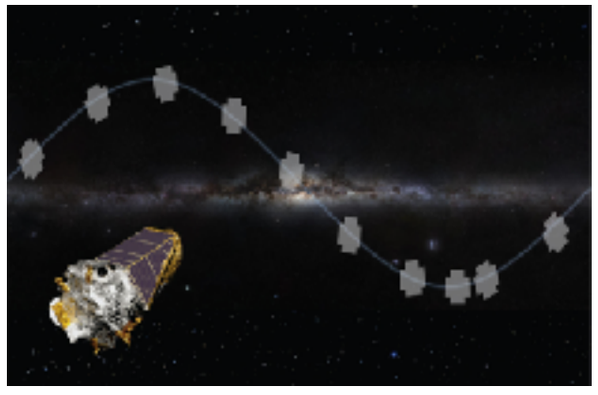
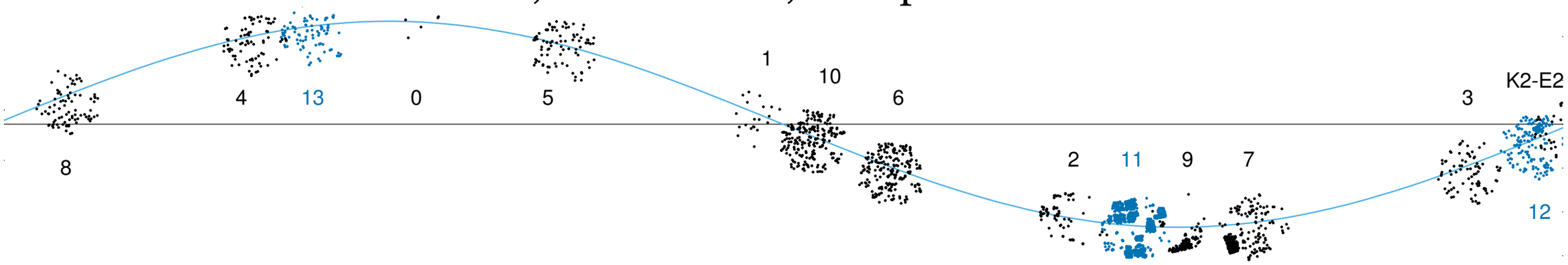


The Kepler/K2 RR Lyrae survey

Róbert Szabó

Konkoly Observatory, MTA CSFK Budapest, Hungary

STARS2016, Lake District, 12 September 2016



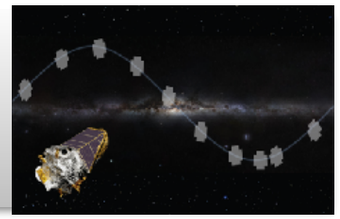
KASC RR Lyrae + Cepheid Working Group,

K. Kolenberg co-lead (CfA Harvard, KU Leuven)

E. Plachy, L. Molnár (Konkoly Observatory)

STARS2016

RR Lyrae stars - introduction

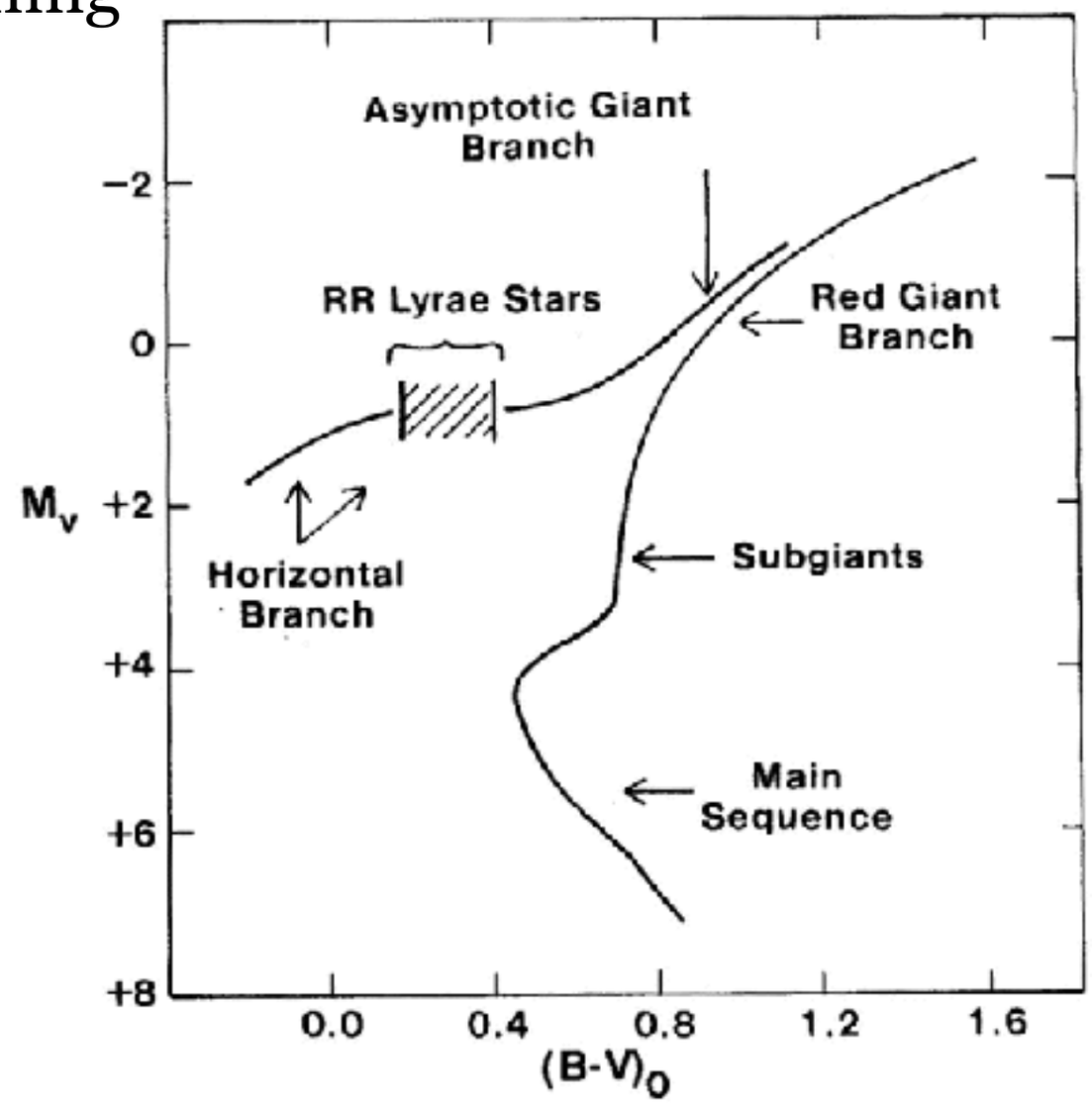


- old, low mass, He-core, H-shell burning **horizontal branch stars**
- globular clusters, field, halo, extragalaxies, …
- 0.5-1.5^{m} amplitude, 0.2-1.0^{d} period

- RRab: fundamental mode
- RRc: first radial overtone
- RRd: fundamental + first overtone

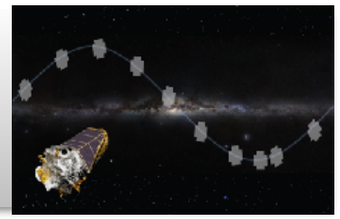
- Blazhko effect:
  amplitude and phase modulation

- distance indicators,
  galactic structure tracers



H. A. Smith: RR Lyrae stars 1995

RR Lyrae stars - introduction



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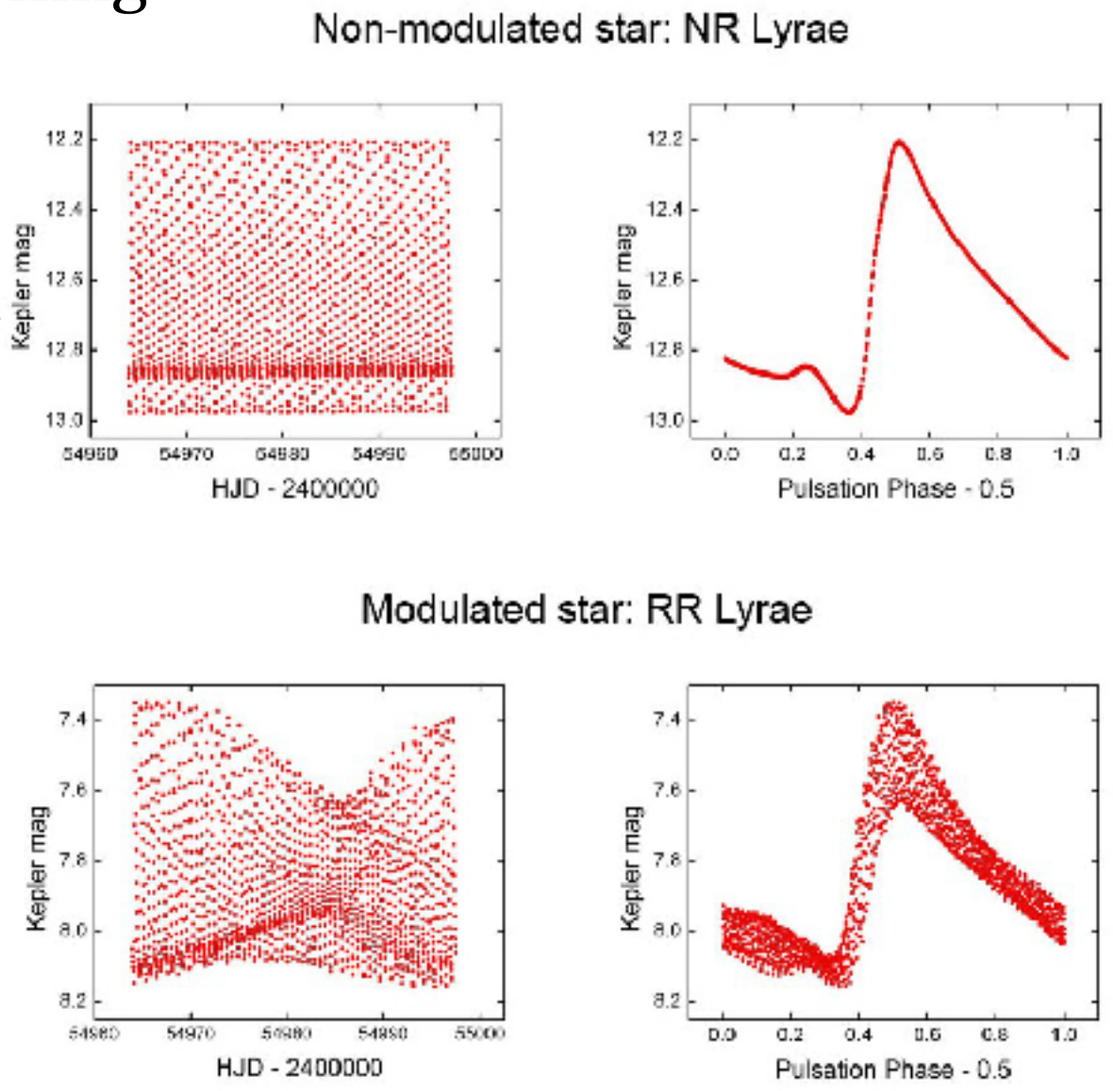
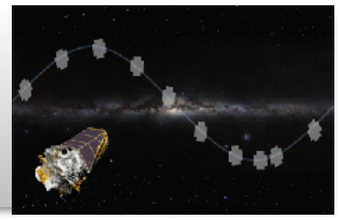


Gilliland et al. 2010, PASP, **122**, 131

RR Lyrae stars - introduction



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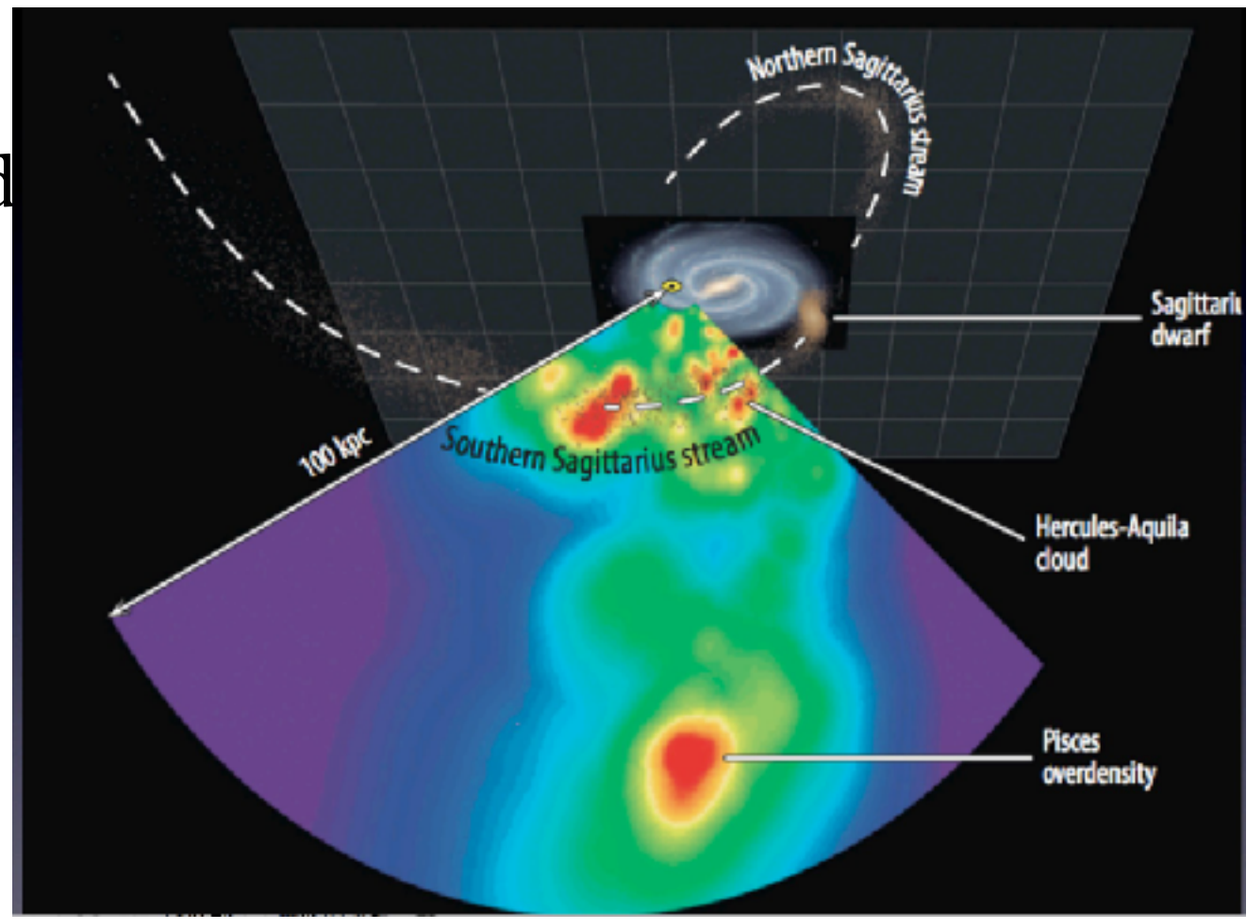
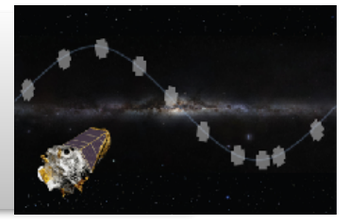


based on RR Lyrae in SDSS
Sesar et al. 2011, ApJ, **731**, 4

RR Lyrae: the space photometric revolution



Monoperiodic (mostly)

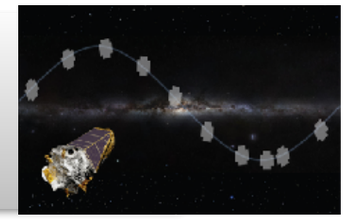
Radial pulsation

Simple light curves

Blazhko-effect: rare

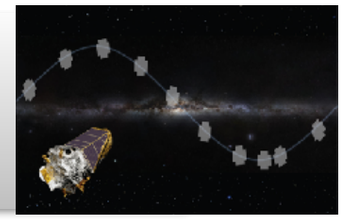
Blazhko-effect: simple

RR Lyrae: the space photometric revolution



2006	2016
Monoperiodic (mostly)	Multiperiodic
Radial pulsation	Radial + Nonradial
Simple light curves	Complex light curves
Blazhko-effect: rare	Blazhko-effect: ~50%
Blazhko-effect: simple	Blazhko-effect: complex, multiple modulations

