanderbilt University
Dennis Stello, University of New South Wales
Jamie Tayar, University of Florida
Gerard T. van Belle, Lowell Observatory
Joel C. Zinn, California State University, Long Beach

**Abstract:** Asteroseismology has transformed stellar astrophysics. Red giant asteroseismology is a prime example, with oscillation periods and amplitudes that are readily detectable with time-domain space-based telescopes. These oscillations can be used to infer masses, ages and radii for large numbers of stars, providing unique constraints on stellar populations in our galaxy. The cadence, duration, and spatial resolution of the Roman galactic bulge time-domain survey (GBTDS) are well-suited for asteroseismology and will probe an important population not studied by prior missions. We identify photometric precision as a key requirement for realizing the potential of asteroseismology with Roman. A precision of 1 mmag per 15-min cadence or better for saturated stars will enable detections of the populous red clump star population in the Galactic bulge. If the survey efficiency is better than expected, we argue for repeat observations of the same fields to improve photometric precision, or covering additional fields to expand the stellar population reach if the photometric precision for saturated stars is better than 1 mmag. Asteroseismology is relatively insensitive to the timing of the observations during the mission, and the prime red clump targets can be observed in a single 70 day campaign in any given field. Complementary stellar characterization, particularly astrometry tied to the Gaia system, will also dramatically expand the diagnostic power of asteroseismology. We also highlight synergies to Roman GBTDS exoplanet science using transits and microlensing.

## 1 Background & Motivation

Asteroseismology – the study of stellar oscillations – has been revolutionized by space-based time domain surveys such as CoRoT, Kepler/K2, and TESS. It has led to major breakthroughs in stellar astrophysics such as the discovery of rapidly rotating cores and magnetic fields in evolved stars [1, 2, 3, 4] and the systematic measurement of stellar masses, radii, and ages [5]. While the discussion here focuses on stochastically-excited solar-like oscillators, many of these processes can also be probed in classical pulsators such as OB stars, Cepheids, RR Lyrae and $\delta$ Scuti stars [6, 7, 8], providing a window into not only stellar physics, but galactic astronomy and – through contributions to understanding the distance ladder – to cosmology.

Asteroseismology of red giants is a particularly powerful tool for studying stellar populations. This is because red giants oscillate with $\gtrsim 0.1$ mmag amplitudes and periods of hours to days, allowing detections with moderate cadence and photometric precision out to large distances. Global frequency properties can be used to infer masses, ages, and evolutionary states for large numbers of giants [9, 10]. Kepler asteroseismology was used as a fundamental calibrator in spectroscopic surveys [11] and Gaia [12], yielded age estimates of nearby thin and thick disc stars [13], and has been used to age-date mergers of dwarf satellites [14]. It also uncovered unexpected populations, such as massive stars – typically an indication of youth – that have high alpha-capture to iron – typically, an abundance pattern indicating old age [15]. While the origin of this population is contested [16], it provides an example of the value of asteroseismology for population studies.

However, asteroseismology has so far sampled only a limited portion of the galaxy. The seminal Kepler field is relatively nearby, and red giants had a complex selection function [17]. The K2 mission covered populations along the ecliptic plane, but with a relatively modest total sample size and depth [18, 19]. TESS provides an all-sky survey that is large but shallow [20] due to the small aperture. No space-based asteroseismic survey has so far sampled the crowded and distant stellar populations in the Galactic bulge. The bulge harbors a unique population born with high star formation efficiency in the earliest phases of Galactic evolution [21]. Much of what we do not know about the formation of the Milky Way stems from our current inability to probe stellar populations in the inner Galaxy, which harbors a non axisymmetric bar whose chemodynamical evolution is complicated and poorly understood. Exploring how the structure, kinematics and chemistry of the inner Galaxy depends on age offers a way to unlock its formation history. The bulge is also the closest analog to the spheroidal populations of other disk galaxies and entire elliptical galaxies, and thus will aid in understanding star formation in high-redshift galaxies currently studied with JWST. **The Roman Galactic Bulge Time Domain Survey (GBTDS) provides the first opportunity to apply the powerful tool of asteroseismology to measure masses and ages of stellar populations in the galactic bulge.** It will also serve as an important precursor for planned dedicated space-based asteroseismology missions in dense stellar environments [22].

