

Identification and characterization of 15 265 super-Nyquist frequencies in 1309 δ Scuti stars from *Kepler* photometry

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ABSTRACT

The frequency of the pressure (p) mode in δ Scuti stars can exceed the Nyquist limit of *Kepler* long-cadence photometry. These “super-Nyquist frequencies” (SNFs) are observed as “reflected” peaks at lower frequencies, i.e., they are Nyquist aliases that pose a threat to asteroseismic diagnostics. Their impact on δ Scuti p modes has yet to be comprehensively explored. We performed a systematic survey to search for SNFs in 1838 *Kepler* δ Scuti stars through a novel technique based on a sliding Lomb-Scargle periodogram, identifying 15 265 confirmed SNFs in 1309 stars, from a total of 259 883 frequencies. We observe that the total number of detected frequencies per star remains featureless across the δ Scuti instability strip; however, young stars pulsate in higher frequencies and so have significantly more SNFs on average. Both the number and the rate of SNFs diminish accordingly as δ Scuti stars become more evolved, which is consistent with both observation and stellar models. Furthermore, our method detects a greater fraction of modes as SNFs at higher frequencies, rising from approximately 1% at 20 μ Hz to 23% at the Nyquist limit. The rate of underdetection is highest amongst low-amplitude modes. The SNF modulation patterns can be well distinguished from phase modulations induced by binarity or nonlinear mode interactions. We provide a frequency catalog for future asteroseismic studies of δ Scuti stars, wherein we identify each peak as being real or an alias, enabling further investigations into regular patterns of pulsation modes, linear combination frequencies, and theoretical modeling.

Key words. asteroseismology – methods: statistical – techniques: photometric – catalogs – stars: oscillations – stars: variables: δ Scuti

1. Introduction

Asteroseismology, a unique technique for probing the internal structures of stars through pulsation modes, is now applied to various types of stars across the entire Hertzsprung-Russell diagram (see, e.g., Aerts 2021; Kurtz 2022). As one of the popular classes of pulsators, δ Scuti stars are numerous and typically exhibit relatively high amplitudes. These intermediate-mass stars typically have masses of 1.5–2.5 $M_{\odot}$ and effective temperatures of $T_{\text{eff}} \approx 6400$ –8600 K, lying at the intersection of the classical instability strip and the main sequence (Breger 2000; Rodríguez & Breger 2001). Their pulsations are driven by the κ mechanism operating in the He II ionization zone, which primarily excites low-order pressure (p) modes with typical periods ranging from ~ 15 min to 5 h. In addition to these p modes, many δ Sct stars also exhibit low-frequency gravity (g) modes and, in more evolved objects, mixed modes that display g-mode sensitivity near the core and p-mode characteristics near the surface (Osaki 1975; Balona & Dziembowski 2011).

Before space photometry, the discovery of δ Scuti stars from ground-based observations led to progress in mode identification and stellar modeling, although it was hindered by daily aliasing and poor frequency resolution (see, e.g., Watson 1988;

Breger & Pamyatnykh 1998; Balona & Evers 1999; Rodríguez & Breger 2001). These photometric limitations were partially ameliorated by observations from multisite networks or Antarctica (see, e.g., Handler et al. 2000; Breger et al. 2005; Zong et al. 2015), which provided richer pulsation spectra with improved frequency resolution. Subsequently, spaceborne photometry initiated a new era for the asteroseismology of δ Scuti stars, revealing a wealth of low-amplitude frequencies with sharp frequency resolution (see, e.g., Poretti et al. 2009; Balona 2014).

The Kepler and Transiting Exoplanet Survey Satellite (TESS) missions have collected high-quality photometry for thousands of δ Scuti stars (Borucki et al. 2010; Uytterhoeven et al. 2011; Ricker et al. 2015; Grootkin et al. 2024; Zhou 2025), brought advances in linear asteroseismology regarding pulsation properties. For example, δ Scuti stars have been found to exhibit regular frequency spacings (Antoci et al. 2011; Bedding et al. 2020), possess a remarkably high fraction of additional low-frequency g modes (Balona 2014), and reveal statistical relations in period-luminosity (Barac et al. 2022) and frequency patterns dependent on stellar parameters (Bowman & Kurtz 2018; Barceló Forteza et al. 2018). Their instability strip can now be better constrained through observational efforts (Murphy et al. 2019; Grootkin et al. 2024). Furthermore, their frequency properties are valuable for constraining physical processes involving

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stellar rotation (Ramón-Ballesta et al. 2021), magnetic fields (Neiner & Lampens 2015; Zwintz et al. 2020), and tidal interactions (Handler et al. 2020; Rappaport et al. 2021). These stars may reside in binary systems (Chen et al. 2022), which is essential for understanding mass-transfer processes (Guo et al. 2017), or be located in open clusters, allowing for precise age dating (Pamos Ortega et al. 2022; Bedding et al. 2023). Moreover, artificial intelligence has been introduced into δ Scuti studies for tasks such as light curve identification (Barbara et al. 2022), emulating model grids (Scutt et al. 2023), and classifying island modes (Mirouh et al. 2019).

Beyond these advances in pulsation properties, *Kepler* and TESS opened new avenues for characterizing temporal variations of pulsation amplitude and phase. Shibahashi & Kurtz (2012) proposed a theoretical framework for detecting orbital companions via frequency modulation, and determining their orbital parameters (Shibahashi et al. 2015), which was subsequently adapted to discover hundreds of new binaries via pulsation timing in *Kepler* A/F pulsators (Murphy et al. 2018). Regarding amplitude variation, Breger & Montgomery (2014) and Barceló Forteza et al. (2015) observed clear correlations between three interacting modes, interpreting them as non-linear resonant couplings. This phenomenon was found to be common following a survey of large-amplitude pulsations in 983 δ Scuti stars (Bowman et al. 2016). Notably, geometric effects in binary systems can induce amplitude modulation of δ Scuti pulsations, over short timescales (see, e.g., Kurtz et al. 2020). Recently, amplitude and phase modulations have gained increasing attention in δ Scuti studies, as the diversity in modulation patterns remains not fully understood (see, e.g., Niu et al. 2023).