RR Lyrae: the space photometric revolution



2016

irregular Blazhko modulations

additional frequencies

multiple Blazhko modulations

new explanation for the Blazhko effect

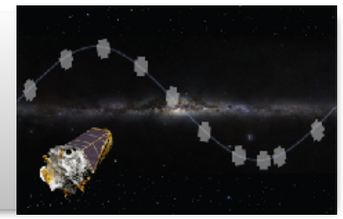
period doubling

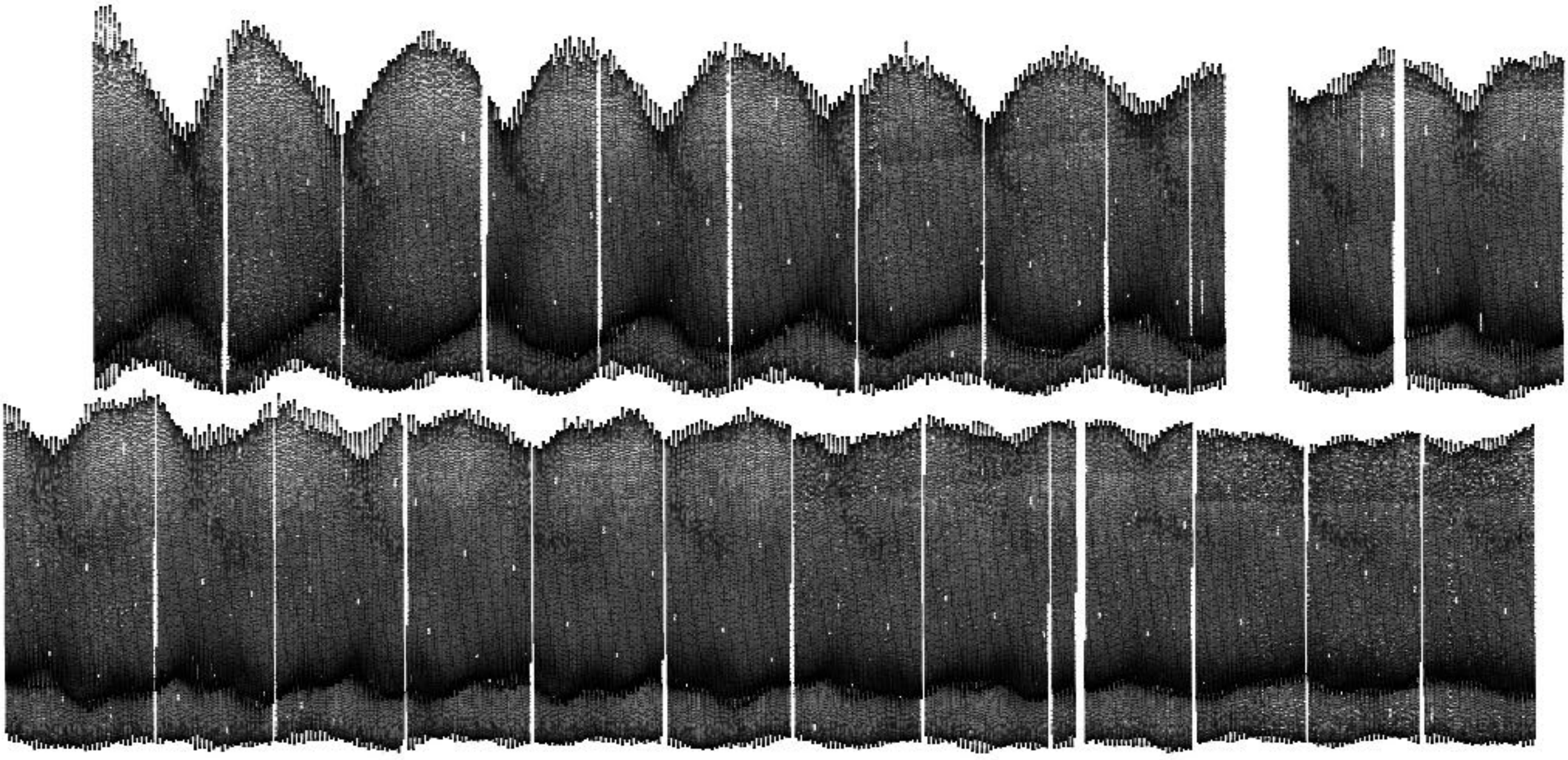
high-order resonances

chaos?

high radial overtones

The Kepler legacy - period doubling

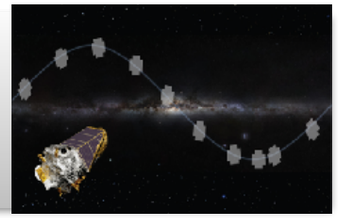


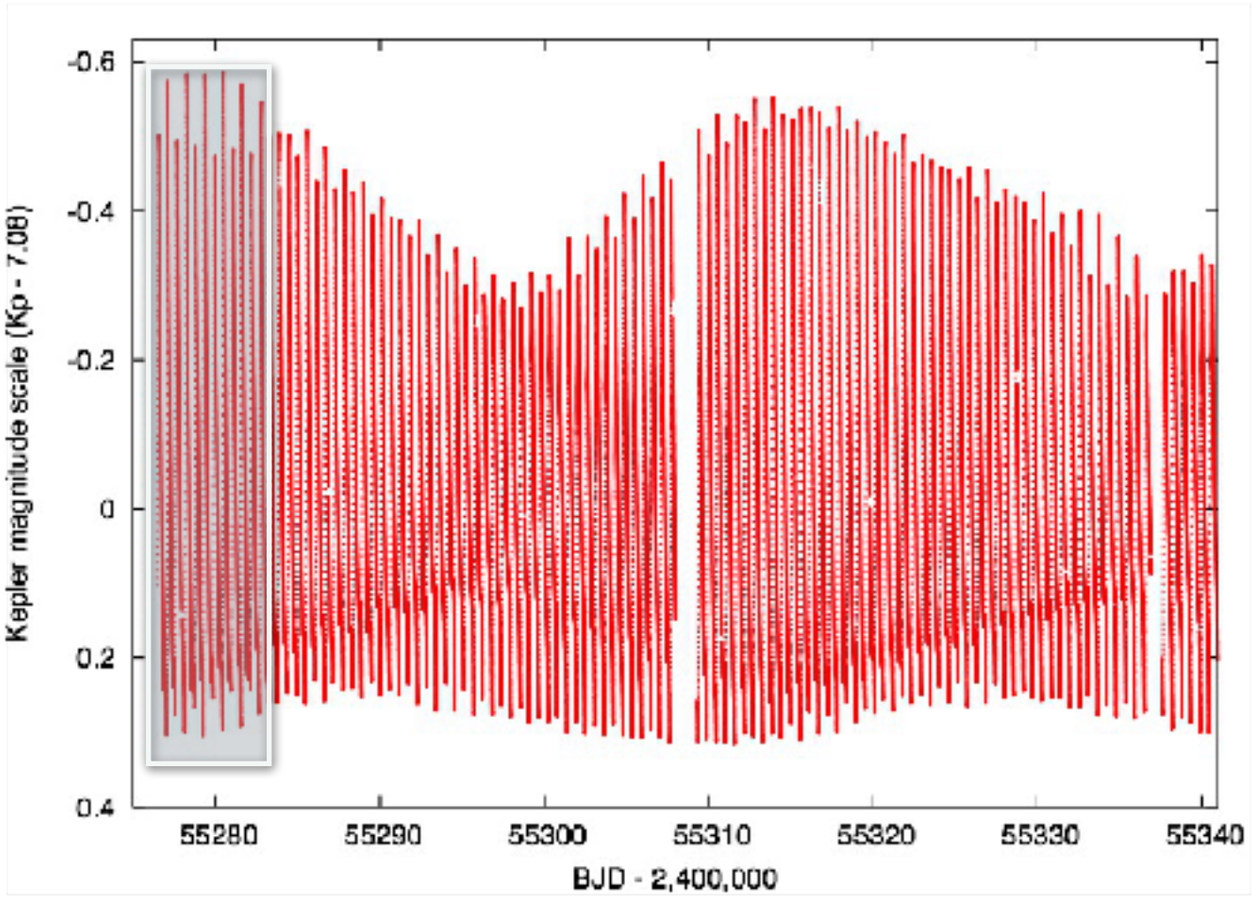


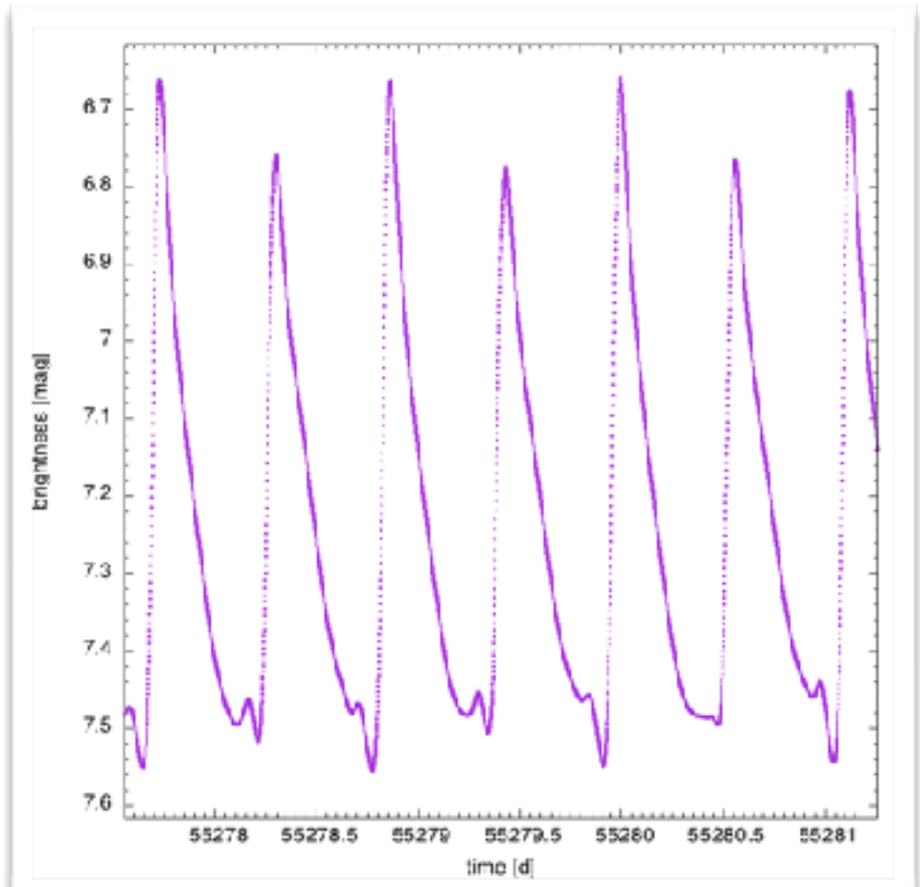
Q5-Q12 (2yr) short-cadence Kepler light curve of RR Lyrae

Kolenberg et al., 2010, ApJL, **713**, L198, Szabó et al. 2010, MNRAS, **409**, 1244
Szabó et al. 2014, A&A, **570**, A100

The Kepler legacy - period doubling





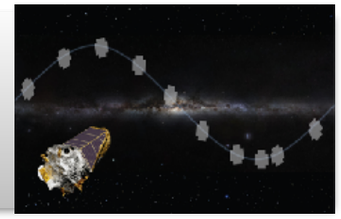


Period-doubling: only in Blazhko-modulated RRab stars

Kolenberg et al., 2010, ApJL, **713**, L198,
Szabó et al. 2014, A&A, **570**, A100

Szabó et al. 2010, MNRAS, **409**, 1244

The Kepler legacy - period doubling



Resonance paradigm:

Cause of the period doubling: 9:2 **resonance** with the 9th radial overtone.
The same resonance may cause the Blazhko-modulation.

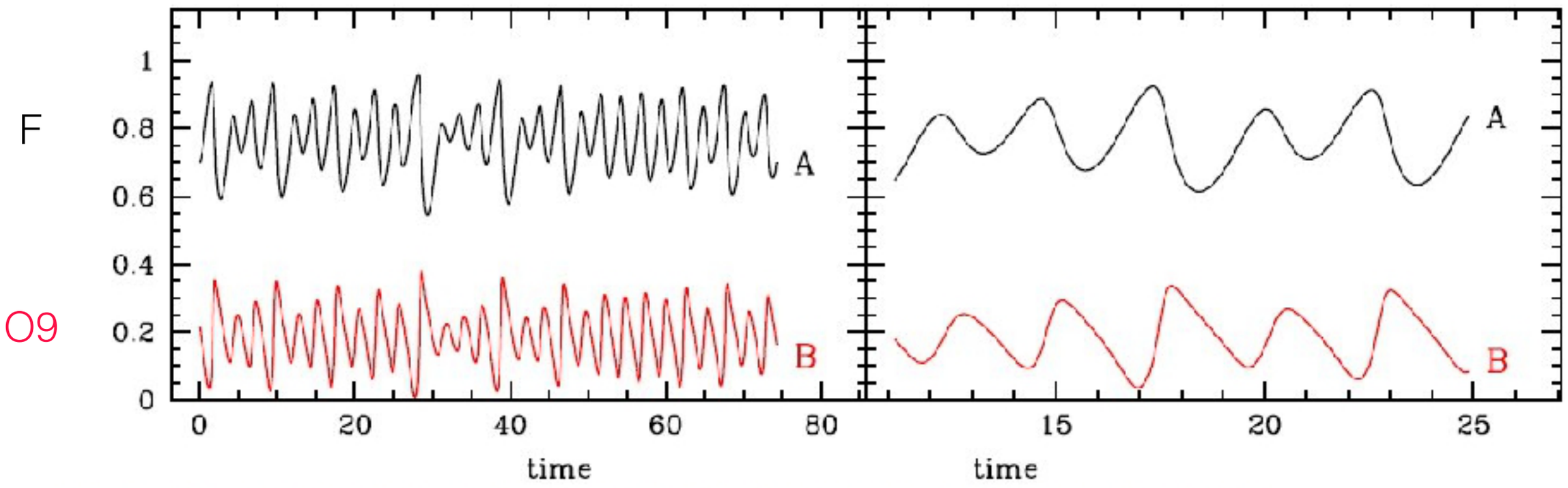
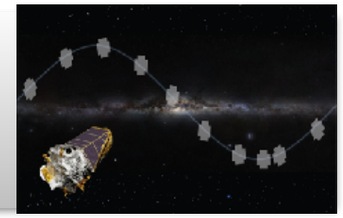


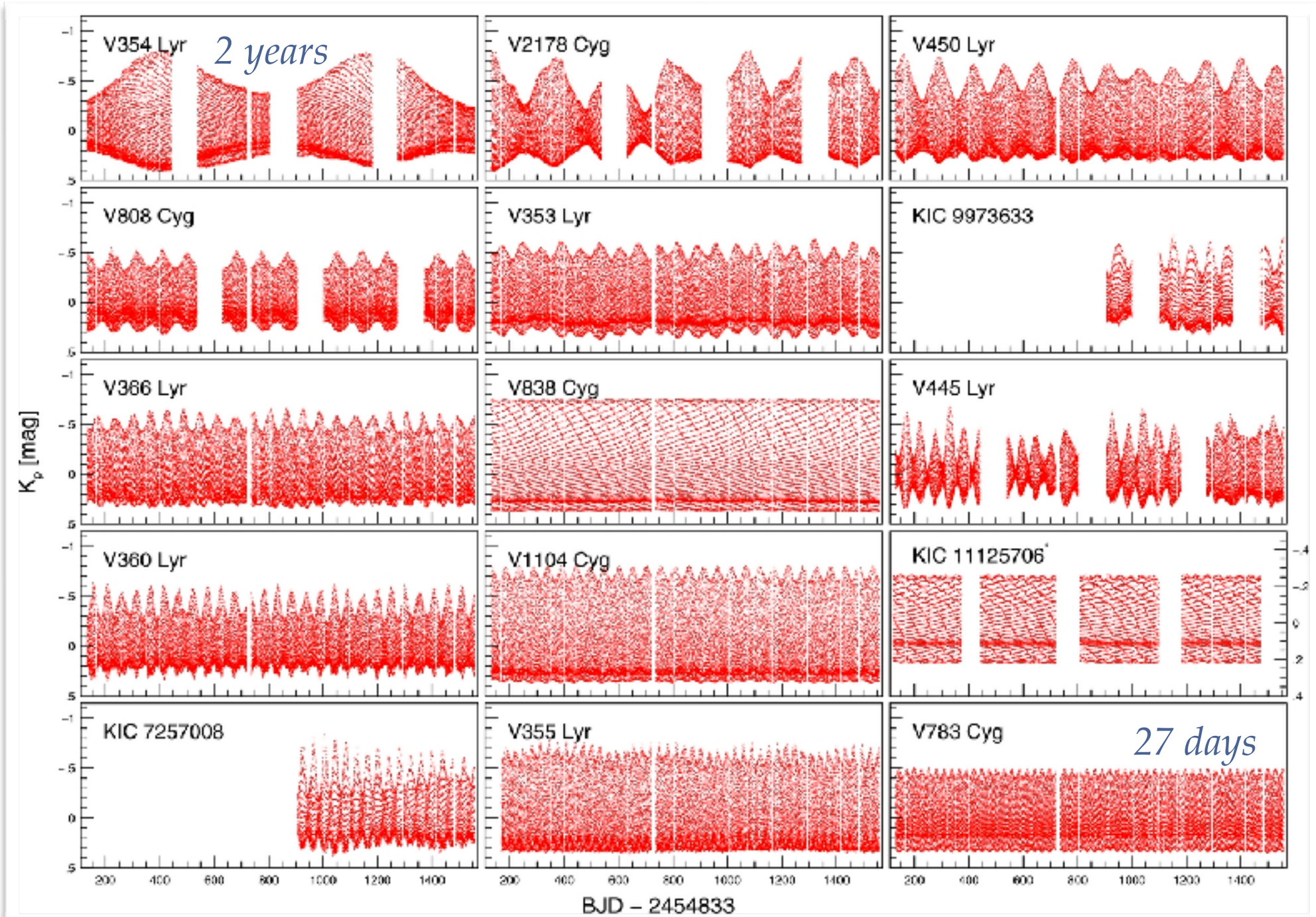
FIG. 1.— Temporal modulation of the two amplitudes of the irregularly modulated period two pulsation.