Figure 1 illustrates the potential of the Roman GBTDS for red giant asteroseismology. The Roman yield was estimated with a Galaxia simulation [23] of a 2.8 square degree FOV (corresponding to ten pointings) centered at (l,b)=(0.5,-1.5), using a photometric precision ($\sigma$) model for saturated stars [24], scaling relations for oscillation amplitudes ($A$) [25, 26] and requiring $\mathrm{SNR} = \mathrm{A}/(\sigma/\sqrt{\mathrm{N}}) > 15$ with $N = 41472$ for six 70-day long campaigns with 15 minute cadence. Roman will for the first time perform space-based asteroseismology towards and beyond the galactic center, and is expected to increase the current yield by at least one order of magnitude ($\approx 6 \times 10^5$ detections).

## 2 Science Requirements

### 2.1 Photometric Precision

Oscillation amplitudes increase linearly with luminosity, ranging from a few parts per million in the Sun to a few percent at the tip of the red giant branch. Photometric precision is the primary driver for the feasibility of asteroseismology, and in most cases is more important than cadence for a fixed photon noise.

A large fraction of red giants in a given stellar population are Helium-core burning ("red clump") stars, a long-lived phase of stellar evolution following the tip of the red giant branch. A red clump star in the galactic bulge has $H \approx 13$ mag and thus will saturate the Roman detector in a single read. Techniques developed for saturated star photometry with Kepler/K2 [27] will not be directly applicable to Roman due to the different behaviour of H4RG detectors. Photometric precision estimates for saturated stars with Roman either assume a nominal noise floor of 1 mmag / 15-min cadence [28, 29, 30], or that the precision improves for brighter stars with careful modeling of the wings of the PSF [24]. Figure 2 shows a simulated red clump star power spectrum using the original Kepler data and different assumptions for photometric precision. Oscillations are clearly detectable ($\mathrm{SNR} \gtrsim 15$) with the improved saturated star precision, but become nearly undetectable ($\mathrm{SNR} < 10$) with a nominal noise of 1 mmag/15-min, which would reduce the yield by a factor of 3. Assuming a strategy where Roman can observe fields twice as fast (and thus increase the nominal precision by a factor $\sqrt{2}$) nearly compensates for the SNR loss and would result in a similar yield as with improved saturated star precision, partially because of additional detections for non-saturated stars.

**We conclude that asteroseismology of red giant stars using the GBTDS requires a minimum photometric precision of 1 mmag / 15-min or better for saturated stars.** Investigations of saturated star photometry will be critical for the success of GBTS asteroseismology.

### 2.2 Observing Cadence, Field Selection, and Filters

Oscillation periods scale inversely with surface gravity, ranging from 5 minutes in Sun-like stars to weeks and months for evolved red giants. The nominal 15 min GBTDS cadence yields a Nyquist frequency of 560 $\mu$Hz, which is sufficient for stars in and above the red clump as well as most other pulsators, except compact pulsators (e.g. hot subdwarfs and white dwarfs) and rapidly oscillating Ap stars. The upper cadence limit for red-giants is 30 min, corresponding to a Nyquist frequency at the base of the red-giant branch.

Asteroseismic inference is often divided into “global asteroseismology”, which involves the determination of stellar radii, masses and ages, and “boutique asteroseismology”, which aims to infer interior properties such as rotation. The latter will not be feasible with Roman given time baseline limitations, and require a dedicated asteroseismology mission in crowded fields such as HAYDN [22]. The former is sufficient to study stellar populations, and relies on sampling a large area to probe the formation history of our galaxy. Recent results using luminous giants from ground-based surveys have demonstrated the strong potential to study the galactic bulge, providing the first kinematic map of the far side of the galactic bar [31] (Figure 3). However, ground-based surveys only reach very luminous stars for which asteroseismic mass and age measurements are not possible. Roman will extend this success by enabling mass and age measurements over similar distance ranges (see Figure 1). **Increasing the number of fields observed by the Roman GBTDS would significantly enhance the asteroseismic science yield.** For example, additional fields covering a range longitudes will help explore the horizontal structure of the non-axisymmetric bar and fields at a wider range of latitudes would provide insights into the vertical structure of stellar populations in the bulge.

Red giant asteroseismology is relatively insensitive to the timing of the GBTDS campaigns throughout the mission. However, pulsation timing for classical pulsators such as $\delta$ Scuti stars [32, 33] would benefit from having campaigns spaced as widely in time as possible.