Crucially, some pulsation modes in δ Scuti stars can exceed the Nyquist frequency of the *Kepler* long-cadence (LC) photometry (Murphy et al. 2013). In this regime, reflected alias signals show characteristic amplitude and phase modulation caused by the sampling process (Murphy et al. 2014; Bowman et al. 2016). These high frequencies, when aliased to lower frequencies by the Nyquist limit, are termed super-Nyquist frequencies (SNFs). The modulated time sampling of *Kepler* data introduces distinctive multiplet patterns in the periodograms of reflected frequencies (Murphy et al. 2013), while barycentric time corrections induce periodic amplitude and frequency modulations that serve as diagnostic features of SNFs (Zong & Charpinet 2021). Leveraging these characteristics, Wang et al. (2025) proposed a time-dependent analysis to identify SNFs using the sliding Lomb–Scargle periodogram (sLSP). Their simulations confirmed the feasibility and computational efficiency of this method, subsequently applying it to 611 γ Doradus stars, which raised a cautionary note that hybrid p modes could be aliased frequencies mixed with SNFs up to $\sim 7\%$. Following this, Yang et al. (2025) extended the approach to δ Sct stars, analyzing 1400 frequencies in 68 targets from the literature and distinguishing six previously unknown reflected SNFs.

However, a systematic survey of SNFs across the entire δ Sct population has yet to be explored. To address this, we apply the sLSP technique to 1838 δ Sct stars from the prime *Kepler* photometry, based on an automated implementation to upgrade the sLSP workflow. The structure of this paper is organized as follows. Section 2 describes the data and the automated pipeline used to identify SNFs. Section 3 presents the main results of the survey, including the statistical distribution and physical implications of SNFs in δ Sct stars. Finally, Section 4 discusses these findings and summarizes the main conclusions of this work.

2. Data and methods

The *Kepler* Mission provides high-precision, nearly continuous photometry that is ideal for δ Sct studies. Observations are organized into quarters (Q0–Q17), which were typically about three months long and separated by $\sim 90^\circ$ spacecraft rolls, with some differences at the beginning and end of the mission. The primary mission provided two observing cadences: long cadence (LC; ~ 29.4 min) and short cadence (SC; ~ 58.9 s) (Borucki et al. 2010).

In this paper, we use Q to denote these observing segments and require a sufficiently long time baseline for robust frequency analysis. We constructed our sample based on two foundational catalogs: the 983 δ Sct stars in Bowman et al. (2016) and 1988 stars in Murphy et al. (2019). After cross-matching and removing duplicates, we retained only those stars with light curves spanning more than 14 *Kepler* quarters to ensure a sufficient frequency resolution and time baseline, yielding a final sample of 1838 stars.

Photometric data for all targets were retrieved from the Mikulski Archive for Space Telescopes (MAST)¹. We primarily utilized the Pre-search Data Conditioning Simple Aperture Photometry (PDCSAP; Smith et al. 2012; Stumpe et al. 2012) light curves, which were processed by the NASA *Kepler* Data Processing Pipeline (Jenkins et al. 2010). These data were obtained in LC mode with a typical sampling interval of $\Delta t \approx 29.4$ minutes, corresponding to a Nyquist frequency of $f_{ny} \approx 283 \mu\text{Hz}$. Data processing was performed following the procedures outlined in Xing et al. (2024) and Wang et al. (2025). The light curves were initially cleaned and normalized using the *lightkurve* package (Lightkurve Collaboration 2018). For a subset of stars exhibiting poor data quality or significant contamination in the standard apertures, we downloaded the corresponding target pixel files (TPFs). For these cases, we defined custom apertures using a threshold mask within the *lightkurve* package (Lightkurve Collaboration 2018) and re-extracted the light curves; see detailed processes in Ma et al. (2023). To remove instrumental systematics and stitch the observational quarters, the light curves were detrended using the *flatten* routine from the *wotan* package (Hippke et al. 2019). This step effectively removed residual long-term trends, while preserving the intrinsic stellar variability. Finally, the cleaned and detrended light curves were analyzed using the *FELIX* software (Charpinet et al. 2010; Zong et al. 2016) to extract a comprehensive list of significant pulsation frequencies.

The barycentric time correction applied to *Kepler* photometry causes the Nyquist frequency to vary periodically with the orbital motion of *Kepler*. This effect introduces a predictable modulation pattern in the frequencies above f_{ny} , a signature addressed by Murphy et al. (2013). To capture this behavior, the sliding Lomb–Scargle periodogram (sLSP) divides the light curve into successive, overlapping time windows, computes a periodogram in each window, and then tracks the temporal evolution of each candidate peak in frequency and amplitude. Reflected SNFs are identified by their nearly periodic modulation patterns in these time series. The challenge is particularly acute in δ Scuti stars given their dense frequency spectra. Accordingly, we developed sLSP4SNFs², a robust and systematic pipeline, dedicated to the automated identification of SNFs via signatures characterized by Wang et al. (2025).