Szabó et al. 2010, MNRAS, **409**, 1244
Buchler & Kolláth, 2011, ApJ, **731**, 24

Kolláth et al. 2011, MNRAS, **414**, 1111

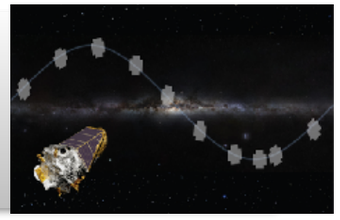
The Kepler Blazhko zoo

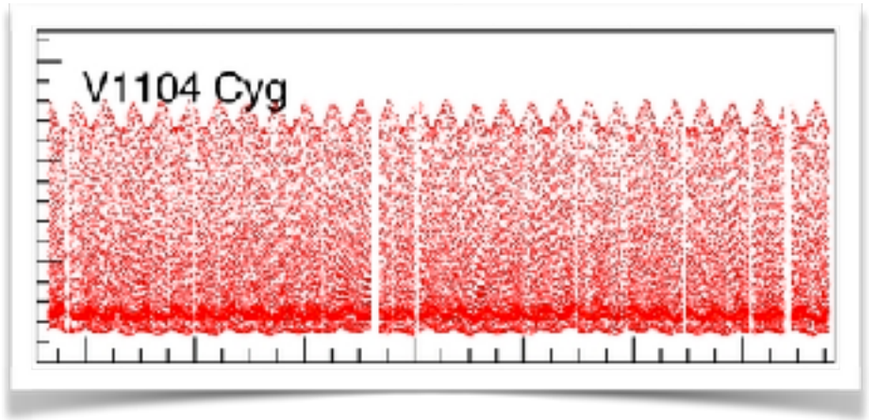




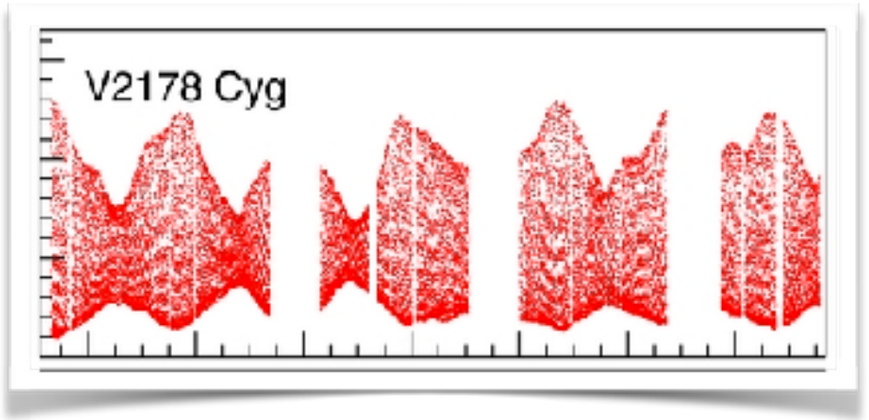
Benkő et al. 2014, ApJS, **213**, 31

The Kepler Blazhko zoo
Multiperiodic modulations are the norm

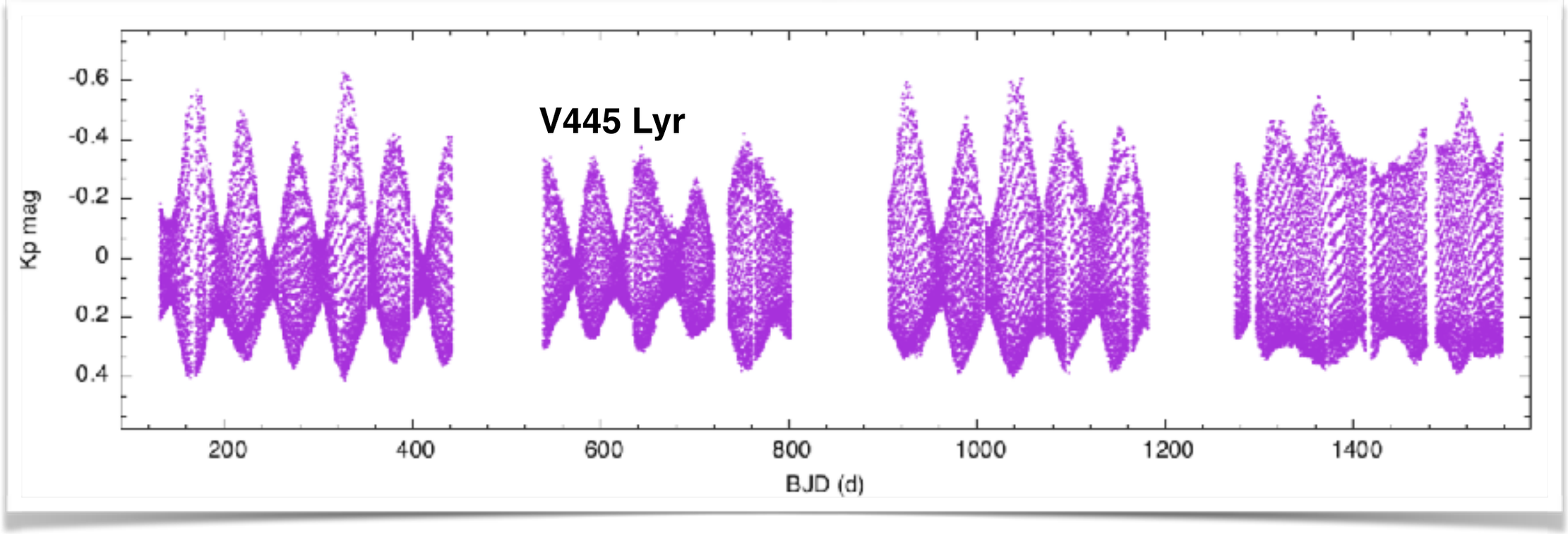




Fairly regular

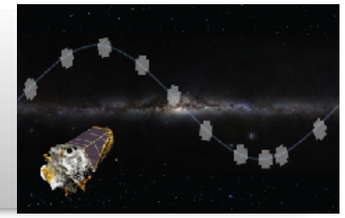


What is this one doing?!

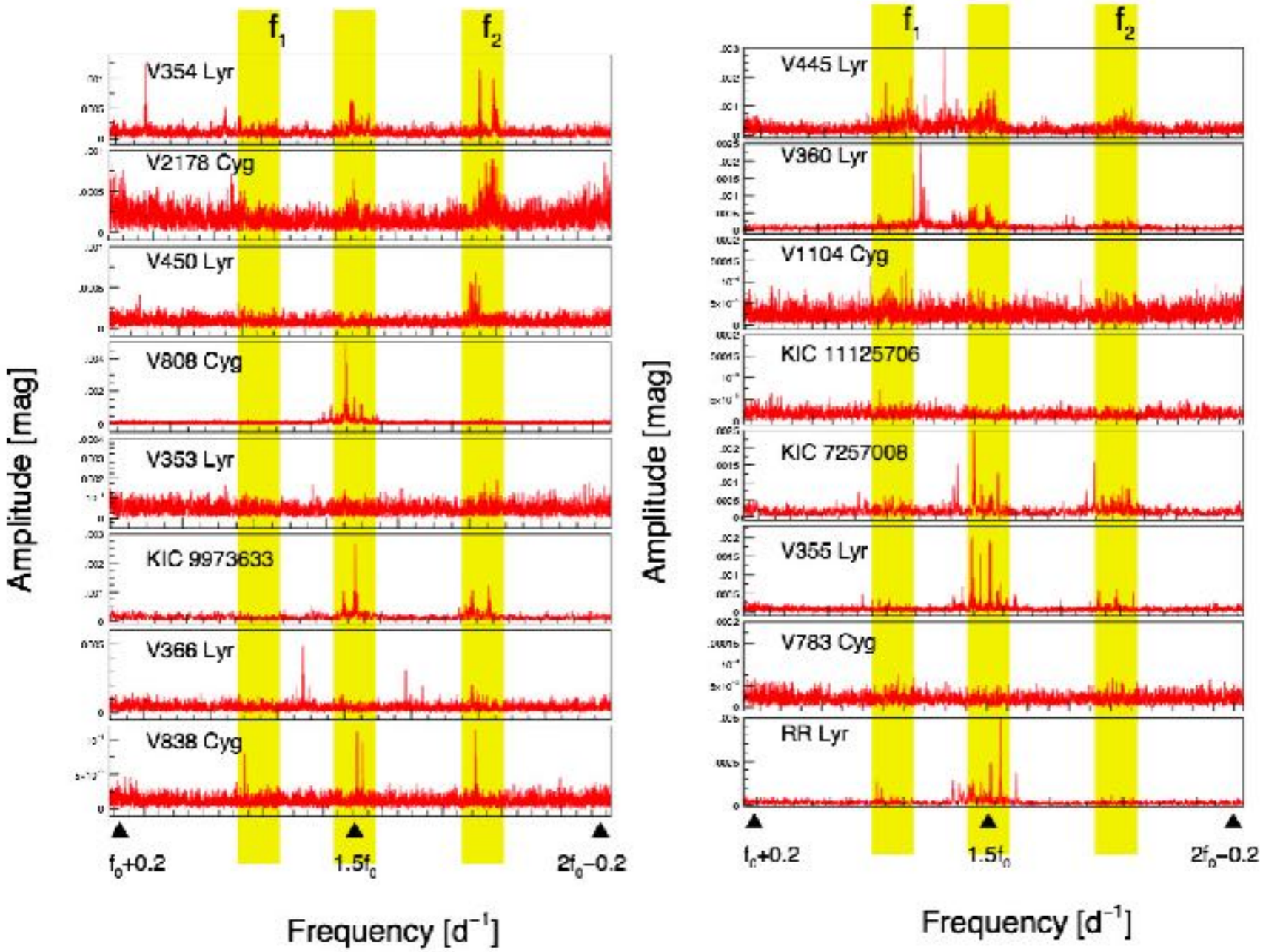


Guggenberger et al., 2012, MNRAS, **424**, 649

Additional modes



Radial modes



- Frequencies around the radial O1, O2 are common

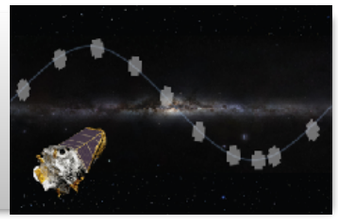
- **Radial modes**
  RR Lyrae: O1
  Molnár et al. 2012

or

- **Nonradial modes**
  in 1:1 resonance with the radial mode
  Dziembowski & Mizerski 2004
  van Hoolst et al. 1998

Kepler Blazhko RRab sample Benkő et al. 2014, ApJS, **213**, 31

Additional modes



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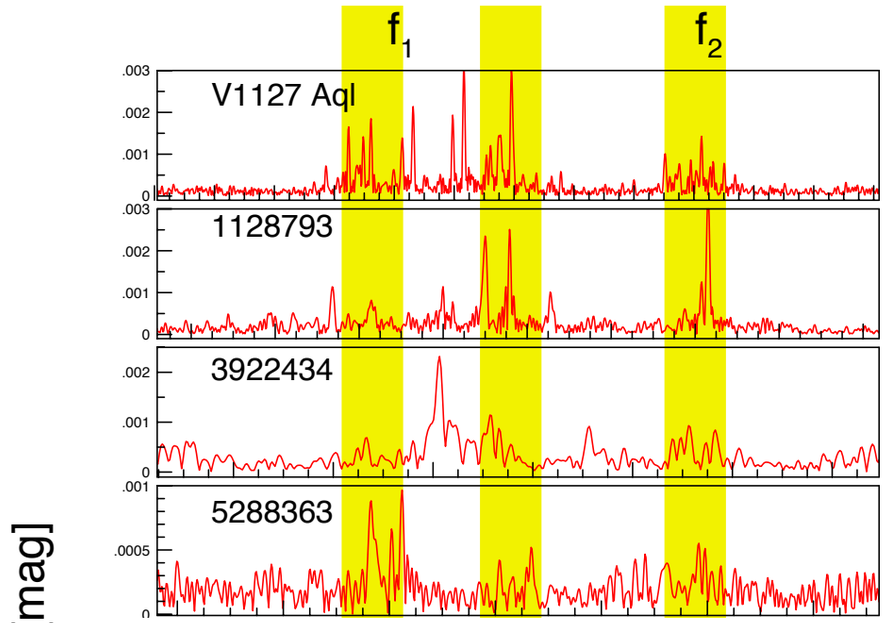


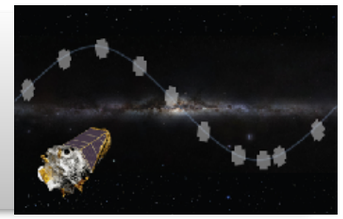
Blazhko RRab

Modulated stars: frequencies around the radial O1, O2 are common.

