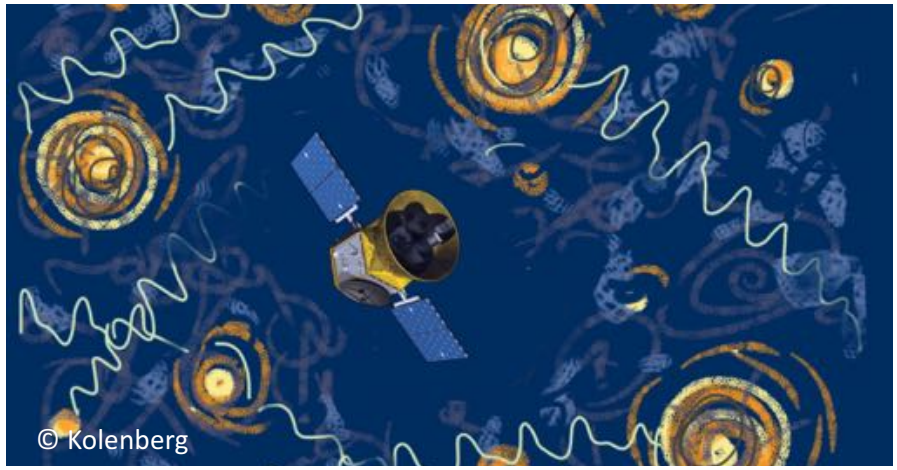
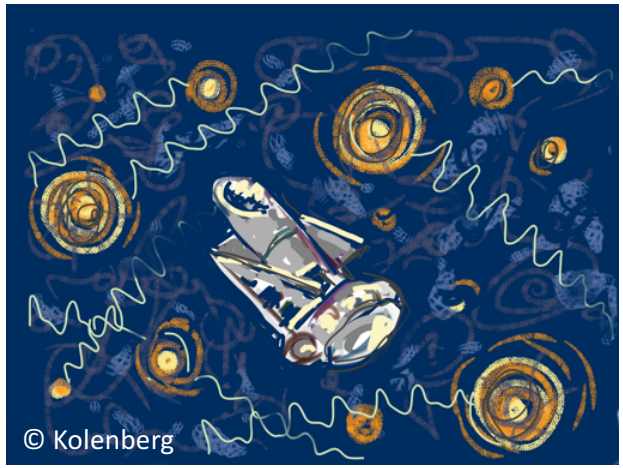
# Classical pulsators and space mission data




Katrien Kolenberg

*4th European Variable Star meeting, 14-15 September 2019, Mira Grimbergen, Belgium*

# Classical Pulsators & Space Missions & You

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# Classical Pulsators & Space Missions & You