¹ <http://archive.stsci.edu/kepler/>

² <https://github.com/XuanWang-star/sLSP4SNFs>

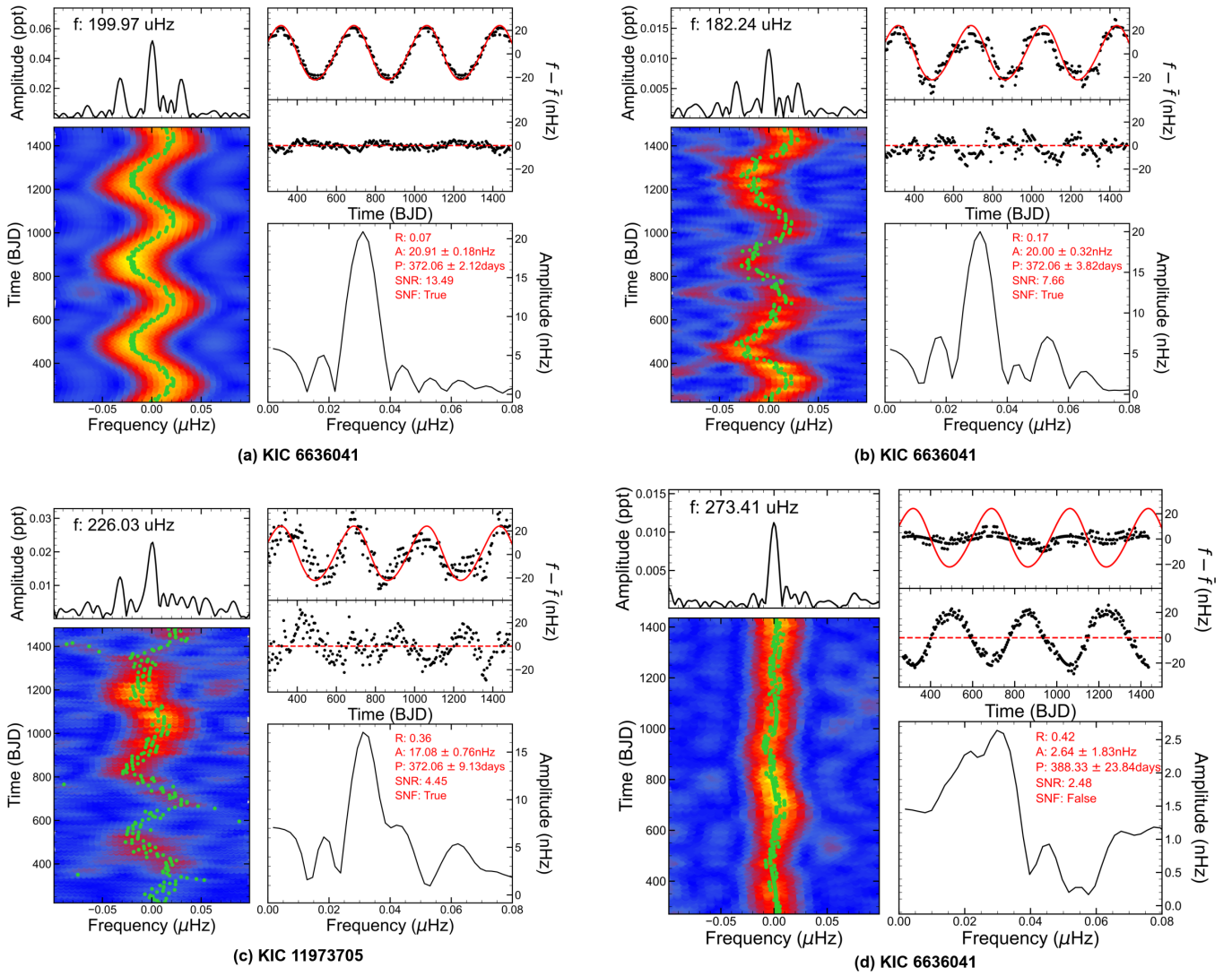


Fig. 1. Representative diagnostic plots generated by our automated pipeline. The classification results of four distinct types of candidate frequencies are shown as follows: panels (a), (b), and (d) correspond to KIC 6636041, while panel (c) corresponds to KIC 11973705. Panels (a)–(c) are classified as SNFs, whereas panel (d) is classified as not an SNF. Each diagnostic plot displays a composite of five subplots: (*top left*) The local LSP with the target frequency marked. (*bottom left*) A sliding Lomb-Scargle periodogram (sLSP) showing the time-dependent frequency behavior, with amplitude indicated by the color. The green dots mark the frequency of maximum amplitude within each LSP segment centered around that frequency at given time. (*top right*) The modulated frequency time series, $f(t)$ (black points), compared with the theoretical SNF modulation pattern derived from the spacecraft orbit (red curve). The residuals of the fit are shown in the *middle right*, marked with a dashed horizontal line at zero. (*bottom right*) The LSP of $f(t)$, annotated with the key diagnostic parameters used for classification: the residual variance (R), modulation amplitude (A_{mod}), modulation period (P_{mod}), the modulation signal-to-noise ratio (S/N), and the final automated classification flag (true or false).

The pipeline processes each star through a standardized workflow. First, candidate frequencies are selected from the FELIX list with a threshold $\text{S/N} > 8$. The nearby peaks are then consolidated using a grouping algorithm that retains only the highest- S/N component within the frequency resolution. For stars with exceptionally dense spectra, the analysis is restricted to the 1024 strongest frequencies. Each candidate is analyzed using a sliding LSP with a 200-day window (moving in 5-day steps) to produce a time-dependent frequency, $f(t)$. This window/step configuration is chosen as a practical compromise between frequency resolution and computational cost: the 200-day window provides stable local frequency estimates, while the 5-day step samples modulation with sufficient temporal density. This setup is guided by the expected SNF modulation induced by barycentric time correction (Murphy et al. 2013; Wang et al. 2025). Over

the four-year *Kepler* baseline, reflected SNFs are expected to show repeating modulation cycles, providing a practical diagnostic for identification. From this, we compute key diagnostic parameters: the modulating period (P_{mod}), amplitude (A_{mod}), signal-to-noise ratio (S/N_{mod}), and residual, R , which quantifies the goodness-of-fit between the observed $f(t)$ and the theoretical SNF modulation.

We adopted a hierarchical classification strategy to identify valid SNFs after testing the robustness of the sLSP4SNFs pipeline. We applied it to all 45 607 frequencies in γ Dor stars extracted by Wang et al. (2025), which returns 782 SNF candidates. After cross-matching with the 304 SNFs from their visual inspection, candidates that exhibited an exceptionally strong match to the theoretical expectation, defined by $R < 0.3$, were automatically accepted. For candidates with slightly higher

Table 1. SNF catalog for 1309 δ Scuti stars.