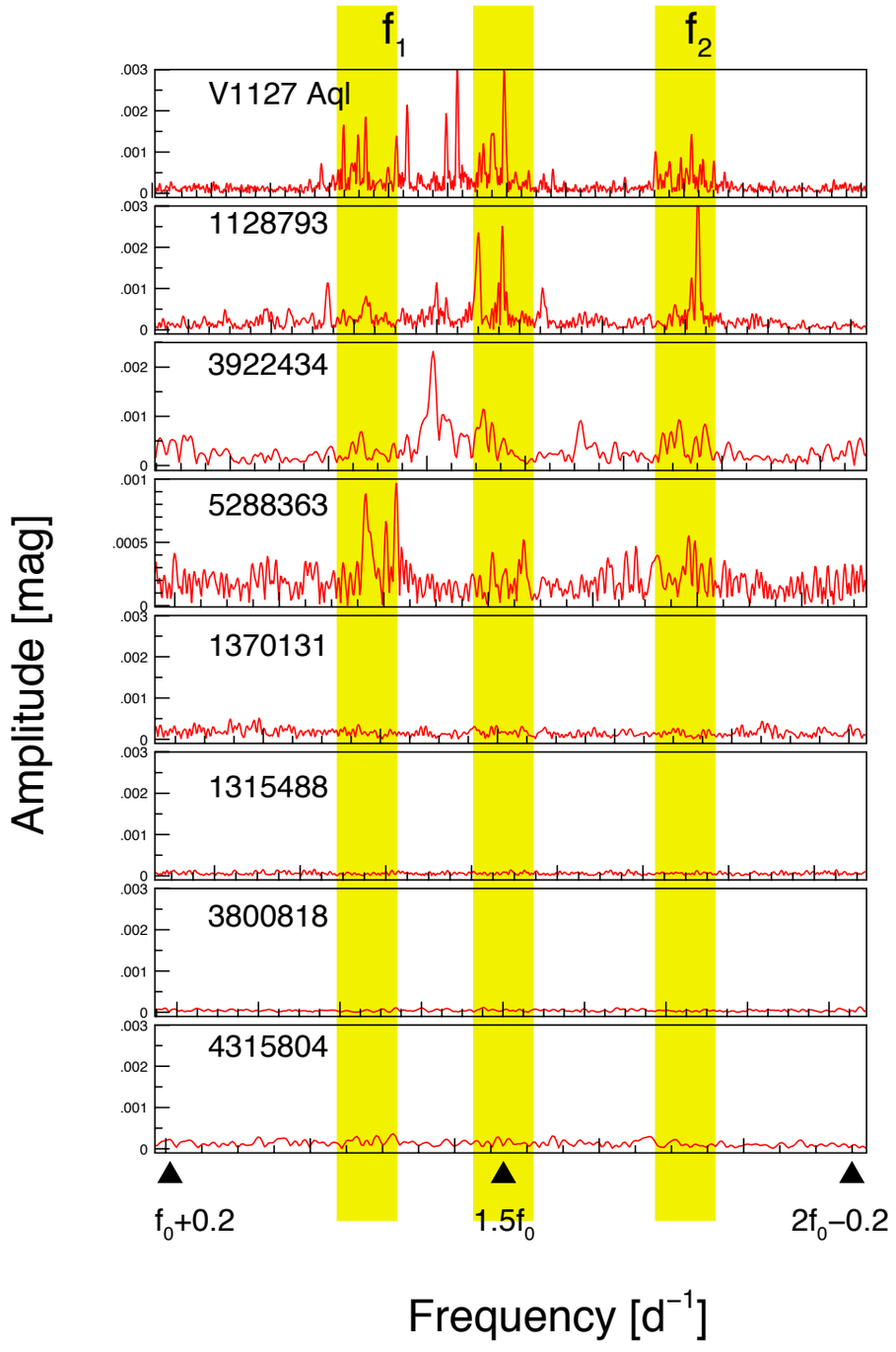
Radial modes or Nonradial modes in 1:1 resonance with the radial mode

CoRoT RRab sample Szabó et al. 2014, A&A, **570**, A100

Additional modes



Radial modes



Blazhko RRab

non-Blazhko RRab

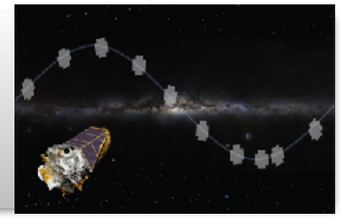
Modulated stars: frequencies around the radial O1, O2 are common.

Radial modes or Nonradial modes in 1:1 resonance with the radial mode

Non-modulated stars: no additional frequencies in the spectra down to the Kepler & CoRoT limits.
Nemec et al. 2011 - Kepler
Szabó et al. 2014 - CoRoT

CoRoT RRab sample Szabó et al. 2014, A&A, **570**, A100

Radial + nonradial puls. modes



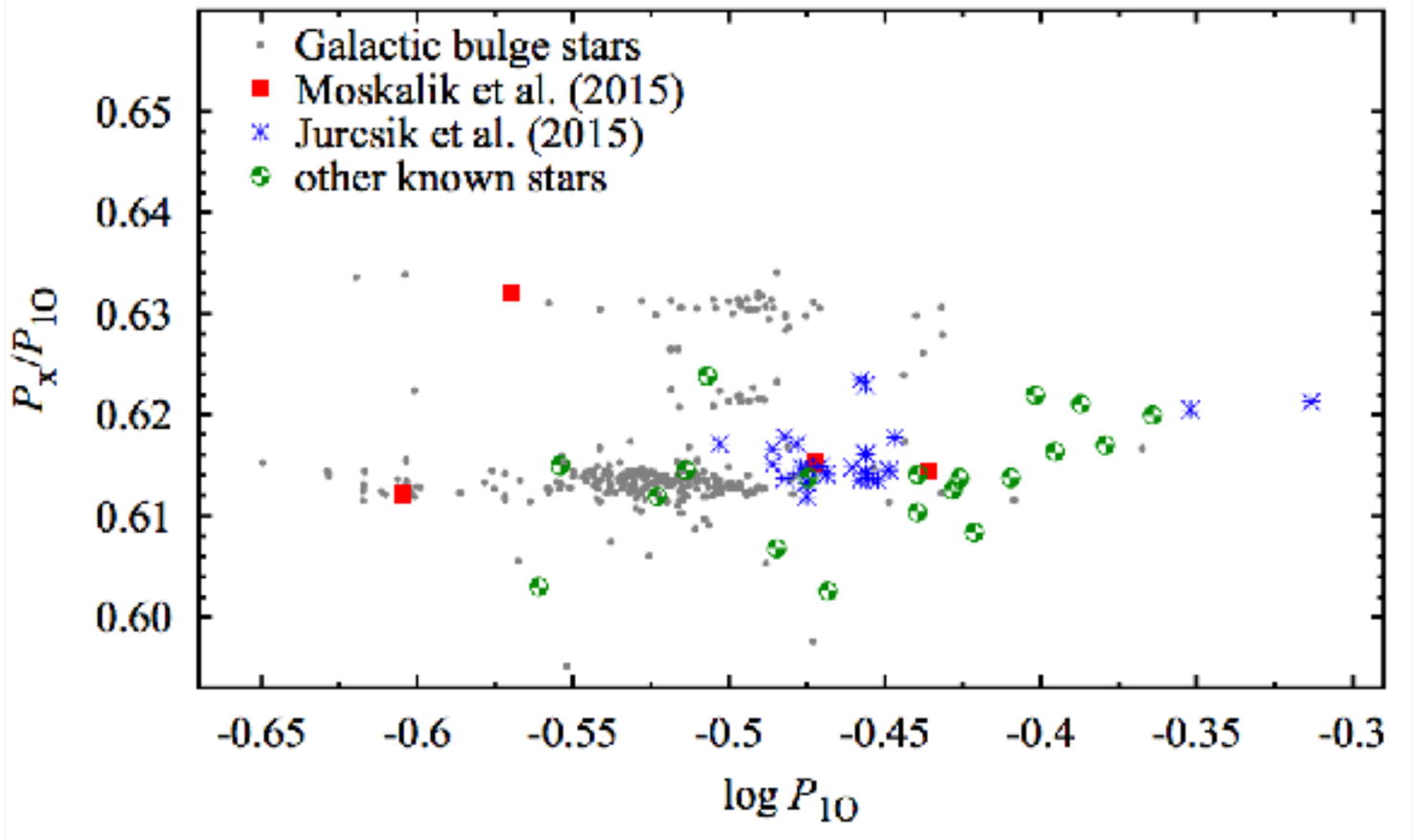
Extra modes are present

- in all BL-modulated RRab stars
- in all RRc stars
- in all RRd stars

BUT absent in

- non-modulated RRab stars

RRc + RRd stars with 0.61 period ratio

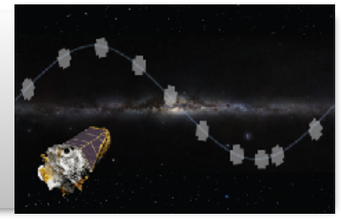


Netzel et al. 2015, MNRAS, **453**, 2022

unstable f-modes of ℓ = 7,8,9 angular degree ?

Dziembowski Comm. from the Konkoly Obs.,**105**, 201, 2016

Radial + nonradial puls. modes



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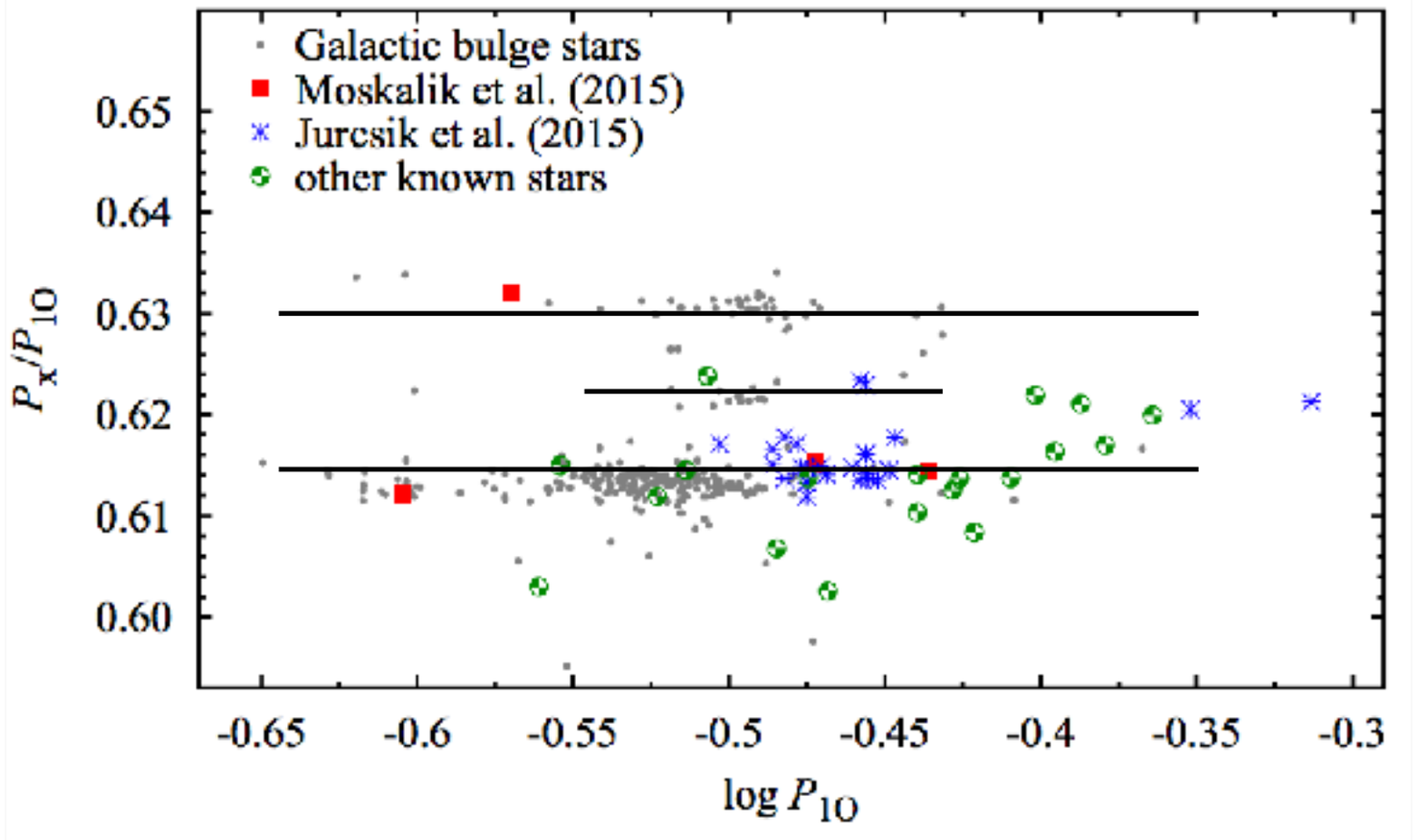

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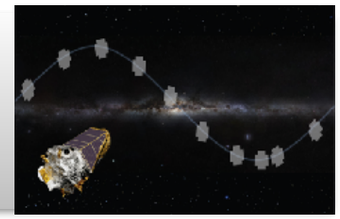
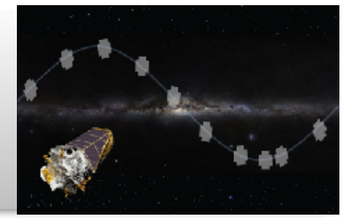


Additional frequencies in space photometric targets

- Blazhko-modulated RRab stars : all
- non-modulated RRab stars: none
- RRc (first overtone pulsators O1): all
- RRd (fundamental mode + O1): all

Additional modes



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- RRc (first overtone pulsators O1): all

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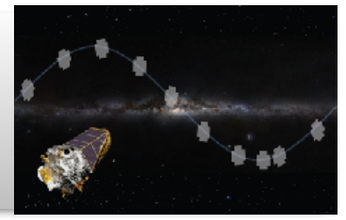
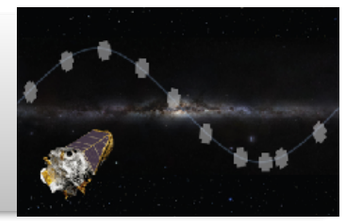
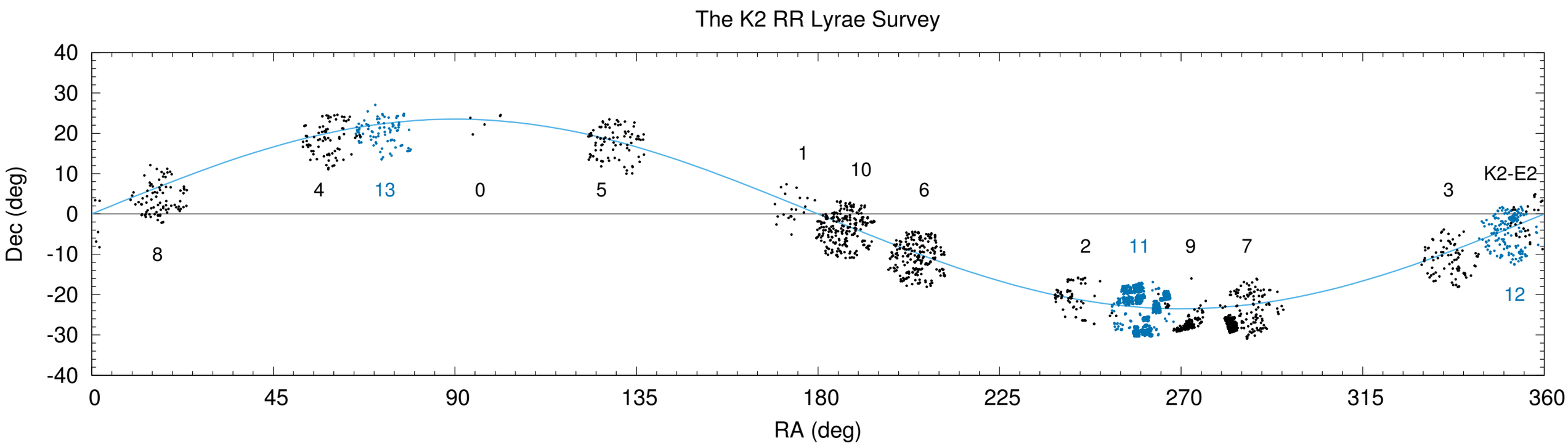
MOST+ Kepler + K2 + CoRoT: additional modes are universal !