Classes of Classical Pulsators

Setting the scene - before the space missions - expectations

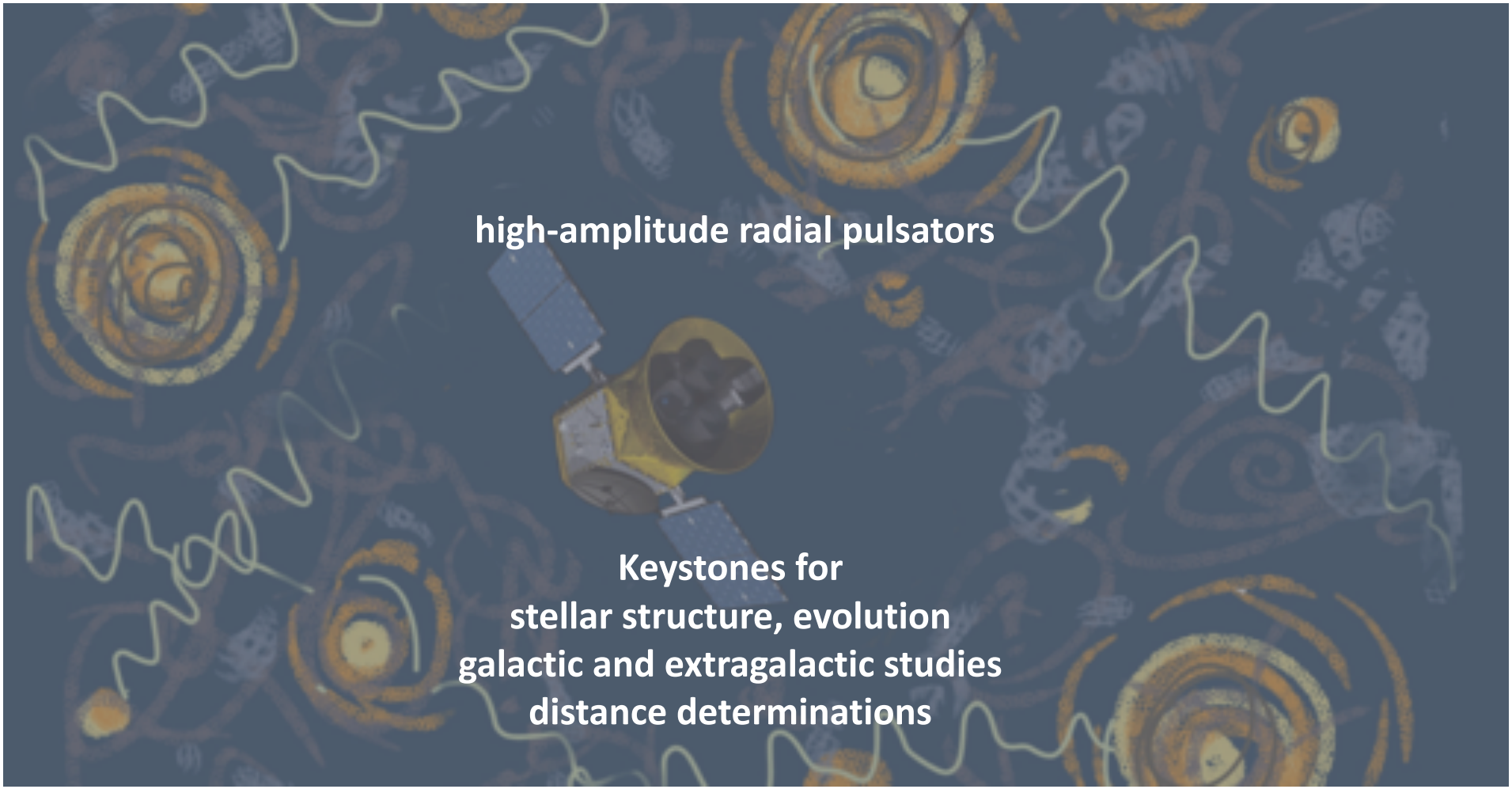
Space photometry – benefits, challenges, opportunities for “amateurs”

**Kepler take-aways**

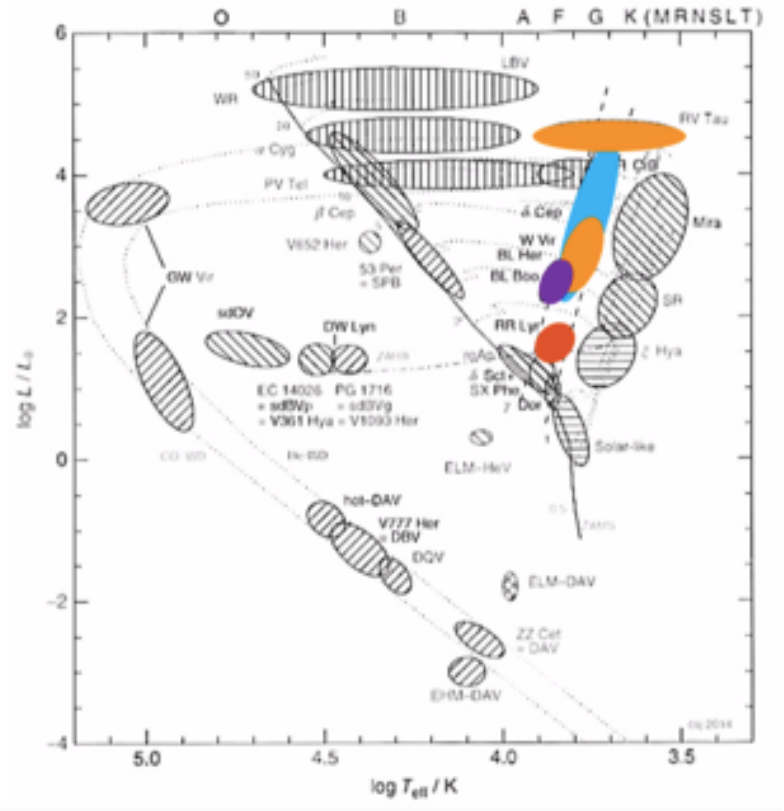
**TESS: First highlights** for (subtypes of) Cepheids, for RR Lyrae stars