Oscillation amplitude increases for blue wavelengths [34]. Compared to Kepler, oscillation amplitudes decrease by $\approx 65\%$ in the Roman F149 filter [24]. Detecting oscillations in multiple passbands can be used for mode identification, which is important for classical pulsators. Observing the same fields in multiple filters thus provides benefit for the time-domain study of classical pulsators ($>1.3\,M_{\odot}$), but overall has lower priority than increasing the number of fields.

### 2.3 Astrometry and Saturated Star Photometry

Global asteroseismology collapses the oscillation spectrum into two properties: the frequency of maximum power $\nu_{\max}$ and the average frequency spacing $\Delta\nu$. When combined with $T_{\mathrm{eff}}$ and abundances, these data can be used to infer mass, radius, and age. However, we will be able to measure $\nu_{\max}$ for many more targets than those for which $\Delta\nu$ can be measured. Fortunately, there is an alternative: one can combine an independent radius with $\nu_{\max}$ to infer mass without $\Delta\nu$. Radii can be inferred from a combination of Gaia luminosity and $T_{\text{eff}}$. The resulting mass uncertainties are competitive with those from full asteroseismic characterization [35]. In the bulge, extinction map uncertainties in the optical will result in large errors in Gaia luminosities. However, idifferential Roman astrometry could be used to infer precise relative parallaxes [24]; when tied to the Gaia system, this could be translated to precise radii. Since red clump stars have similar intrinsic $T_{\text{eff}}$, their radii can be inferred even without detailed spectroscopic data.

Red clump stars are saturated at the distance of the Galactic center, which could be used to centroid images using diffraction spikes [24]. **Both the detection of oscillations and precise Roman parallaxes will therefore benefit from an emphasis on precise and accurate saturated star astrometry and photometry.**

## 3 Synergies with Exoplanet Science

### 3.1 Characterization of Stellar Populations for Transiting Exoplanet Demographics

The Roman GBTDS will detect tens of thousands of transiting exoplanets [28, 30]. Because most asteroseismic detections will be in red clump stars, stars with detected oscillations and transiting planets will be rare. However, GBTDS asteroseismology will constrain the underlying stellar population in the galactic bulge, which will be important for interpreting the exoplanet yield. For example, the demographics of transiting exoplanet hosts (such as their distances and association to the thin and thick disc populations) will be sensitive to the importance of host star abundances on planet formation [30]. Asteroseismology will complement this by mapping the mass and age distributions of the bulge, thin disc, and thick disc populations in the same galactic regions where transiting exoplanets will be found.

### 3.2 Characterization of Microlensing Lens and Source Stars

Characterizing exoplanets using microlensing requires knowledge of distances to the lens and the source stars. Distances to source stars are typically assumed since in most cases the lens and source star cannot be resolved. In some cases, however, the source star will be an evolved red giant, which will result in oscillation signal in the microlensing light curve. Stellar oscillations can be used to derive precise distances by constraining the luminosity, and thus help constrain the properties of planets detected using microlensing. First detections have already been made using OGLE (Figure 4) [36]. **Time-domain stellar variability from oscillation and granulation imprinted on microlensing light curves may allow the systematic characterization of lens and source stars in microlensing detections with the Roman GBTDS.**

## 4 Conclusions

There are strong links between the goals for exoplanet demographics and asteroseismology with the Roman GBTDS. The most natural linkage is the study of red clump (core He-burning) stars in the Galactic bulge.

Relative to microlensing studies, asteroseismology is more sensitive to photometric precision, and prime asteroseismic targets will likely be saturated at the distance of the Galactic center. As a result, controlling photometric noise at the level of 1 mmag/15-min cadence or better is a key scientific requirement for Roman GBTDS asteroseismology. If saturated star photometry is limited to 1 mmag/15-min cadence, observing the nominal fields at higher cadence will be important to reduce noise. If saturated star photometry performs better than 1 mmag/15-min cadence, observing additional fields will increase the scientific yield by probing additional stellar populations. The minimum cadence requirement is 30 minutes.

A second synergy is precise and accurate astrometric data for saturated stars. In particular, tying relative Roman astrometry to the Gaia system is a promising approach that could yield reliable mass estimates for low signal to noise asteroseismic detections. The requirements for red giant asteroseismology with the Roman GBTDS will map to most other types of pulsators in the H-R diagram. Asteroseismology will also provide natural synergies with exoplanet science, including both a deeper understanding of the underlying stellar populations and the characterization of lens and source stars in microlensing events.