K2 Mission along the Ecliptic 2014-



The K2 RR Lyrae Survey



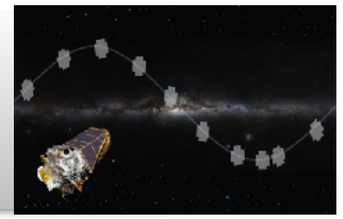


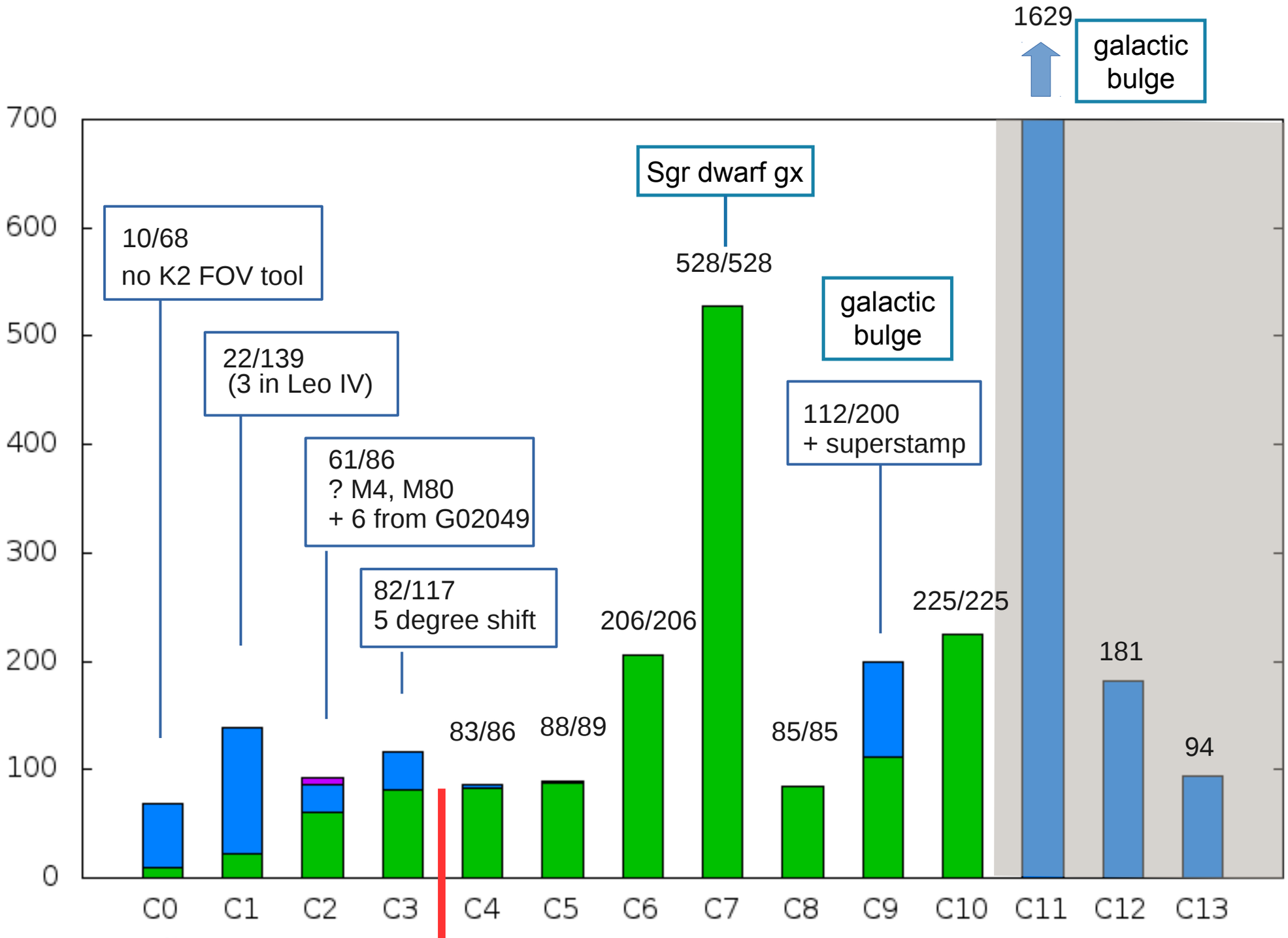
K2 Campaigns C0-C13 along the ecliptic

black: observed
blue: scheduled

NASA Senior Review extended the K2 Mission (June 2016)

RR Lyrae stars in K2 campaigns



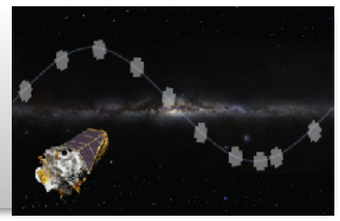


blue: requested

green: observed

STARS2016

Motivations for K2 observations

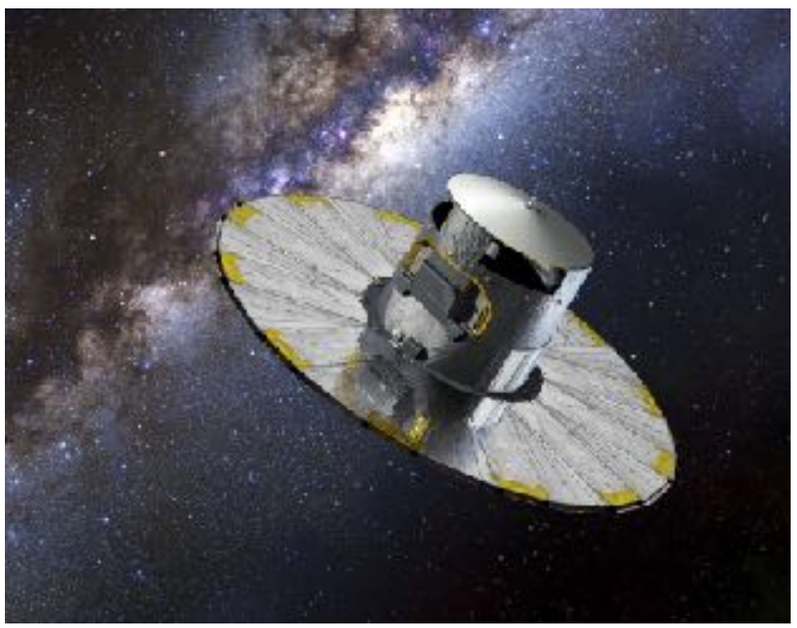


- Original Kepler field: **~50** RR Lyrae
- K2: **thousands** of exquisite **RR Lyrae** light curves

- K2 is a **statistical mission**:
- **occurrence rate** of dynamical phenomena (resonances, extra modes, period doubling, Blazhko-modulation) and
- **dependence** on age, metallicity, (extra)galactic environment, location —> **better understanding**
- **rare objects**

- Golden (well-observed) sample,
- **synergies** with Gaia and LSST
- (parallaxes, proper motions, distances)

- **Galactic structure studies:**
- halo streams, dwarf galaxies



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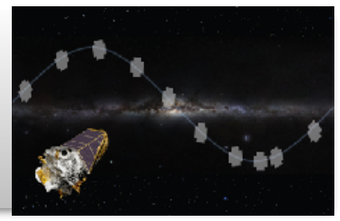

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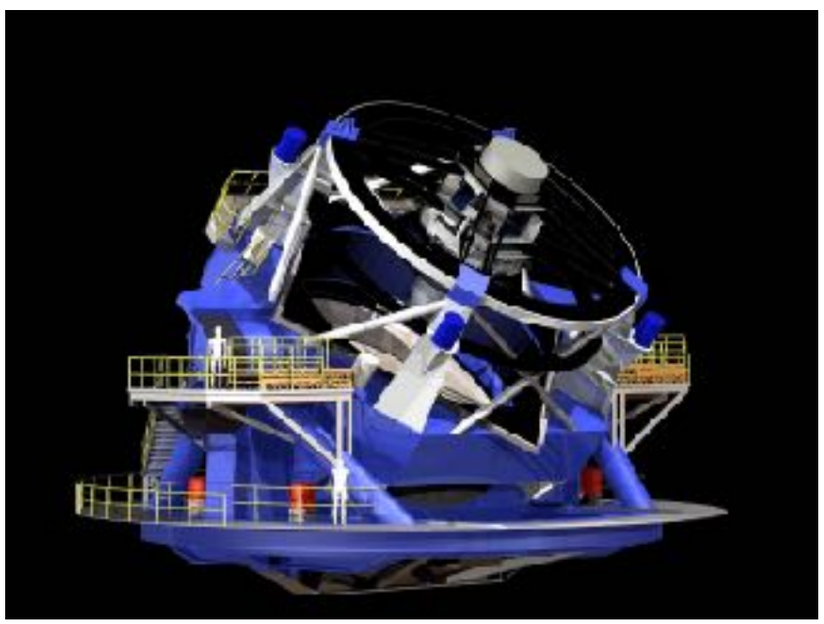
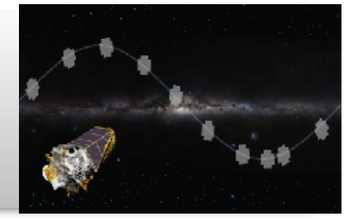


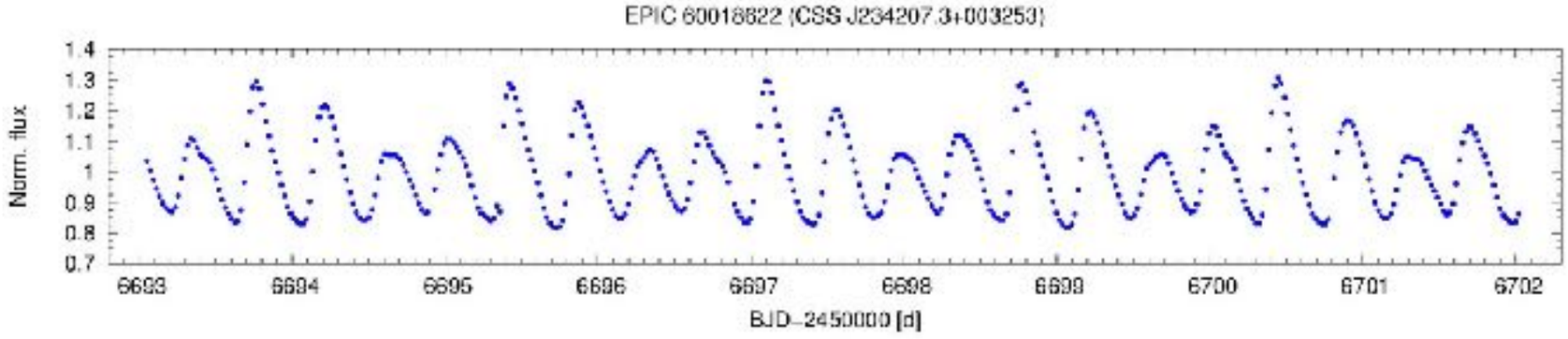
K2 results



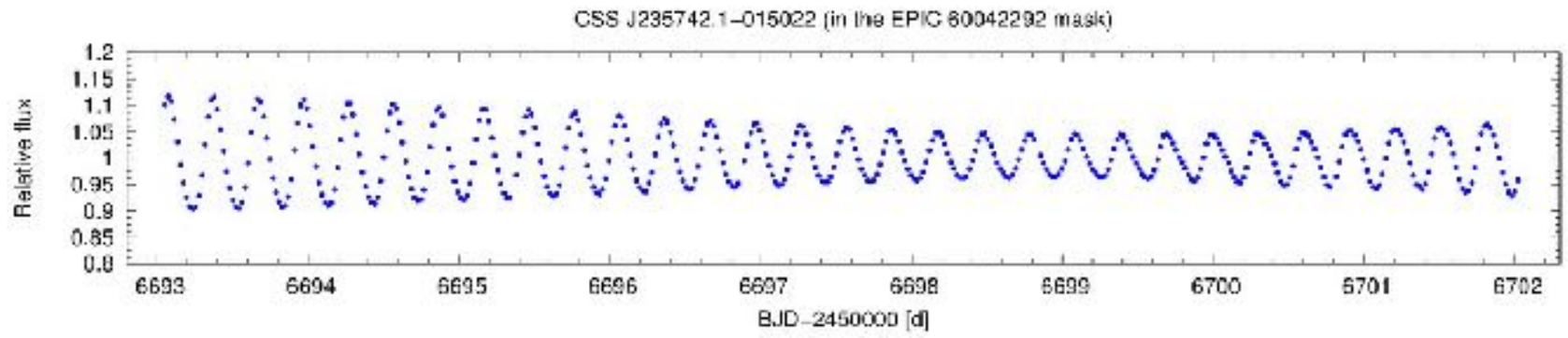
- rare objects (RRd stars, ultra-long period Blazhko modulations, etc.)

- strongly amplitude-modulated RRc

RRd

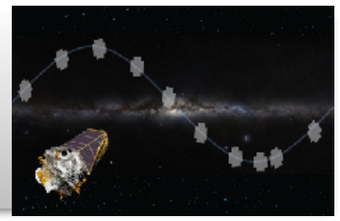


AM RRc

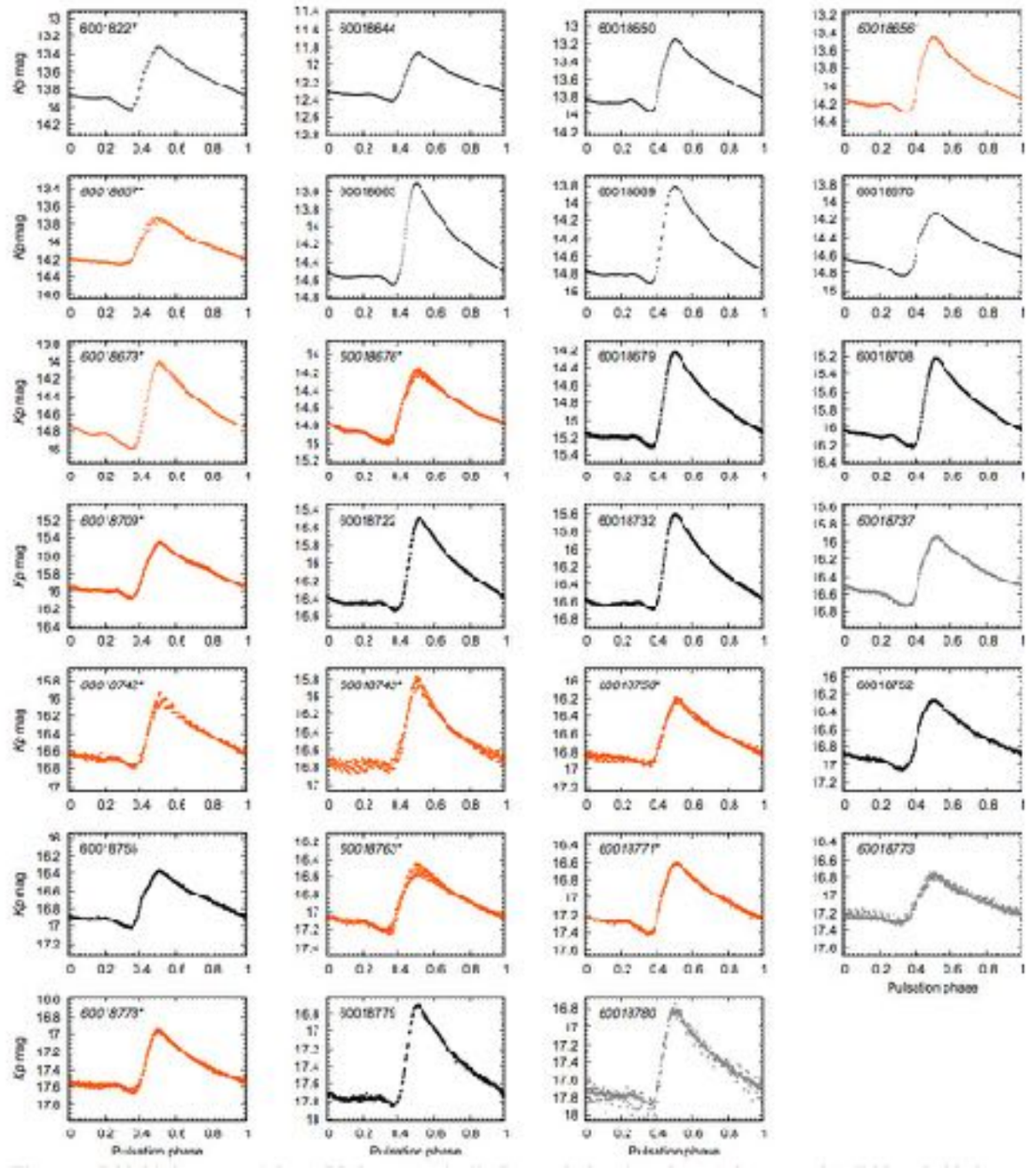


Molnár et al. 2014, IBVS, 6108

K2-E2 field

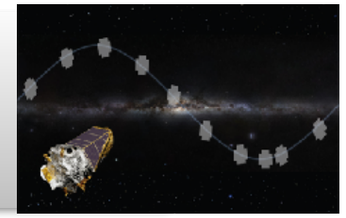


- Most of the stars were discovered in the Catalina Sky Survey (CSS)
- **27 RRab stars** (11 modulated, 3 uncertain, **13 non-modulated**)
- 4 RRc
- 2 RRd