Hopes, plans and fine-tuned expectations

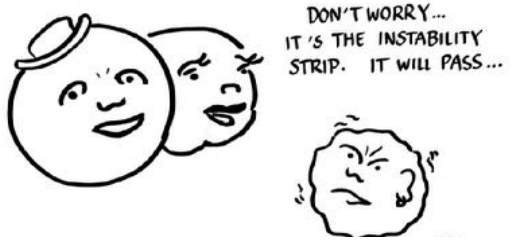
Take-home messages - for Pro-Am collaborations


high-amplitude radial pulsators
Keystones for
stellar structure, evolution
galactic and extragalactic studies
distance determinations

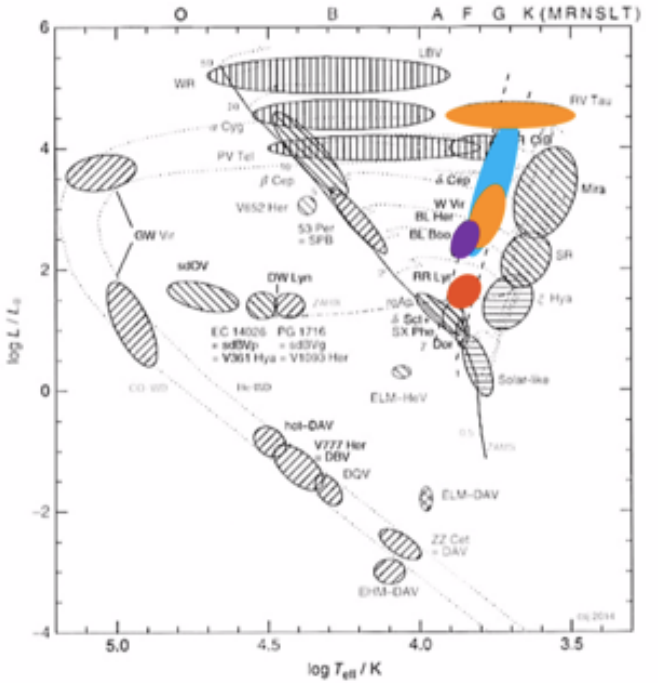
# Classes of Classical Pulsators




HRD of pulsating stars, adapted from Jeffery (2008)



# Classes of Classical Pulsators



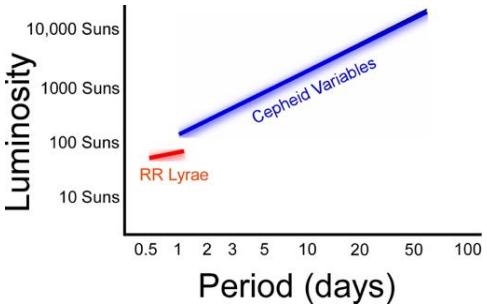

**Classical Cepheids:** Pop. I. , 4-9 $M_{\odot}$, period: ~ 1 d - hundreds of days

**Type II Cepheids:** Pop. II., 0.5-0.8 $M_{\odot}$, 3 subtypes according to evolutionary stages and period: 1 d < BL Her < 4 d < W Vir < 20 d < RV Tau