KIC	Frequency (μHz)	σ_f (μHz)	Amplitude (ppt)	σ_A (ppt)	S/N_{FELIX}	S/N_{mod}	f_R (μHz)	C	Range	SC
1026294	258.409096	0.000216	0.0108	0.0005	20.1	6.0	308.0149038	0	1	-9
1026294	250.283514	0.000007	0.4032	0.0006	653.6	16.4	316.1404861	0	1	-9
1026294	247.072167	0.000037	0.0696	0.0006	117.5	15.8	319.3518327	0	1	-9
1026294	229.689858	0.000014	0.1866	0.0006	312.5	12.3	336.7341418	0	1	-9
1026294	222.255286	0.000019	0.1288	0.0006	226.1	15.4	344.1687140	0	1	-9
1026294	218.260433	0.000136	0.0176	0.0006	32.0	10.5	348.1635669	0	1	-9
1026294	206.899067	0.000161	0.0158	0.0006	27.0	13.6	359.5249334	0	1	-9
...	...	...	...	...	...	...	...	...	...	...

Notes. Parameters include the KIC identity, pulsation frequency, and amplitude with their respective uncertainties (σ_f , σ_A), along with the detection significance (S/N_{FELIX}) derived from FELIX. S/N_{mod} represents the significance of the frequency modulation detected by our automated sLSP analysis. The real frequency above the Nyquist limit is denoted as f_R , and C is the classification flag, indicating a combination frequency (1) or an independent frequency (0). In the column Range, the Nyquist interval is inferred from amplitude ratio method: integer $n \in [1, 4]$ correspond to ranges above the Nyquist frequency of $[nf_{\text{ny}}, (n+1)f_{\text{ny}}]$, and -9 indicates no available determination from the amplitude ratio. The column SC: 1 indicates confirmation by available SC photometry, and -9 denotes no available SC photometry. See details in the text. The full catalog of 15 265 SNFs is available in machine-readable form at the CDS.

residuals ($0.3 \leq R < 0.5$), we imposed stricter criteria requiring significant modulation significance ($S/N_{\text{mod}} > 3$) and a modulation period consistent with the *Kepler* orbital year ($P_{\text{mod}} \approx 372$ d). If a candidate failed to meet these criteria using the 200-day window, the entire analysis was repeated using a 300-day window to enhance frequency resolution for weaker signals.

The sLSP4SNFs automatically generates a comprehensive diagnostic plot for each candidate, summarizing the classification metrics, and outputs a catalog of quantitative parameters. We applied this pipeline to our full sample of 1838 δ Scuti stars. Figure 1 displays representative diagnostic plots ordered by signal quality, ranging from high-confidence detections to clear non-detections. For frequencies with high S/N_{mod} , we clearly observe that our measured frequency modulation follows a pattern consistent with the numeric expectation, resulting in minimal residuals. However, in some cases, a frequency may exhibit intrinsic modulation superimposed on the SNF pattern, which requires further inspection; for instance, the frequency around 226.03 μHz in KIC 11973705 (Fig. 1c). A systematic review of these diagnostic plots indicated that candidates in the marginal regime of $S/N_{\text{mod}} \in (3, 5)$ frequently exhibited ambiguous signatures. Consequently, we implemented a final manual vetting step for all candidates in this specific S/N range to ensure the reliability of the final catalog, whereas candidates with lower S/N_{mod} were automatically discarded.

3. Results

Our automated pipeline initially identified 14 976 SNF candidates from a total of 259 883 candidate frequencies across 1838 δ Scuti stars. As established in Section 2, candidates in the low- S/N regime require manual vetting. Accordingly, all 2862 candidates with a modulation signal-to-noise ratio (S/N_{mod}) below 5 were subjected to visual inspection. This process led to the rejection of 152 unreliable detections, resulting in a high validation rate of 94.7% for our automated low- S/N classification. This yields a final, robust catalog of 14 824 confirmed SNFs in 1291 stars, demonstrating that SNFs are a common feature, present in 70.2% of the sample. Representative examples of the SNF catalog entries are listed in Table 1, while the complete catalog is available in a machine-readable format online.

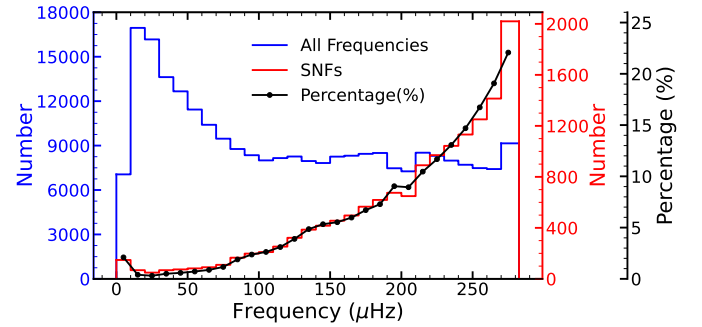


Fig. 2. Distribution of all 259 883 frequencies in 1838 δ Scuti stars. The blue histogram represents all frequencies, while the red one corresponds to the 14 824 SNFs. The black dots indicate the percentage of SNFs relative to all detected frequencies.

Figure 2 displays the frequency distribution of all extracted frequencies and identified SNFs. We observe that the number of frequencies initially decreases as the frequency increases after peaking at ~ 10 μHz , which is consistent with the high density of g modes at low frequencies in hybrid δ Scuti stars. The distribution gradually flattens around ~ 100 μHz ; this behavior is different from that found in γ Dor stars (Wang et al. 2025). In contrast, the number of SNFs rises monotonically with frequency, with their fraction increasing from approximately 1% at low frequencies (~ 10 – 50 μHz) to $\sim 23\%$ near the *Kepler* LC Nyquist limit of $f_{\text{ny}} \sim 283$ μHz . This trend indicates that a significant portion of high-frequency p modes reside above f_{ny} , consistent with the finding of Murphy et al. (2019), and that recovering SNFs is essential to obtain the correct pulsation content.