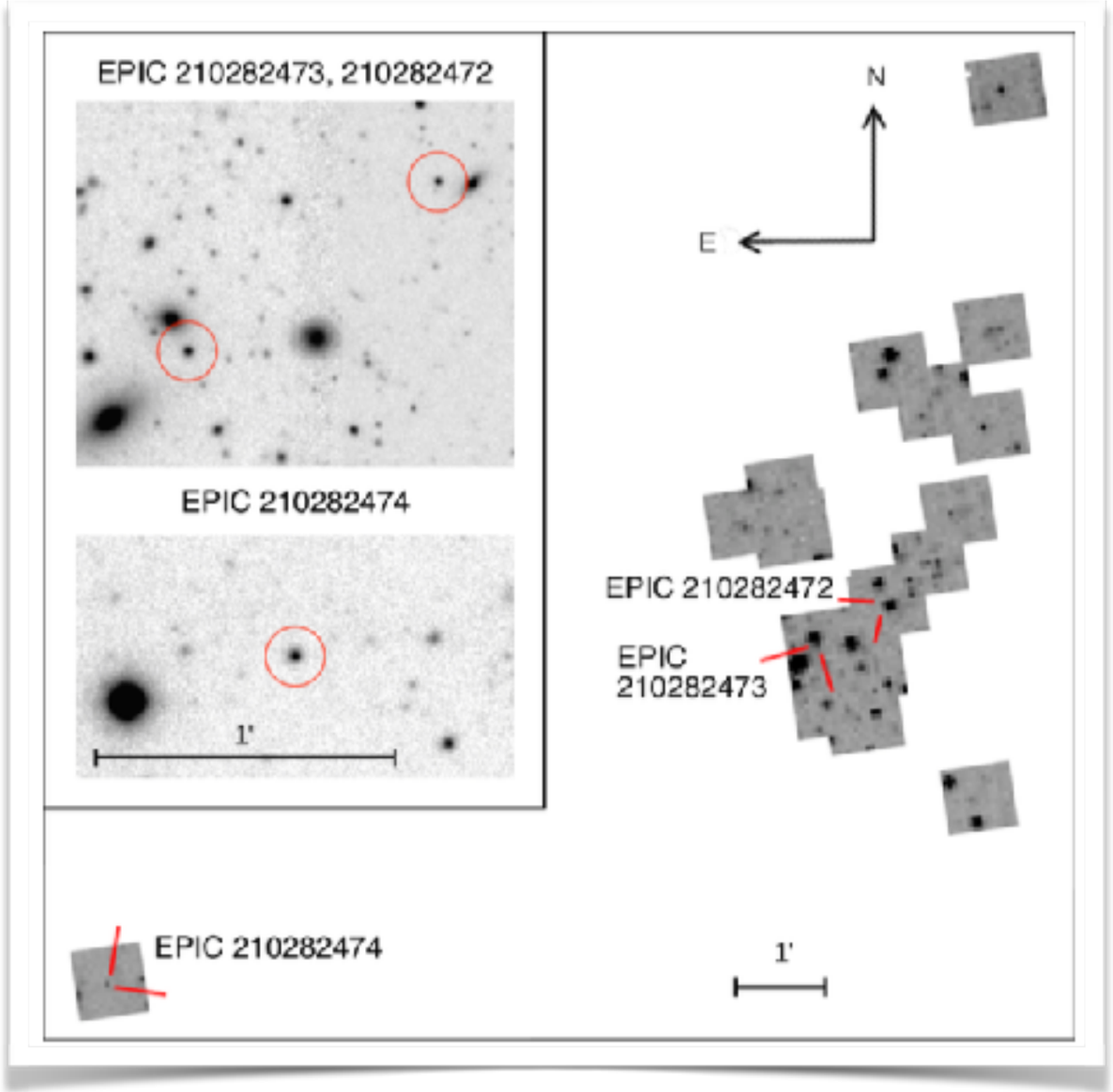


Molnár et al. 2015, MNRAS, **452**, 4283

RR Lyrae stars in Leo IV

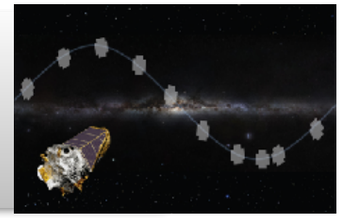


- very small, old dSph
- distance: 160 kpc
- 3 known RR Lyr stars
- V ~ 21.5 mag
- doable with K2

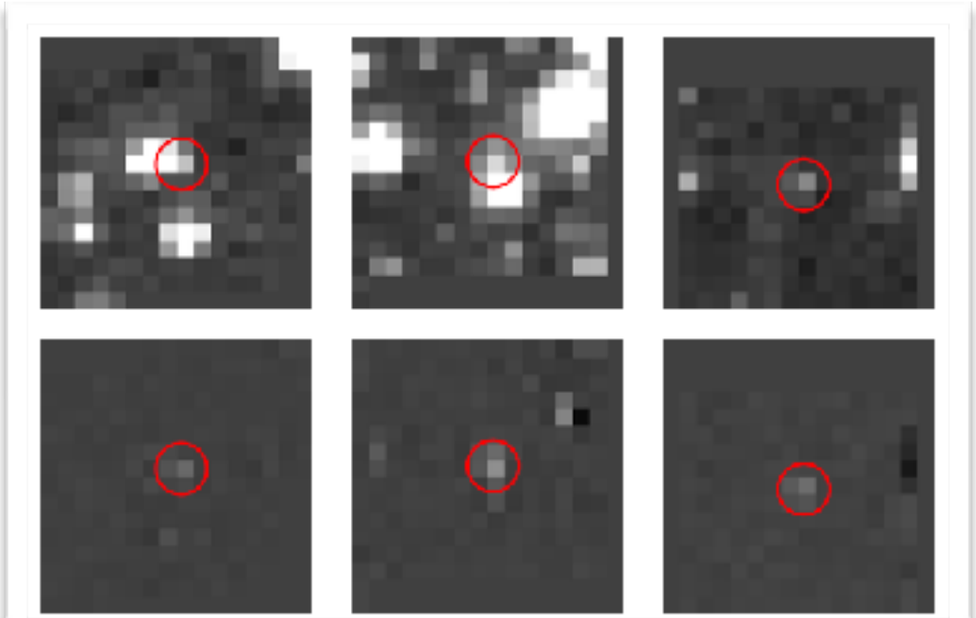


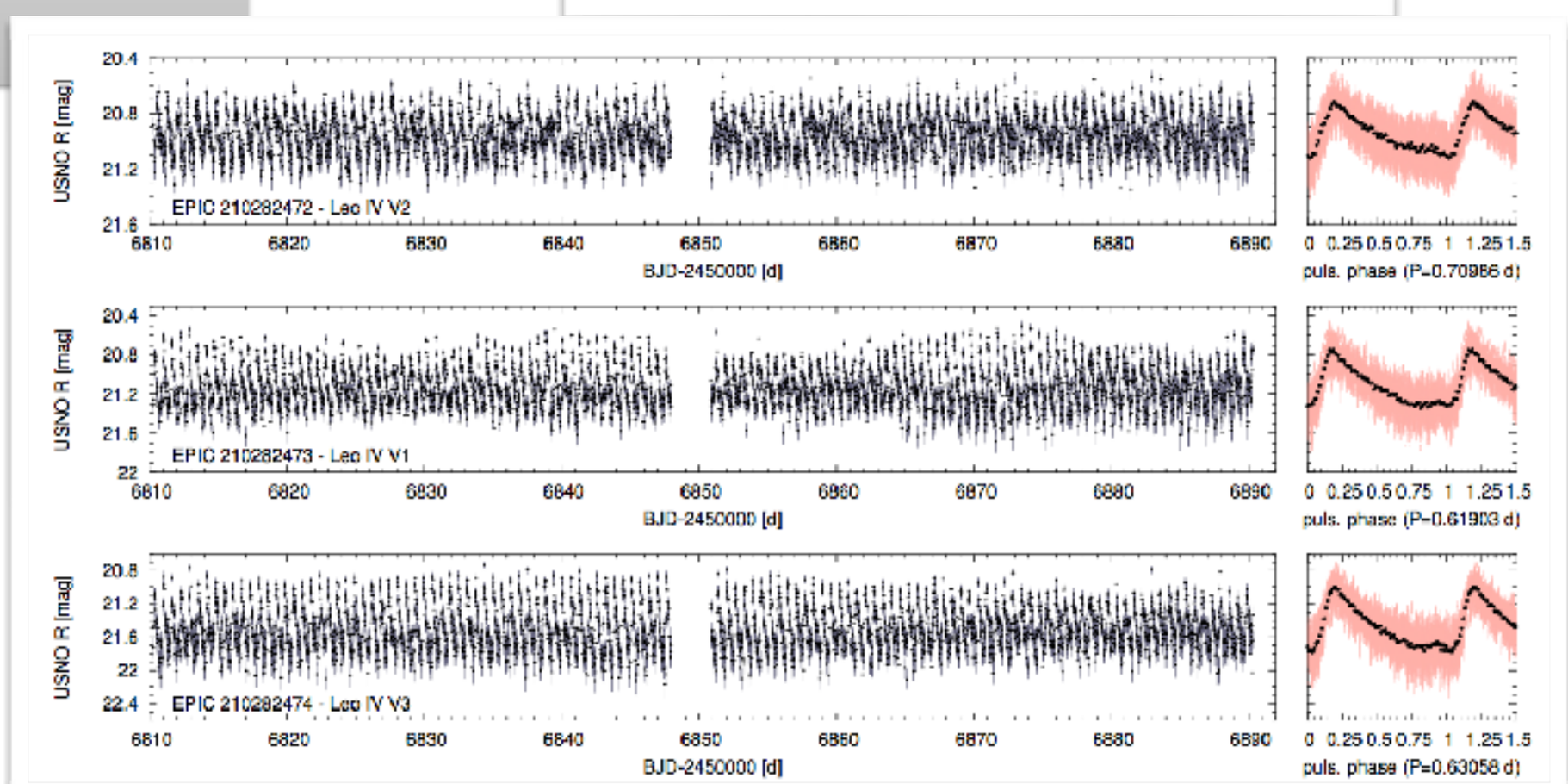
Molnár et al. ApJ, 812, 2, 2015

RR Lyrae stars in Leo IV

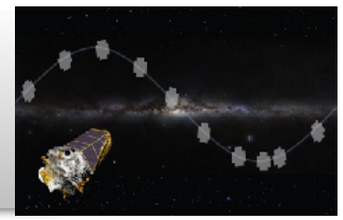


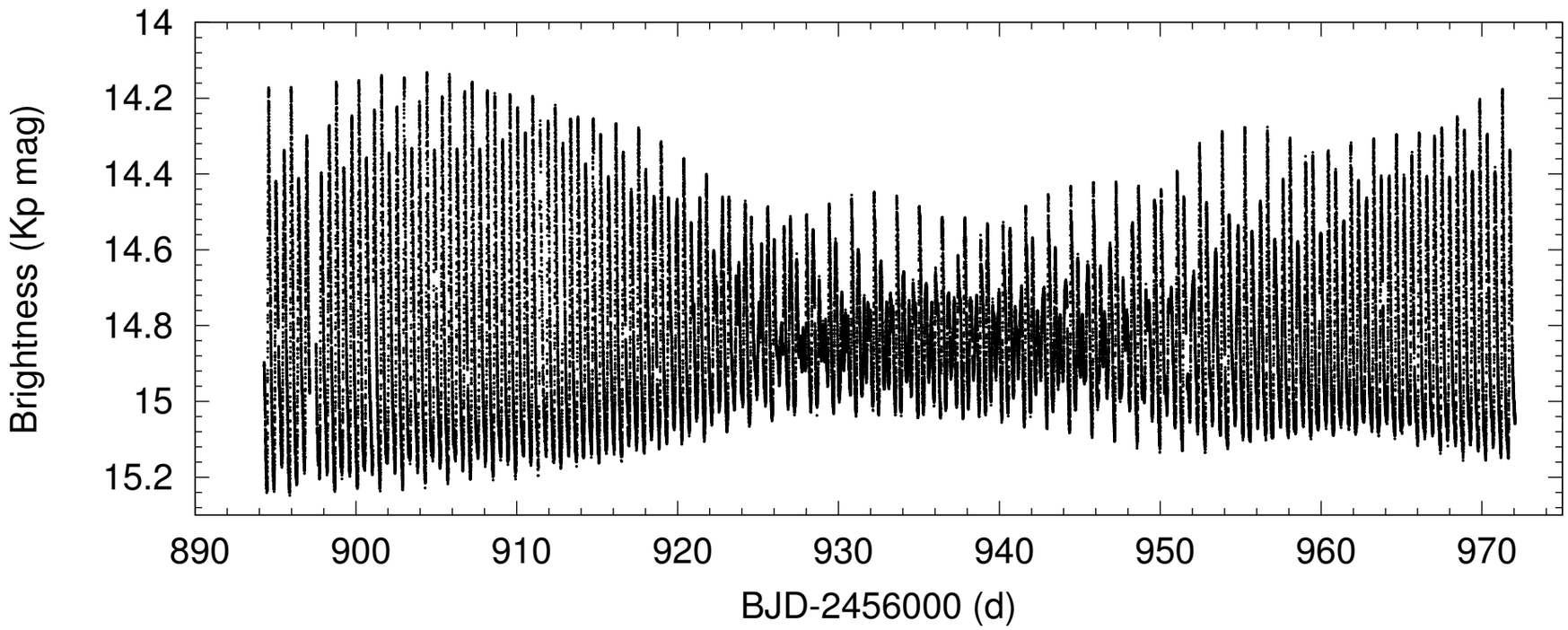
- differential image photometry
- all 3 stars recovered
- clear 30-day modulation
- will be useful for TESS, PLATO





A rare gem: modulated RRd star with K2





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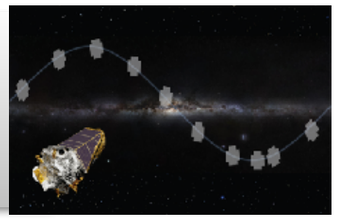