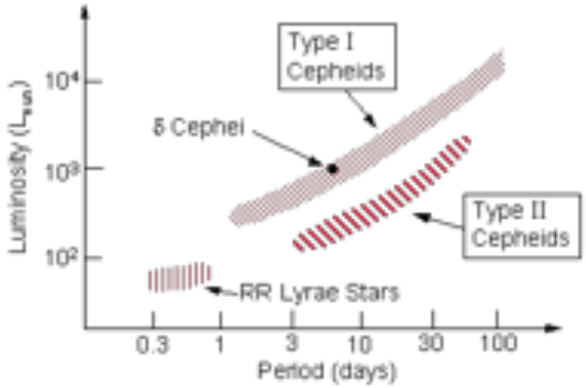
**RR Lyraes:** Pop. II., 0.5-0.6 $M_{\odot}$, period: ~0.2 - 1 days

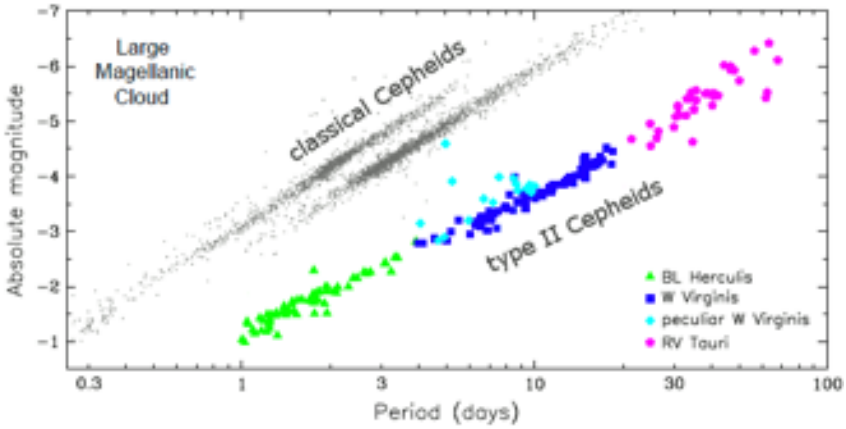
**Anomalous Cepheids:** Pop. II, in between RR Lyrae and Type II, uncertain origin, 1.3-2 $M_{\odot}$ , period: ~0.4 - 3 days,