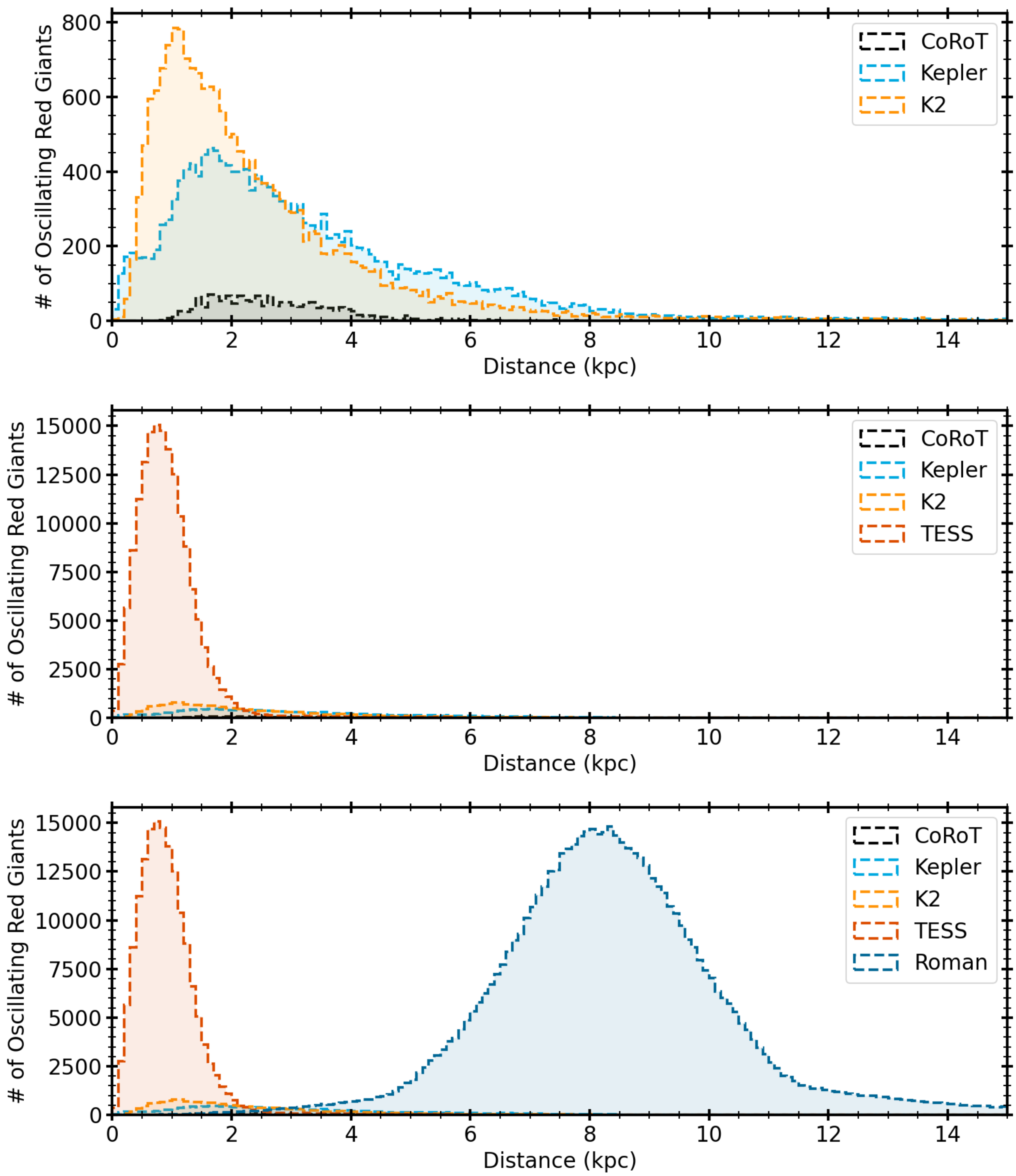


Figure 1: Distances of red giants with detected solar-like oscillations from space-based telescopes. Top panel: asteroseismic red giant yield from CoRoT ($\approx$ 2000 stars) [37], Kepler ($\approx$ 16000 stars) [38] and K2 ($\approx$ 20000 stars) [19]. Middle panel: same as top panel but adding the first all-sky asteroseismic yield from TESS (160,000 stars) [20]. Bottom panel: same as middle panel but adding the expected yield from the Roman GBTDS ($\approx$ 600,000 stars) assuming photometric noise performance from Gould et al. [24].