To investigate the distribution of the true pulsation frequencies, we recovered them from the observed SNFs. Our automated method is designed to identify the modulation signature characteristic of real frequencies, f_R , restricted to the frequency range between the Nyquist frequency and twice its value ($f_{\text{ny}} < f_R < 2f_{\text{ny}}$), although some pulsation frequencies can exceed $2f_{\text{ny}}$ (see, e.g., Bedding et al. 2020). This is because the robustness of SNFs in that higher frequency range has yet to be fully validated, constrained by the current lack of a sufficient known sample. Thus

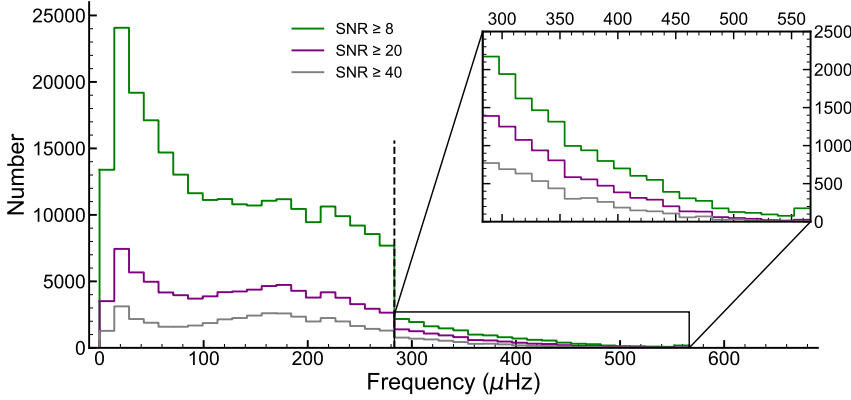


Fig. 3. Distribution of all frequencies, including recovered SNFs, in the *Kepler* δ Scuti sample. The vertical dashed line indicates the *Kepler* LC Nyquist frequency, and the inset panel highlights the SNF region. Note that the discontinuity decreases as S/N increases.

the real frequency is recovered from its observed alias, f_{obs} , using the standard reflection relation:

$$f_R = 2f_{\text{ny}} - f_{\text{obs}}. \quad (1)$$

The resulting distribution of these recovered frequencies reveals a prominent discontinuity at f_{ny} (the mean Nyquist frequency of 283.212 μHz), as shown in Fig. 3. This step feature marks the boundary above which all identified frequencies are those recovered by our automated pipeline from their aliased signals. The sharp drop in density at f_{ny} is a consequence of the inherent incompleteness of our pipeline: if all SNFs could be recovered, a smoother distribution would be expected. Nevertheless, the large population of frequencies now identified above f_{ny} demonstrates the efficiency of our approach in detecting high-frequency pulsations. A close inspection of Fig. 3 reveals a notable trend: as the S/N threshold is raised, the number of recovered SNFs declines more slowly than that of the real frequencies below f_{ny} . This suggests that the recovery rate of SNFs identified by our pipeline increases with S/N. The frequency ratio across f_{ny} exceeds 50% at S/N=20. Our results indicate that a significant fraction of SNFs is missing among lower-S/N frequencies via our sLSP4SNFs code.

Based on our frequency samples, we searched for combination frequencies in both the original and recovered sets, as the recovery of SNFs may affect linear combination relationships. The identification process consisted of screening for harmonics ($f_n \approx n \cdot f_i$, integer $n \leq 99$) to isolate independent frequencies by order of their amplitudes, followed by a search for linear combinations of two frequencies ($f_{\text{comb}} = af_i + bf_j$), where $a, b \in \{-1, +1\}$ among them. We accepted a candidate frequency, f_k , as a combination of independent frequencies f_i and f_j only if

$$|f_k - (af_i + bf_j)| \leq 3\sqrt{\sigma_k^2 + \sigma_i^2 + \sigma_j^2}, \quad (2)$$

where σ denotes the frequency uncertainty.

Our analysis identified 1438 linear combination frequencies in the original extraction results and 1733 after SNF recovery. The combination frequencies identified by our method are labeled with “1” in Table 1. This difference of approximately 17% between the two counts reflects the shift of aliased SNFs to their real frequencies, which is crucial for future precise seismic modeling.

To investigate the stellar properties linked to SNF occurrence, we examined the distribution of our sample on the Hertzsprung–Russell (HR) diagram. We constructed stellar models using the stellar evolution code MESA (Modules for Experiments in Stellar Astrophysics, Paxton et al. 2019). A grid of 154

evolutionary tracks was computed with initial masses of $M \in [1.5, 2.5] M_\odot$ ($\Delta M = 0.1 M_\odot$), metallicity $Z \in [0.004, 0.030]$ ($\Delta Z = 0.002$), and other parameters set to default values. Each evolutionary track consists of 300 discrete models; for each model, we calculated the theoretical frequencies for p modes with $\ell = 0, 1, 2$ and $n_p = 1-7$ using the stellar oscillation code GYRE (Townsend & Teitler 2013). For comparison with observations, we selected six representative tracks with masses of $M = 1.5, 1.7, 1.9, 2.1, 2.3, 2.5 M_\odot$ and a solar metallicity of $Z = 0.014$. Among the 1838 stars analyzed, 1776 have available T_{eff} and luminosity parameters provided by Murphy et al. (2019). Figure 4a shows the distribution of all stars colored by their total number of detected frequencies, revealing no clear systematic trend across the instability strip. In contrast, Fig. 4b colors the stars by the number of SNFs detected in them, showing a pronounced enhancement toward the hotter, less luminous region near the ZAMS. A similar pattern is observed in Fig. 4c, which shows the fraction of SNFs relative to the total number of detected frequencies per star. A clear decrease in the SNF fraction is observed as stars evolve away from the ZAMS, correlating well with the median eigenfrequencies from GYRE models. These findings indicate that the prevalence of SNFs is higher in younger δ Scuti stars, rather than a higher number of detected frequencies.

4. Discussion and summary

As first proposed by Wang et al. (2025), the sLSP method is highly effective for the identification of SNFs. Its efficacy has been demonstrated in both γ Dor and δ Scuti stars (Yang et al. 2025). To perform a comprehensive survey of SNF identification in δ Scuti stars, we developed an automated pipeline, sLSP4SNFs, designed to classify SNFs using a multi-parametric diagnostic framework (Section 2). Using this pipeline, we successfully identified 14 824 SNFs in 1291 stars, extracted from a comprehensive dataset of 259 883 frequencies with S/N > 8 across 1838 *Kepler* δ Scuti pulsators.