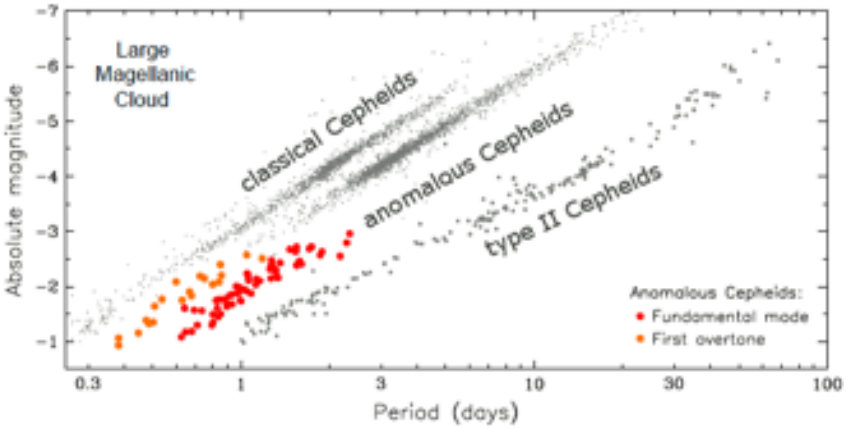
# Classes of Classical Pulsators

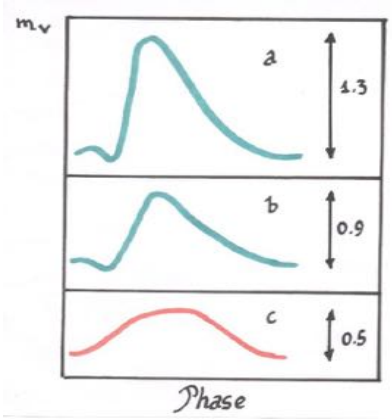



## Leavitt Law



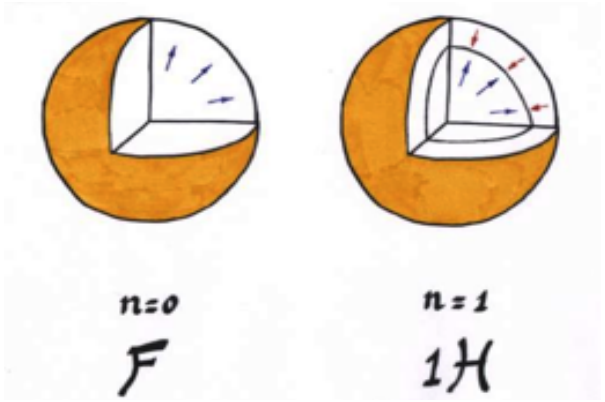






RRab F

RRc 1H

RRd F + 1H

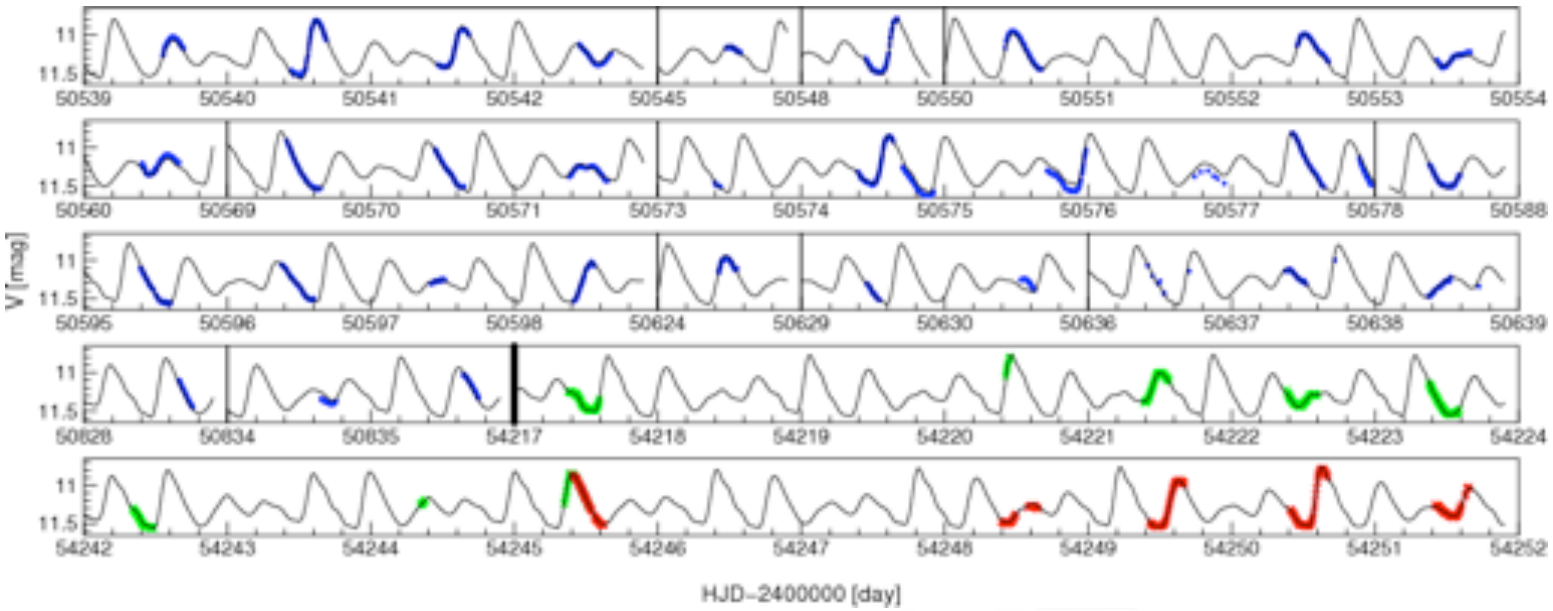



n=2, …

**Pulsation modes: radial pulsation**

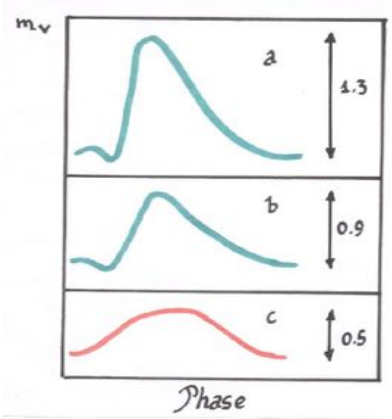
→ expected period ratios