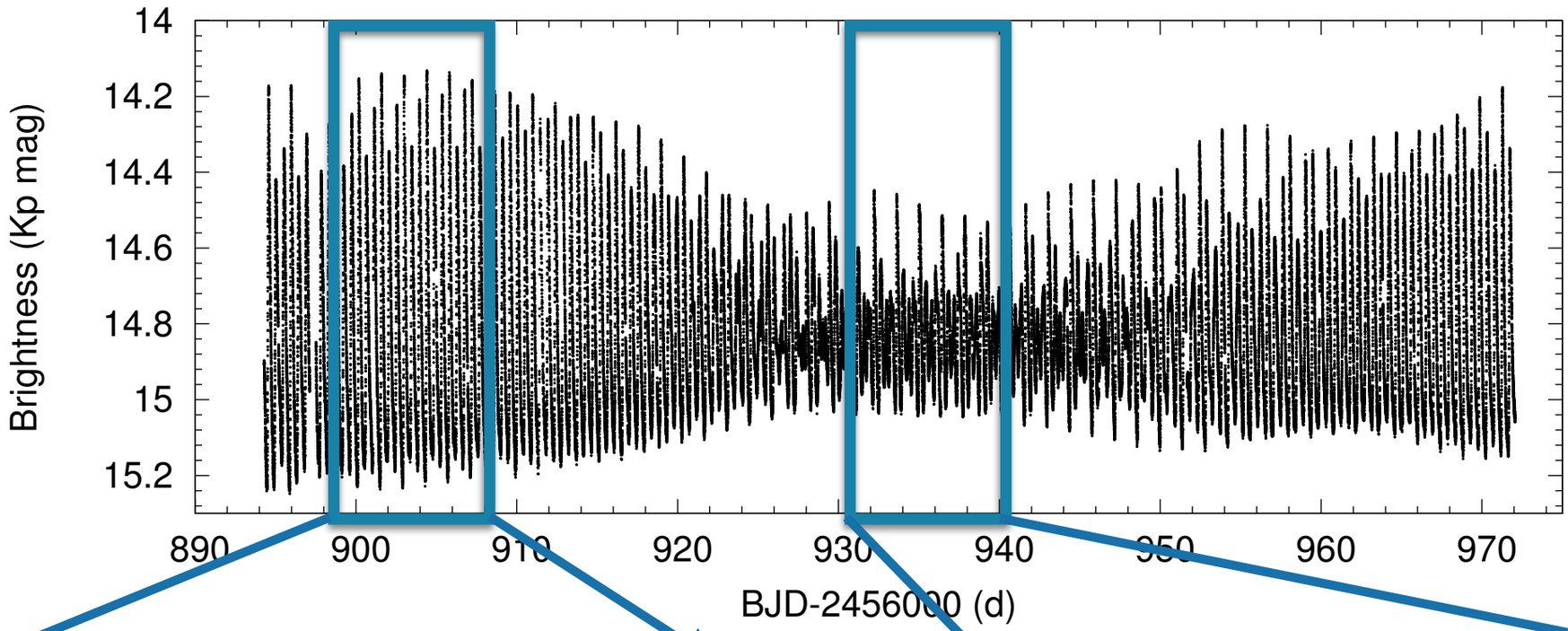

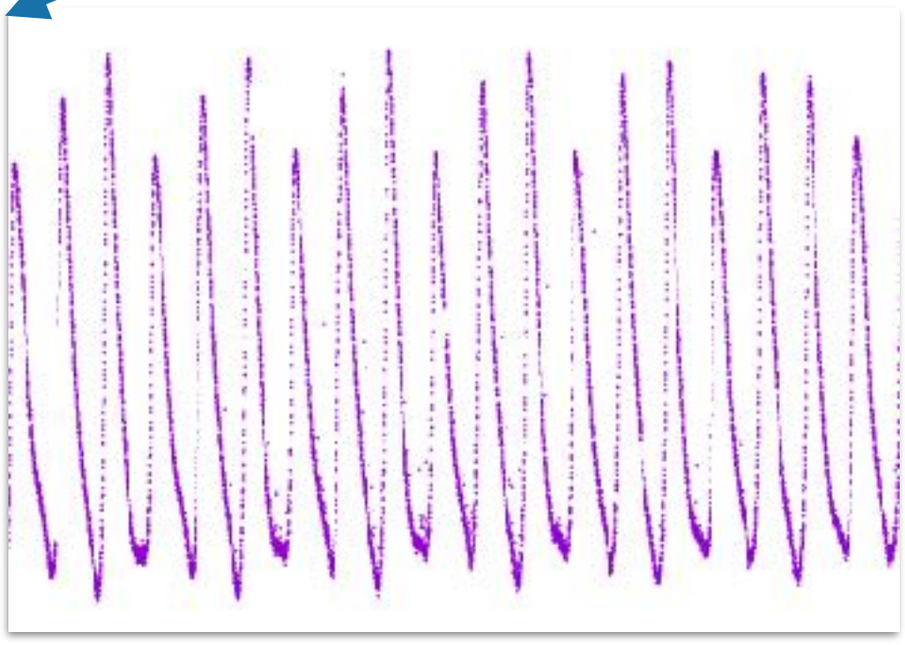

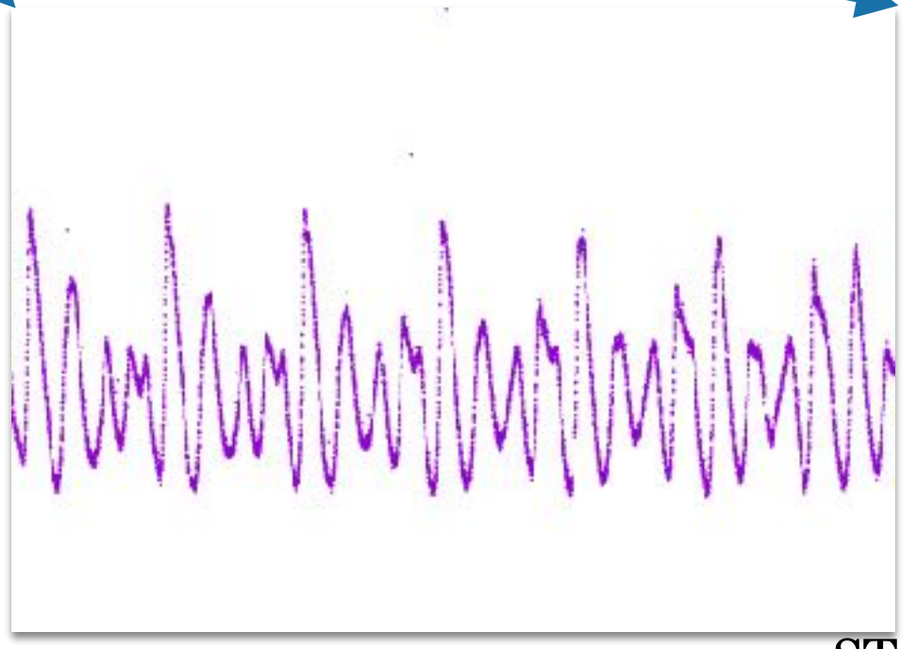

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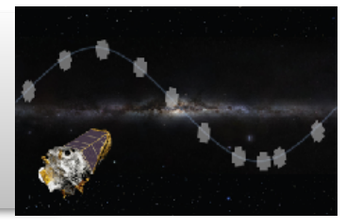

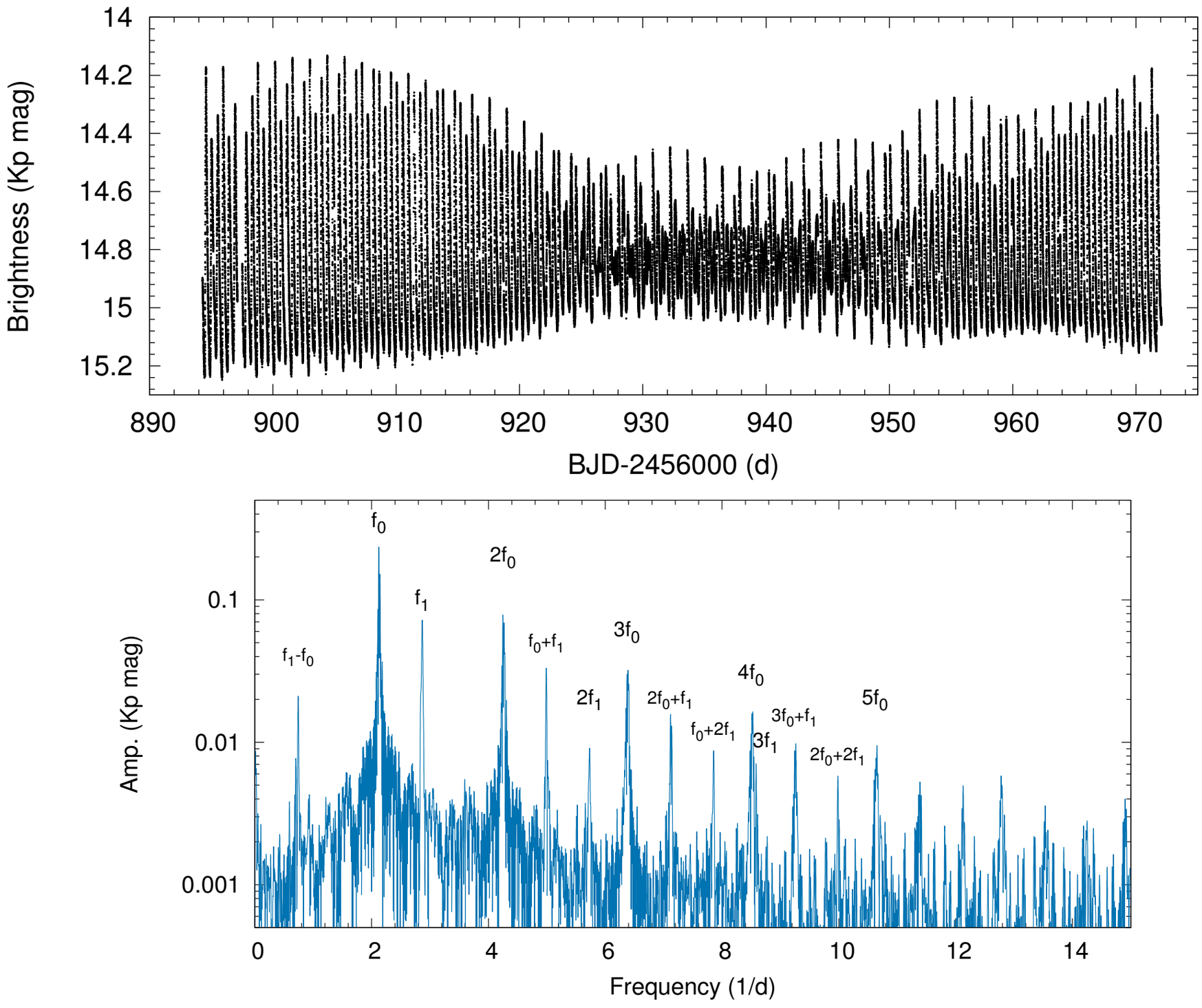

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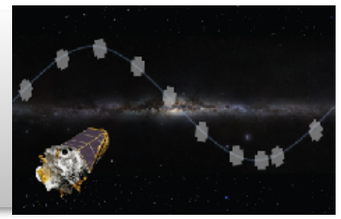
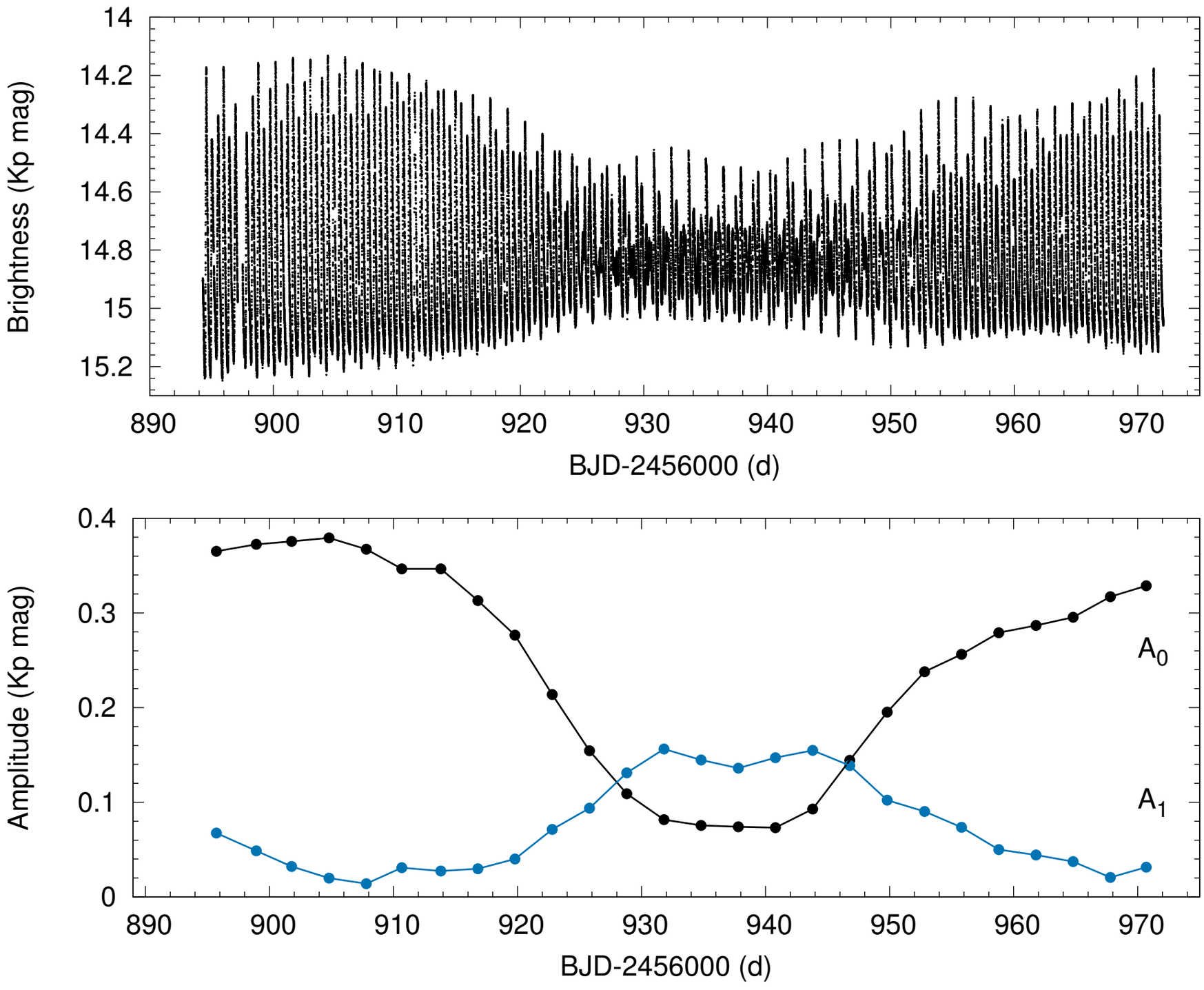
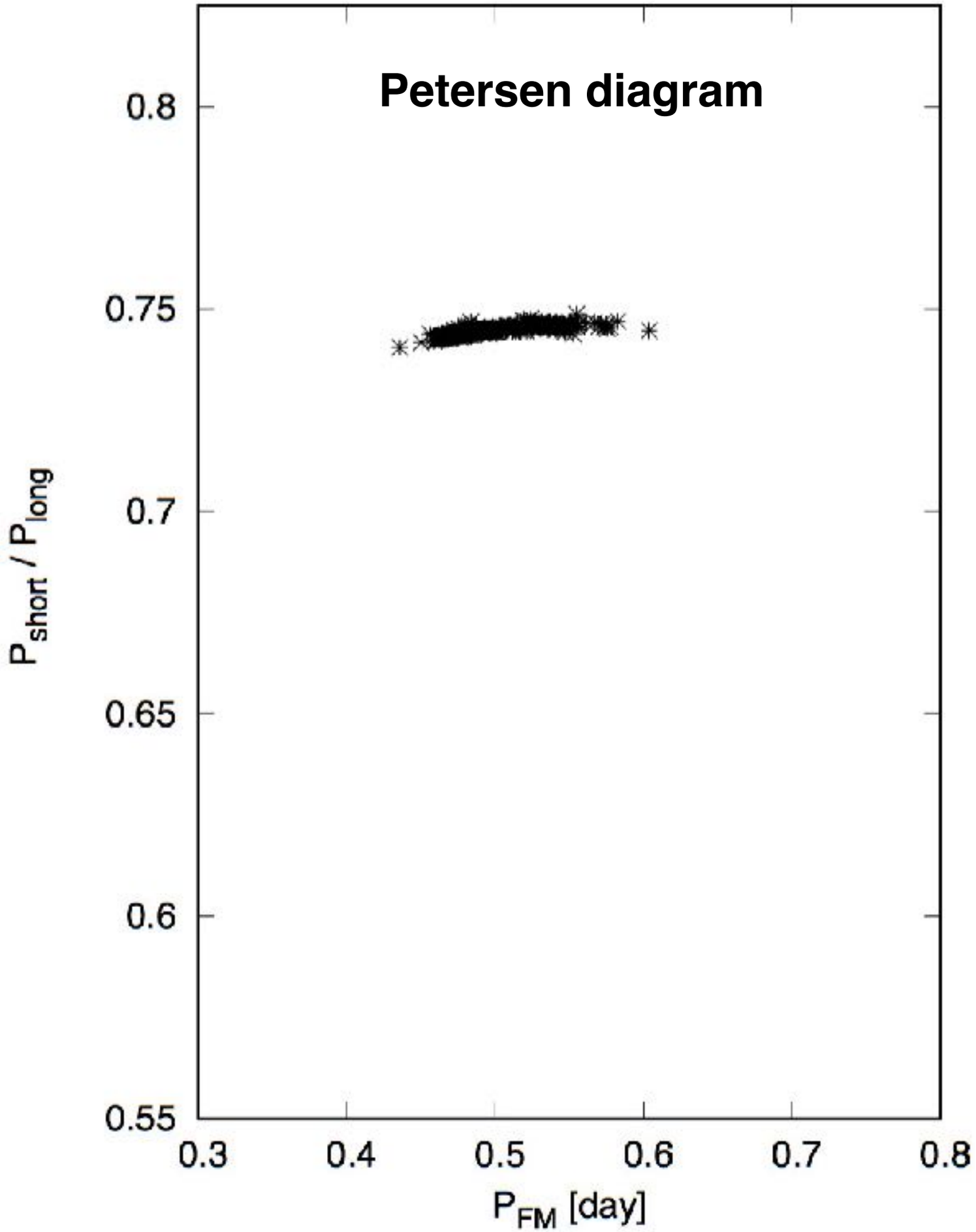





Petersen diagram
0.8
0.75
0.7
0.65
0.6
0.55
0.3
0.4
0.5
0.6
0.7
0.8
P_short / P_long
P_FM [day]

Strongest peaks may be offset from ratios we would expect.

The attitude correction frequency of K2. No blue points along these lines.

Orange diamonds are all from RR Lyr!

Anomalous RRds really spread out, and overlap with some RRabs.

Classical RRd stars are confined to this thin band. Crosses are weird ones (e.g. Blazhko, mode switchers). Note overlap with some RRab additional modes: likely those are the <u>radial first overtone</u> in at least some of them too.

What The Frequency???