4.1. The robustness of the SNF catalog

The confidence of our identification was evaluated through manual vetting. This involved five iterations of random sampling, where each iteration consisted of 200 SNFs: 100 with $S/N_{\text{mod}} \in [5, 10]$ and 100 with $S/N_{\text{mod}} \geq 10$. We found no misclassifications in the high-significance group ($S/N_{\text{mod}} \geq 10$). For the intermediate group, the five trials yielded 1, 3, 2, 2, and 3 misclassified cases, respectively, resulting in a false-alarm probability (FAP) of 2.2%. This indicates that the majority of

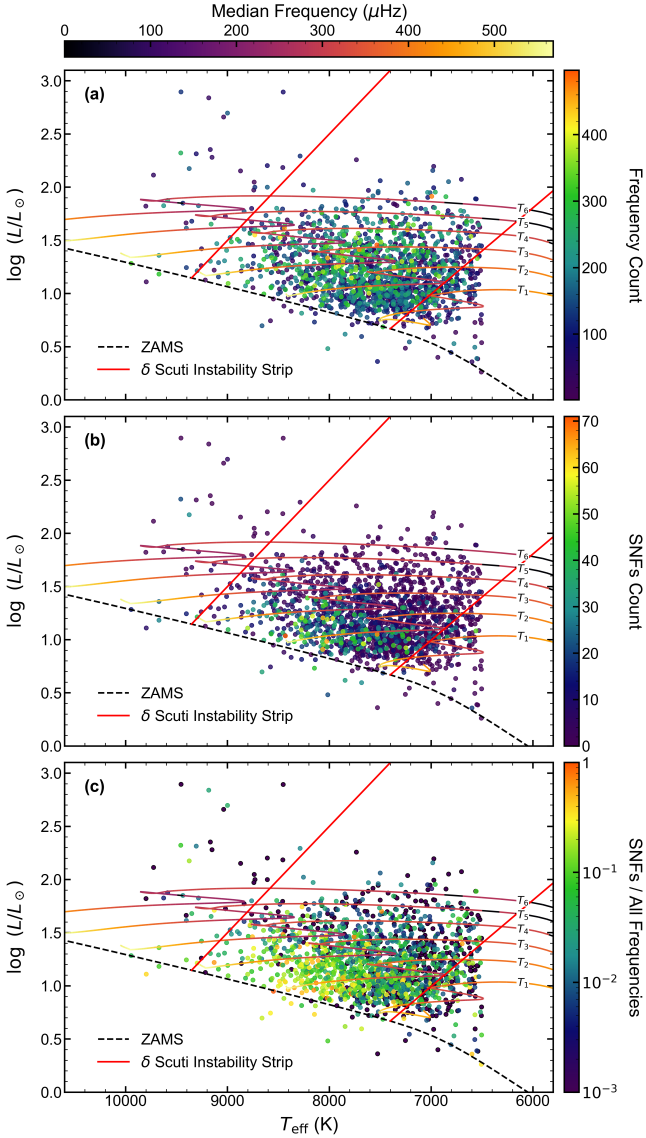


Fig. 4. HR diagrams of the 1776 δ Scuti stars in our sample. The data points are color-coded according to the right-hand color bars, representing: (a) the total number of detected frequencies; (b) the number of recovered SNFs; and (c) the fraction of SNFs relative to the total number of frequencies. The solid red curves and the dashed black line mark the observational instability strip for δ Scuti stars introduced by [Murphy et al. \(2019\)](#) and the zero-age main sequence (ZAMS), respectively. The curves (labeled T_1 – T_6 from bottom to top) show six representative evolutionary tracks with masses of $M = 1.5, 1.7, 1.9, 2.1, 2.3, 2.5 M_\odot$ and metallicity $Z = 0.014$. The color of these tracks indicates the median values of theoretical pulsation frequency for a given mode with fixed n , ℓ , and m , as mapped by the top color bar.

candidates in this range are bona fide SNFs. Nevertheless, these false positives might be considered intrinsic SNFs if the selection criteria were relaxed. Figure 5 shows an example of such a misidentified SNF, where the frequency modulation pattern closely mimics that of an intrinsic signal. The intrinsic amplitude and frequency modulation of such signals may compromise the classification accuracy of the sLSP4SNFs code. We note that these potential false SNFs are retained in our final catalog, as their manual removal through visual inspection would be prohibitively labor-intensive. For less significant candidates with $S/N_{\text{mod}} \in (3, 5)$, sLSP4SNFs achieved a validation recovery rate of 94.7% after manual inspection (see Section 2).

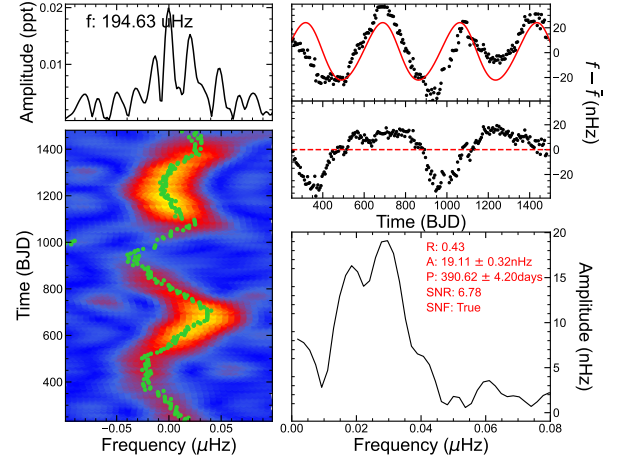


Fig. 5. Same as Fig. 1 but for a potential false-alarm SNF in KIC 7848288.

The robustness of our SNF catalog was further vetted through two independent approaches. We first sought *Kepler* short-cadence (SC) data for our 1291 SNF hosts, which we found for 324 (25%) of them. *Kepler* SC data have a cadence of 58.85 s, corresponding to a Nyquist frequency of $\sim 8496 \mu\text{Hz}$, well above the LC Nyquist limit ([Borucki et al. 2010](#)). Of the 3889 SNFs found in the LC data, 323 (8.3%) were undetectable in the SC data because their amplitudes are at or below the noise level³. For the remaining 3566, we confirmed 3509 (98.4%) common SNFs at their expected positions in the $[f_{\text{ny}}, 2f_{\text{ny}}]$ range. The remaining 57 (1.6%) SNF candidates are false positives and no further attempt was made to recover them. The consistency between the two comparison results confirms the reliability of the majority of our SNF candidates.