# RR Lyrae Stars: General Properties




& RRd F+1H

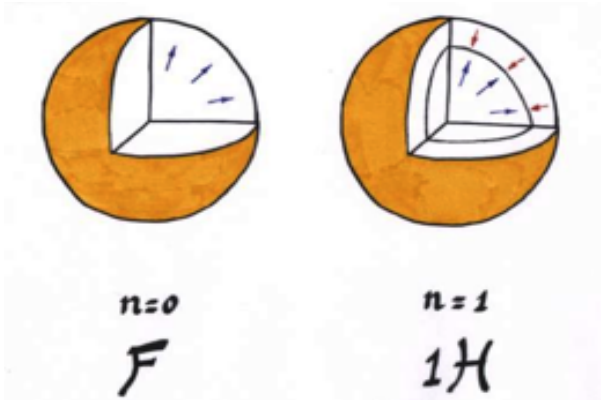
# Classes of Classical Pulsators




RRab F

RRc 1H

RRd F + 1H

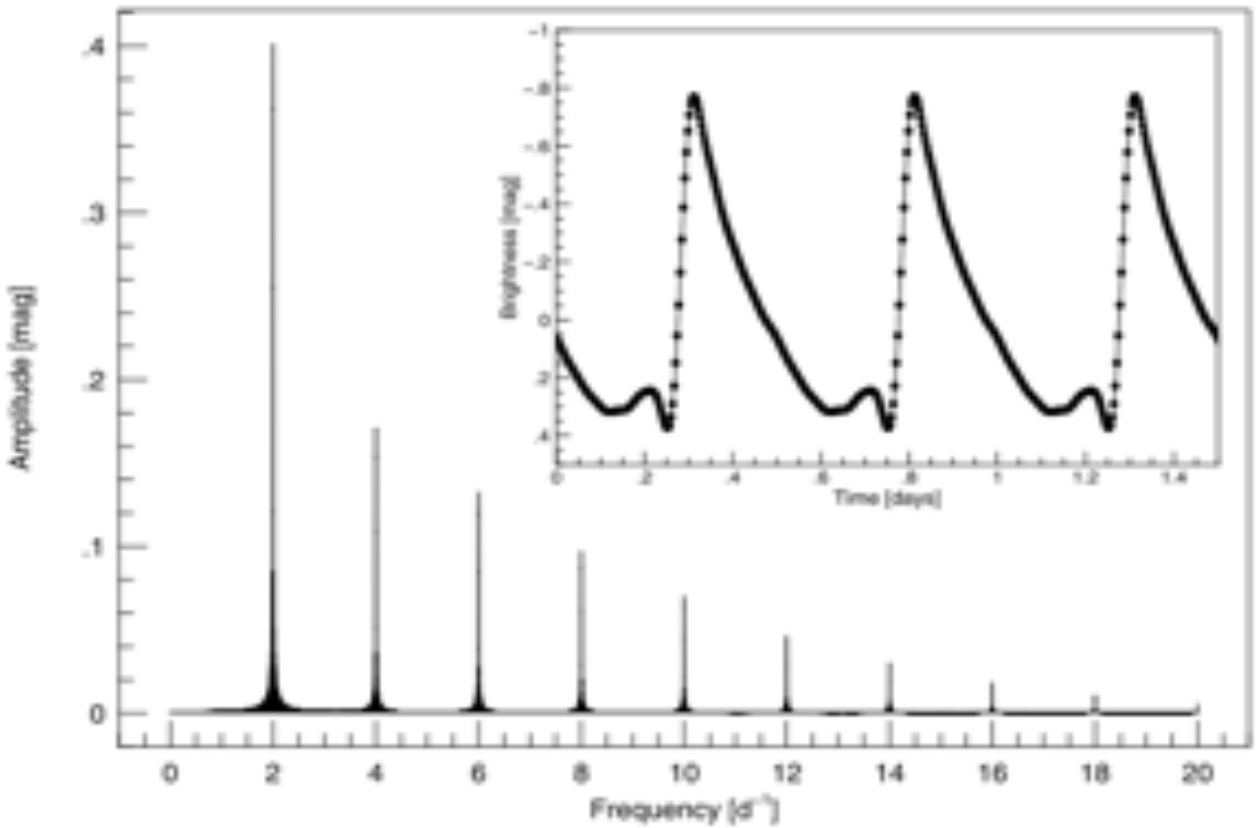



n=2, …

**Pulsation modes: radial pulsation + modulation**
**+ period doubling**
**+ low-amplitude additional modes**
**+ other instabilities**