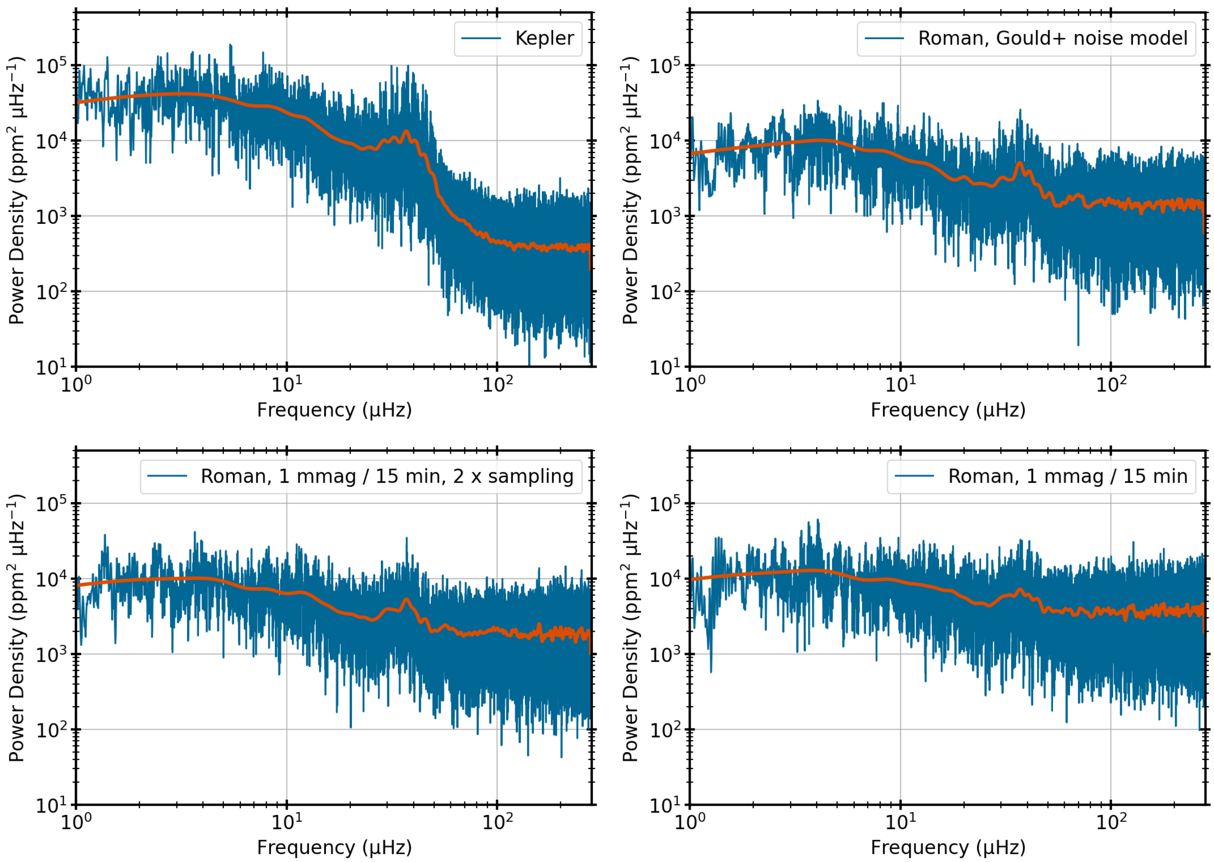


Figure 2: Power spectrum of the oscillating red clump star KIC 2836038 observed by the Kepler space telescope using a nominal Roman GBTDS pointing strategy (six 70 day campaigns with 15 minute cadence, 3 campaigns at the start and 3 campaigns at the end of a 5-year period). Top left: original Kepler data (SNR$> 300$). The power excess at $30-40\mu$Hz is due to solar-like oscillations. Top right: Simulated Roman power spectrum assuming the photometric noise performance following Gould et al. [24] (SNR$\approx$ 15). Bottom left: Same as top right but assuming nominal saturation noise (1 mmag/15-min) but a twice faster sampling strategy (SNR$\approx$ 12). Bottom right: Same as top right but assuming nominal saturation noise (1 mmag/15-min) and cadence (SNR$\approx 9$). Power spectra were smoothed with a Gaussian filter with a width of 0.001 $\mu$Hz (blue) and 1 $\mu$Hz (red). The total expected yield for each noise scenario using a full synthetic stellar population (see bottom panel of Figure 1) is $6 \times 10^5$ stars (top right and bottom left panel) and $2 \times 10^5$ stars (bottom right panel).