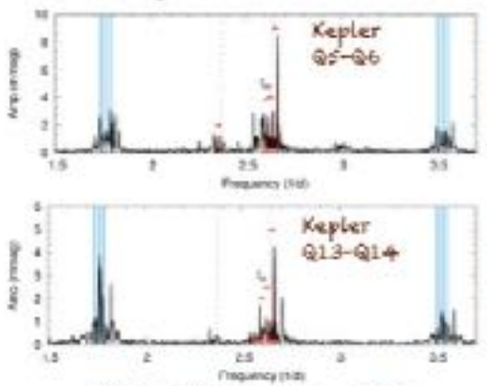
The $P:P_o$ = 2:3 ratio – this is where the half-integer peaks of <u>period doubling</u> (PD) are expected. These are the signs of dynamical instability caused by a 9:2 resonance with the <u>9th overtone</u>.

Is the f_2 group here the <u>second radial overtone</u>? Period ratios agree, but not seen in non-linear 1D hydro models yet.

V1127 Aql, the only short-period one.

P_{short}/P_{long}

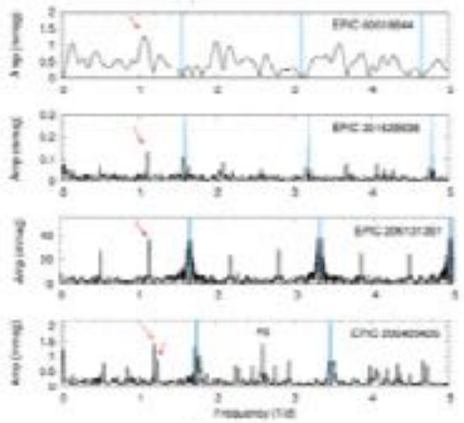
P_{FM} (day)



<u>RR Lyr is super-weird:</u> solid reds are forests of peaks separated by the Blazhko frequency. Dashed reds are expected values.

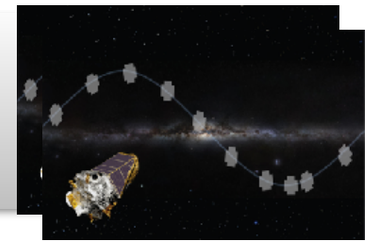
Could these be <u>g-modes</u> up here? Strongest signals have longer periods than the fundamental mode, but...

...the f+fo peak is in the second-overtone region. Non-radial f_2 modes with weird geometry perhaps?



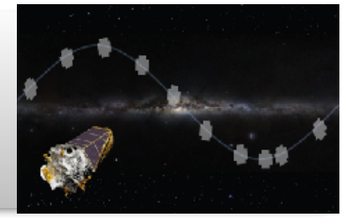
RRabs: blue – K2; red dots – Kepler; red circles – CoRoT; triangles – ground-based RRds: grey – OGLE-IV; black: field; crosses: anomalous

Take home messages



- **Space photometry** has revolutionized the study of classical variable stars
- New **dynamical phenomena** can be studied:
  - period doubling, resonances
  - additional (nonradial) modes
  - complex and frequent modulations
- K2, TESS, PLATO: **bright future** for space photometry
- **K2 RR Lyrae survey:**
  - light curves will be public (contact: rszabo@konkoly.hu)
  - golden sample to calibrate and study upcoming **Gaia** and **LSST** data

Prof. Don W. Kurtz + RR Lyrae stars



The Impact of Large-Scale Surveys on Pulsating Star Research
ASP Conference Series, Vol. 203, 2000
L. Szabados & D. W. Kurtz, eds.

A New Look at the Blazhko Effect in RR Lyrae Stars with High-Quality Data from the MACHO Project

D. W. Kurtz [1], C. Alcock [2,3], R. A. Allsman [4], D. Alves [2,4,5], T. S. Axelrod [6], A. C. Becker [7], D. P. Bennett [2,3,8], K. H. Cook [2,3], K. C. Freeman [6], K. Griest [3,9], M. J. Lehner [3,10], S. L. Marshall [2,3,11], D. Minniti [2,15], B. A. Peterson [6], M. R. Pratt [3,7,12], P. J. Quinn [13], A. W. Rodgers [6,17], C. W. Stubbs [3,7], W. Sutherland [14], A. Tomaney [7], D. L. Welch [15] (The MACHO Collaboration)

Abstract. We present the first results of the analysis of 22 Blazhko stars. We find: 1) Blazhko RRab stars that are nearly pure amplitude modulators; 2) Blazhko RRab stars that have both amplitude and phase modulation; 3) A Blazhko RRab star that has an abrupt period change; 4) Proof of the Blazhko effect in RRc stars. Our data show the character of the amplitude and phase modulations of the light curves over the Blazhko cycles far better than has been previously possible.

Discussion

Luis Balona: Have you seen any significant power in frequencies independent of the main pulsation frequency or the Blazhko frequency? These would be good candidates for nonradial pulsation.

Don Kurtz: Yes, we do sometimes see additional frequencies. However, I have not yet seen one when there is convincing evidence that it is real; i.e. they often are integral numbers of d^{-1}, or are associated with amplitude or phase variability.

Mike Jerzykiewicz: Don, I believe the first analysis which showed equidistant frequency triplets was that of Borkowski on AR Her. The paper was published in Acta Astronomica in 1980.

Don Kurtz: Sorry, Mike. I was unaware of that. I will look it up.

Géza Kovács: What percentage of the MACHO RRab dataset did you sample in your selection procedure of Blazhko stars?

Don Kurtz: I don't know. We were selecting interesting stars to study in detail, rather than doing a systematic survey. For that, see the poster paper by Kovács et al. in these proceedings (p. 313).

Horace Smith: You make a clear case that surveys such as the MACHO survey will revolutionize this subject. I wish to make a plea for continued long-term observations of Blazhko stars as well. Such observations are important for identifying changes in the phase, amplitude, or period of the Blazhko effect on many-year time scales, changes which may help decide among alternative explanations.

Robert Buchler: Have you done any time-dependent Fourier decomposition of the light curves? The temporal variation of these light-curve shape parameters could give us important dynamical information about the Blazhko mechanism, and help us discriminate between some of the proposed models. In the proceedings of the previous pulsation conference in Los Alamos I presented such an analysis that I performed on the old data of Balázs-Detre and of Walraven. What was particularly striking was that the Fourier phase ϕ_{21} was oscillatory, rather than running.

Don Kurtz: I haven't done that yet, but I can and will. I'll send you the results.

Alex Schwarzenberg-Czerny: Important information in the data on the Blazhko effect is the coherence of the modulation. The present surveys are long enough to investigate that, either in the time domain (changes in Blazhko period and amplitude), or in the frequency domain (broadening of sidelobes with respect to the window function central peak).

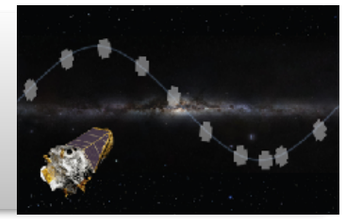
Hiromoto Shibahashi: I noticed from your tables shown us that the relative ratio of the amplitudes of the side-components to the central component of the triplet becomes larger with the increase of the harmonic order. Is it the general tendency common in all the other stars which you have analyzed?

Don Kurtz: Yes, it is. The higher amplitude of the outside pair of frequencies in the harmonic triplets, relative to the central frequency, describes the fact that the light curve is more nearly sinusoidal at Blazhko minimum and more non-sinusoidal at Blazhko maximum. This can be seen in the light curves themselves.

Darragh O'Donoghue: Are the data you have presented consistent with the theories which will be presented at this meeting?

Don Kurtz: By fiddling with various parameters in those theories, the answer is probably yes. That means the solution to the Blazhko effect is still unknown.

Prof. Don W. Kurtz + RR Lyrae stars



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

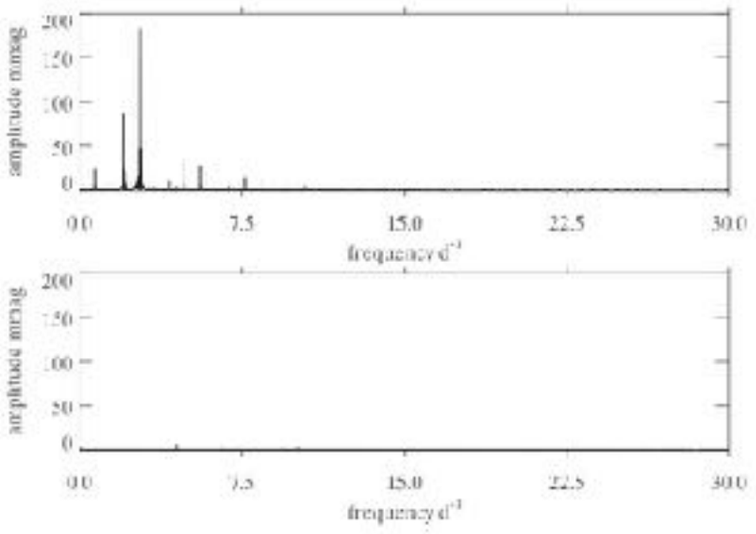
MNRAS 455, 1237–1245 (2016) doi:10.1093/mnras/stv2377

EPIC 201585823, a rare triple-mode RR Lyrae star discovered in K2 mission data

Donald W. Kurtz,[1★] Dominic M. Bowman,[1] Simon J. Ebo,[1] Paweł Moskalik,[2] Rasmus Handberg[3] and Mikkel N. Lund[3]

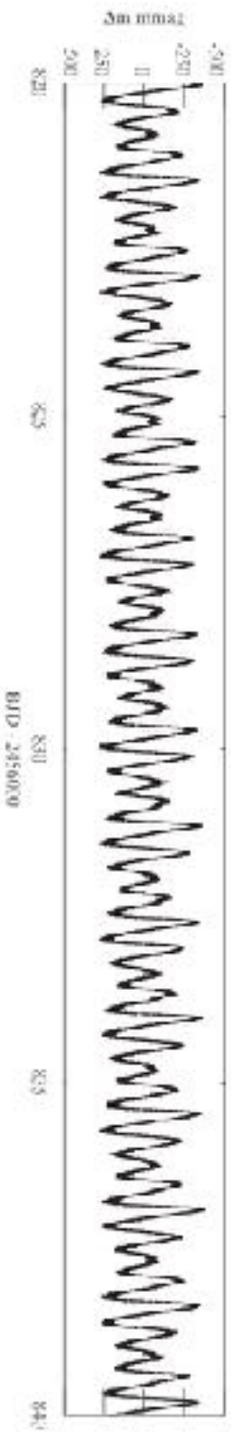
[1] *Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE, UK*
[2] *Copernicus Astronomical Center, ul. Bartycka 18, PL-00-716 Warsaw, Poland*
[3] *Stellar Astrophysics Centre (SAC), Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark*

Accepted 2015 October 11. Received 2015 October 5; in original form 2015 August 5

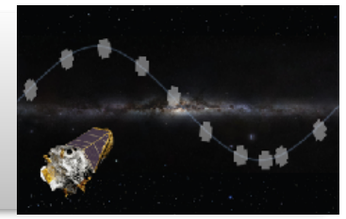


ABSTRACT

We have discovered a new, rare triple-mode RR Lyr star, EPIC 201585823, in the *Kepler* K2 mission Campaign 1 data. This star pulsates primarily in the fundamental and first-overtone radial modes, and, in addition, a third non-radial mode. The ratio of the period of the non-radial mode to that of the first-overtone radial mode, 0.616 285, is remarkably similar to that seen in 11 other triple-mode RR Lyr stars, and in 260 RRc stars observed in the Galactic bulge. This systematic character promises new constraints on RR Lyr star models. We detected subharmonics of the non-radial mode frequency, which are a signature of period doubling of this oscillation; we note that this phenomenon is ubiquitous in RRc and RRd stars observed from space, and from ground with sufficient precision. The non-radial mode and subharmonic frequencies are not constant in frequency or in amplitude. The amplitude spectrum of EPIC 201585823 is dominated by many combination frequencies among the three interacting pulsation mode frequencies. Inspection of the phase relationships of the combination frequencies in a phaser plot explains the 'upward' shape of the light curve. We also found that raw data with custom masks encompassing all pixels with significant signal for the star, but without correction for pointing changes, is best for frequency analysis of this star, and, by implication, other RR Lyr stars observed by the K2 mission. We compare several pipeline reductions of the K2 mission data for this star.



Prof. Don W. Kurtz + RR Lyrae stars



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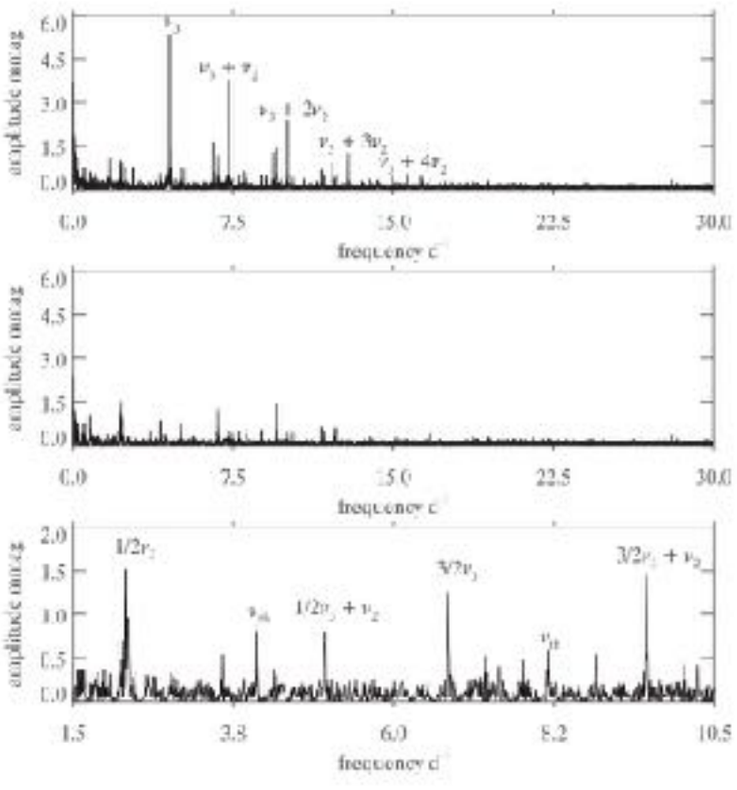

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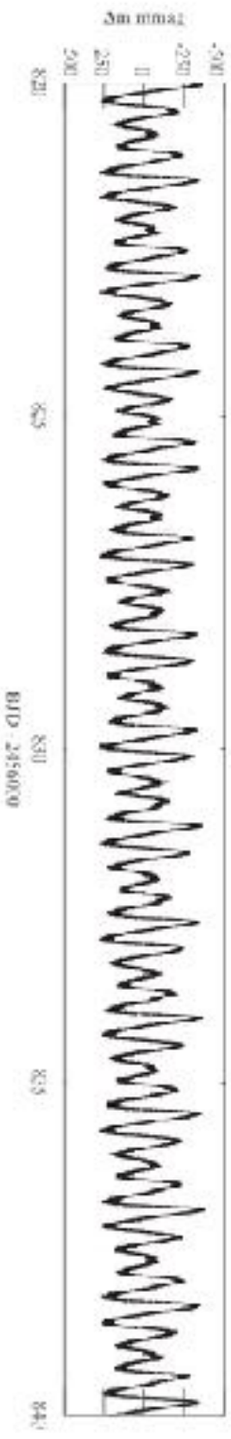
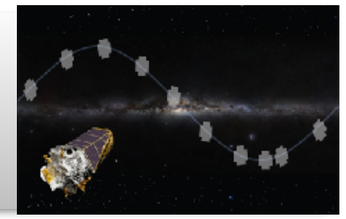


Prof. Don W. Kurtz



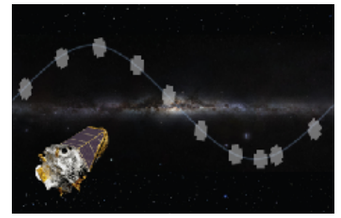
Personal thoughts

He helped in

- **research/scientific questions**
- **research group organization**
- **career development,**
  job/grant applications
- **astronomy outreach**
- **administration**

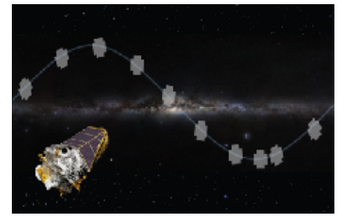
He never said ‘no’

CSFK



Thank you

CSFK



Thank you

Don