In our second validation approach, we applied the technique described by [Murphy et al. \(2013, 2019\)](#), verifying our recovered frequencies on the premise that the real frequency must possess the dominant amplitude compared to its aliases. Of the 14 824 recovered SNFs, 14 509 (97.9%) follow this rule, aligning closely with the results of our manual vetting. Figure 6 displays the results of the amplitude comparison between the SNF aliases in the $[0, f_{\text{ny}}]$ and $[f_{\text{ny}}, 2f_{\text{ny}}]$ ranges, complemented by two representative examples of successful and failed identifications. Additionally, 32 SNFs were assigned to the $[3f_{\text{ny}}, 4f_{\text{ny}}]$ range according to the dominant amplitude. Those extra findings motivate us to combine this method with our sLSP4SNFs code to search for other higher SNFs beyond $2f_{\text{ny}}$. Recognizing that neither approach alone was sufficient for this task, we integrated the two methods. This synergy, combined with an automated search and manual verification, ultimately revealed 207 SNFs within the $[2f_{\text{ny}}, 5f_{\text{ny}}]$ interval. Furthermore, the new method recovered 291 additional SNFs in the $[f_{\text{ny}}, 2f_{\text{ny}}]$ range that had previously been missed by sLSP4SNFs, primarily due to significant residuals and the overly stringent criteria established in Section 2.

We have compiled all SNF entries in Table 1, with their true frequencies recovered through the integration of these methods. Overall, Table 1 presents a total of 15 265 SNFs identified across a sample of 1309 stars. To ensure the robustness of our catalog, we have flagged these two types of cross-identifications with specific labels in Table 1. Users can regard the frequencies for which

³ Typically, only one month of SC data are available, compared to four years of LC data, hence the noise is higher and the frequency resolution is poorer in SC data.

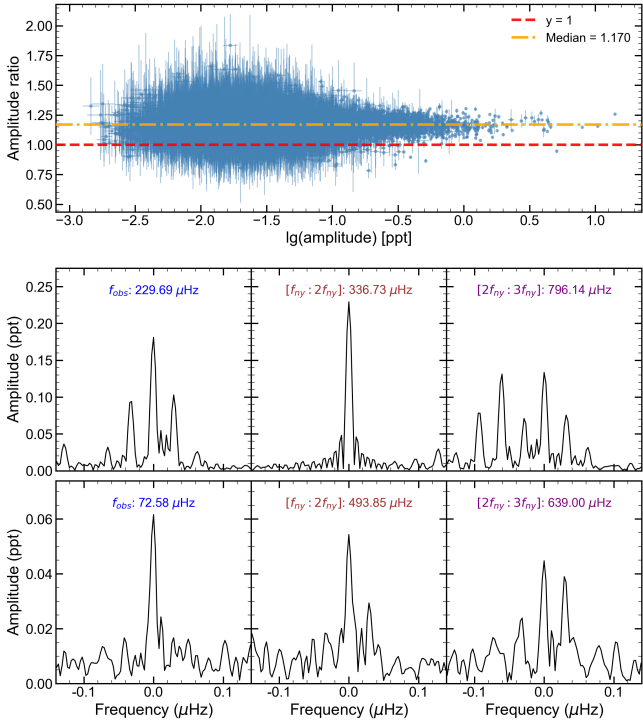


Fig. 6. Validation of 14 824 SNFs via alias amplitude comparison. Top panel: distribution of amplitude ratios for frequency aliases within the $[0, f_{\text{ny}}]$ and $[f_{\text{ny}}, 2f_{\text{ny}}]$ intervals, shown as a function of amplitude on a logarithmic scale. The dashed red and dash-dotted orange horizontal lines mark $y = 1$ and the median amplitude ratio, respectively. Middle panels: representative example of one of the 14 509 confirmed candidates where the physical frequency correctly resides in the $[f_{\text{ny}}, 2f_{\text{ny}}]$ range. Bottom panels: illustrative example of one of the 283 unconfirmed cases that do not satisfy this amplitude criterion. Note the text labels indicate the Nyquist-interval assignment and the corresponding recovered frequency values (e.g., f_{obs} in $[f_{\text{ny}}, 2f_{\text{ny}}]$ and $[2f_{\text{ny}}, 3f_{\text{ny}}]$), where frequencies have been restored to their respective Nyquist intervals.

Table 2. All 259 883 frequencies in 1838 δ Scuti stars.

KIC	Frequency (μHz)	σ_f (μHz)	Amplitude (ppt)	σ_A (ppt)
1026255	24.782977	0.000147	0.0307	0.0010
1026255	49.531118	0.000156	0.0270	0.0010
1026255	74.311904	0.000428	0.0091	0.0009
1026255	192.306487	0.000107	0.0278	0.0007
1573149	85.619497	0.000065	0.0640	0.0010
1573149	171.239513	0.000310	0.0122	0.0009
1575977	1.811605	0.000451	0.1635	0.0170
...	...	...	...	...

Notes. Frequencies are identified with $S/N > 8$ and serve only as reference. Any detailed asteroseismic study would require further analysis of amplitude spectra based on this table, in particular for low-amplitude signals. The full catalog is available in machine-readable form at the CDS.

all methods agree as having the most confident labels. Nevertheless, recognizing that the full catalog of 259 883 frequencies may still be valuable for specific research needs, it is provided in Table 2.