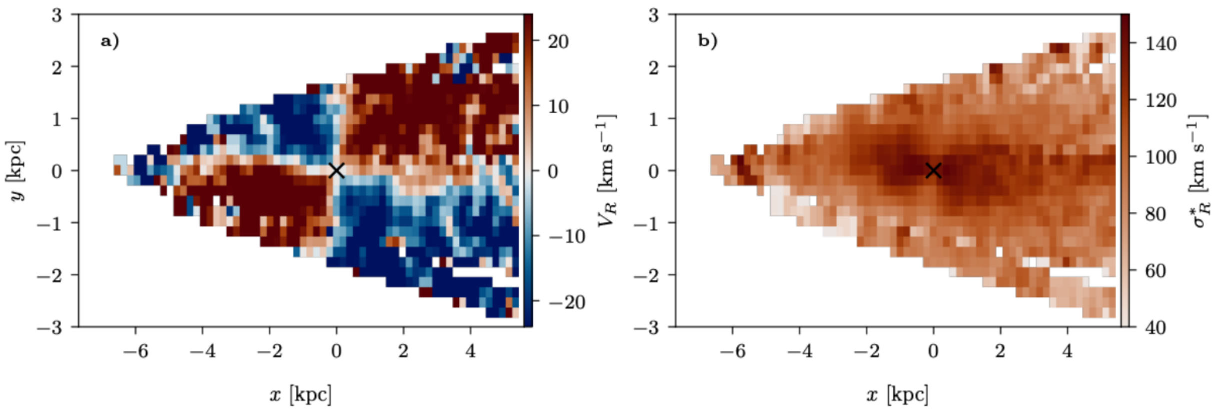


Figure 3: From Hey et al. [31]: the first kinematic map (left: radial velocity; right: velocity dispersion) of the far side of the galactic bulge revealed by combining asteroseismic distances to luminous red giants observed by OGLE with Gaia DR3. The quadrupole pattern is the kinematic signature of the galactic bar. The Roman GBTDS will increase this sample in more extincted regions and provide masses, radii and ages that cannot be derived for the luminous giants for which oscillations can be detected from the ground.

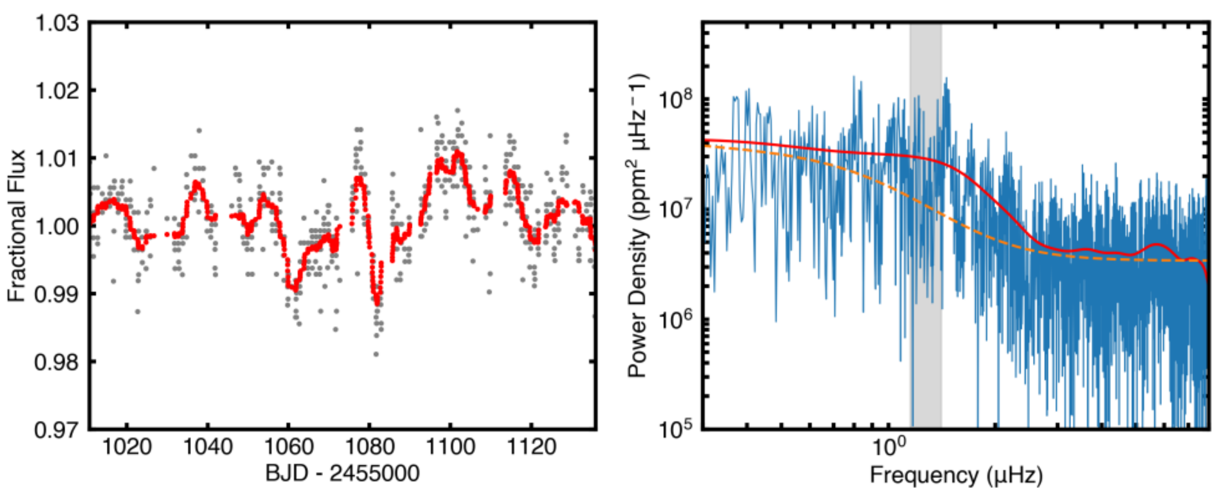


Figure 4: From Li et al. [36]: the first application of asteroseismology for a source star of a microlensing event. Left: portion of the OGLE light curve showing the oscillation signature of the source red giant. Right: Power spectrum showing the oscillation excess centered at $\approx 1\mu$Hz. The red line is a heavily smoothed power spectrum and the orange dashed line is the background model. The oscillations were used to calculate an independent distance to the source star.

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