4.2. The distribution of SNFs

The SNF distribution in δ Scuti stars follows a trend remarkably similar to that of γ Doradus stars, characterized by a distinct and monotonic rise in both population size and detection rate toward higher frequencies. However, since γ Dor stars are dominated by lower-frequency g modes and only γ Dor– δ Sct hybrids will have a few high p modes, we observe a significantly higher number and detection rate of SNFs in δ Scuti stars, whose p modes more commonly have frequencies near the *Kepler* LC Nyquist frequency. Specifically, we find a maximum rate of approximately 23% in this study, compared to about 7% reported for predominantly γ Dor stars. These results imply that any precise seismic analysis of *Kepler* δ Scuti stars must carefully account for the high incidence of SNFs. Currently, as illustrated in Fig. 3, the detection rate shows a discontinuity around the Nyquist frequency, which we would not expect to be present if we had a 100% recovery rate. In fact, one can see that the size of this discontinuity depends on the S/N of the observed peak, meaning that our completeness is higher for more significant modes. The sensitivity of sLSP4SNFs is primarily constrained by the amplitude threshold; consequently, a portion of the SNF population remains undetected because low-amplitude frequencies do not exhibit sufficient diagnostic signatures for reliable classification, lying beyond the recovery capabilities of sLSP4SNFs and also below the required S/N in SC data. The SC spectrum has both a higher noise level and a poorer frequency resolution, making peaks less detectable; the latter specifically complicates peak profiles in dense regions of the amplitude spectrum. In addition, the performance of sLSP4SNFs is very limited in dense frequency regions, thereby impeding the successful identification of SNFs. In such cases, we encourage users to apply the amplitude method as well. At this stage, identifying missing SNFs among low-amplitude signals or in dense frequency regions remains a challenge, implying that we effectively provide only a lower limit for the number of intrinsic SNFs but with high confidence.

Based on our catalog, we performed a statistical analysis examining the dependence of SNFs on stellar parameters and evolutionary stages across the HR diagram (Fig. 4). We report no clear feature for the distribution of the frequency number per star. This stands in contrast to theoretical predictions that stars in the middle of the instability strip should exhibit a higher number of excited radial modes (Antoci et al. 2019). The caveat is that only frequencies with relatively high amplitudes were extracted in this work. However, we do observe a clear trend that younger δ Scuti stars exhibit a higher fraction of SNFs relative to their total frequency count. This distribution is similar to the regular frequency patterns in young δ Scuti stars as identified by large frequency separation, $\Delta\nu$ (Bedding et al. 2020). The SNF fraction gradually decreases as the stars evolve, a result consistent with the median values of our theoretical eigenfrequencies calculated by GYRE. This can be understood in the context of stellar evolution: as stars evolve off the ZAMS, the mean density, $\bar{\rho}$, decreases, causing the eigenfrequencies of a specific p mode (with fixed n , ℓ , and m) to shift toward lower values (Gatunam et al. 2026), as defined by the pulsation constant:

$$Q = P \sqrt{\frac{\bar{\rho}}{\bar{\rho}_\odot}} \sim \frac{\Delta\nu}{\nu}, \quad (3)$$

where P is the pulsation period, $\bar{\rho}_\odot$ represents the mean solar density, ν is the frequency value, and $\Delta\nu \propto (\bar{\rho})^{0.5}$. Consequently, the representative frequencies are less likely to exceed f_{ny} . Therefore, both the SNF count and its corresponding fraction, as a

proxy of higher frequencies, decrease as δ Scuti stars evolve away from the ZAMS phase, which is consistent with the results from both observation and stellar models (Bedding et al. 2020; Murphy et al. 2023; Gatuam et al. 2026).

4.3. Prospects

Our observational results demonstrate that any mode identification in δ Scuti stars should be approached with caution when the sampling cadence approaches or exceeds 30 minutes. The recovery of SNFs can alter the existing relationships among pulsation modes, such as linear combination frequencies, which exhibit a discrepancy of $\sim 17\%$ in our catalog. This subsequently biases the characterization of internal stellar properties derived from seismic models, especially if an independent mode is misidentified as a linear combination, or vice versa. In this context, seismic analysis of δ Scuti stars closer to the terminal-age main sequence (TAMS) appears more reliable than that of younger MS stars, as the probability of SNF pollution is significantly reduced.

Our catalog offers users an easy method of checking whether an observed peak is a Nyquist alias, and provides its real frequency if so. It also provides information on the S/N of the modulation, as a proxy of confidence in the identification. For specific stars, to improve the accuracy of SNF identification, we combined our method with amplitude ratio between aliases and cross-checking available *Kepler* SC data. We also encourage the use of other independent techniques for further validation, such as analyzing amplitude modulation (Zong & Charpinet 2021) and identifying equidistant frequency multiplets (Murphy et al. 2013). The most appropriate method will depend on what data are available, but ideally one can apply multiple methods and arrive at the same conclusions. This workflow will increase the reliability of asteroseismic analyses of δ Scuti stars in the *Kepler* LC data.

Our method is based on the principle that a slight correction to the sampling time introduces periodic frequency modulations with a predictable pattern. Murphy et al. (2014) showed that, in some cases, their signatures may be misinterpreted as systematic phase modulations induced by binarity, especially considering the similarity between SNF modulation and binary modulation with periods around one year. To distinguish between them, one must scrutinize all significant frequencies. Phase modulation from binarity exhibits the same pattern across all significant frequencies and can modulate on various scales as determined by orbital parameters, whereas SNF modulations are restricted to aliased frequencies originating from the super-Nyquist regime with a predicted frequency scale and phase with respect to *Kepler*'s heliocentric orbit. We finally stress that SNFs exhibit a characteristic modulation pattern that is clearly distinguishable from the diverse intrinsic variations of nonlinear mode interactions in different types of pulsators (see, e.g., Bowman et al. 2016; Zong et al. 2016). However, as shown in Fig. 6, the observed modulation can sometimes be a composite of the SNF pattern and intrinsic nonlinear resonance, which complicates the identification of individual SNF frequencies.

We end this paper with a brief summary: we have established a comprehensive catalog of high-confidence SNFs for *Kepler* δ Scuti stars, demonstrating that SNFs are a ubiquitous feature in high-frequency pulsators observed with *Kepler* long-cadence photometry. This catalog provides a foundation for future asteroseismic investigations of δ Scuti stars. It enables future studies to reexamine previous mode identifications and, based on our findings, to identify regular frequency spacings in young stars and reevaluate linear combination frequencies. Our

findings clearly reveal that SNF modulation patterns are distinct from those induced by intrinsic nonlinear resonances or binary orbital effects, providing a robust method of disentangling these phenomena.

Data availability

The full versions of Tables 1 and 2 are available at the CDS via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/710/A245>.

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