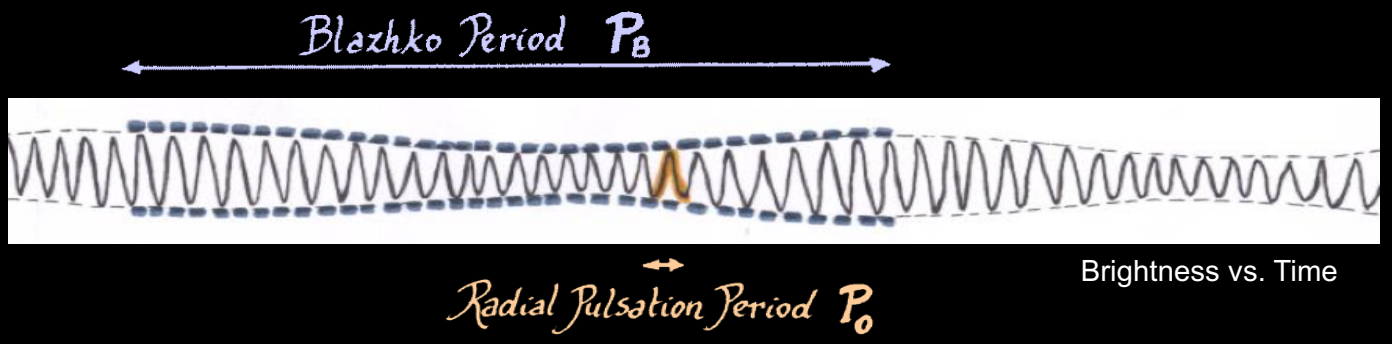
**(cycle-to-cycle changes, period jitter)**

**Light curve & Fourier decomposition**



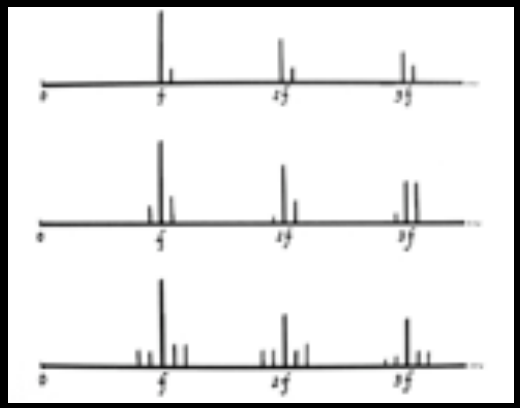

**+ deviations**

*(Blazhko 1907)*

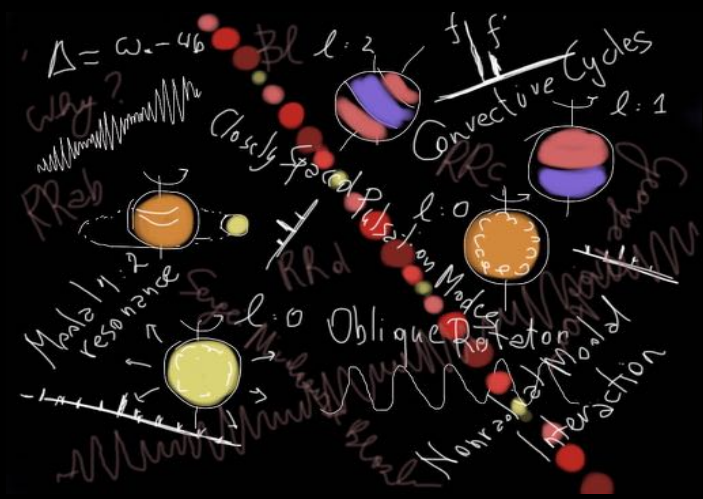


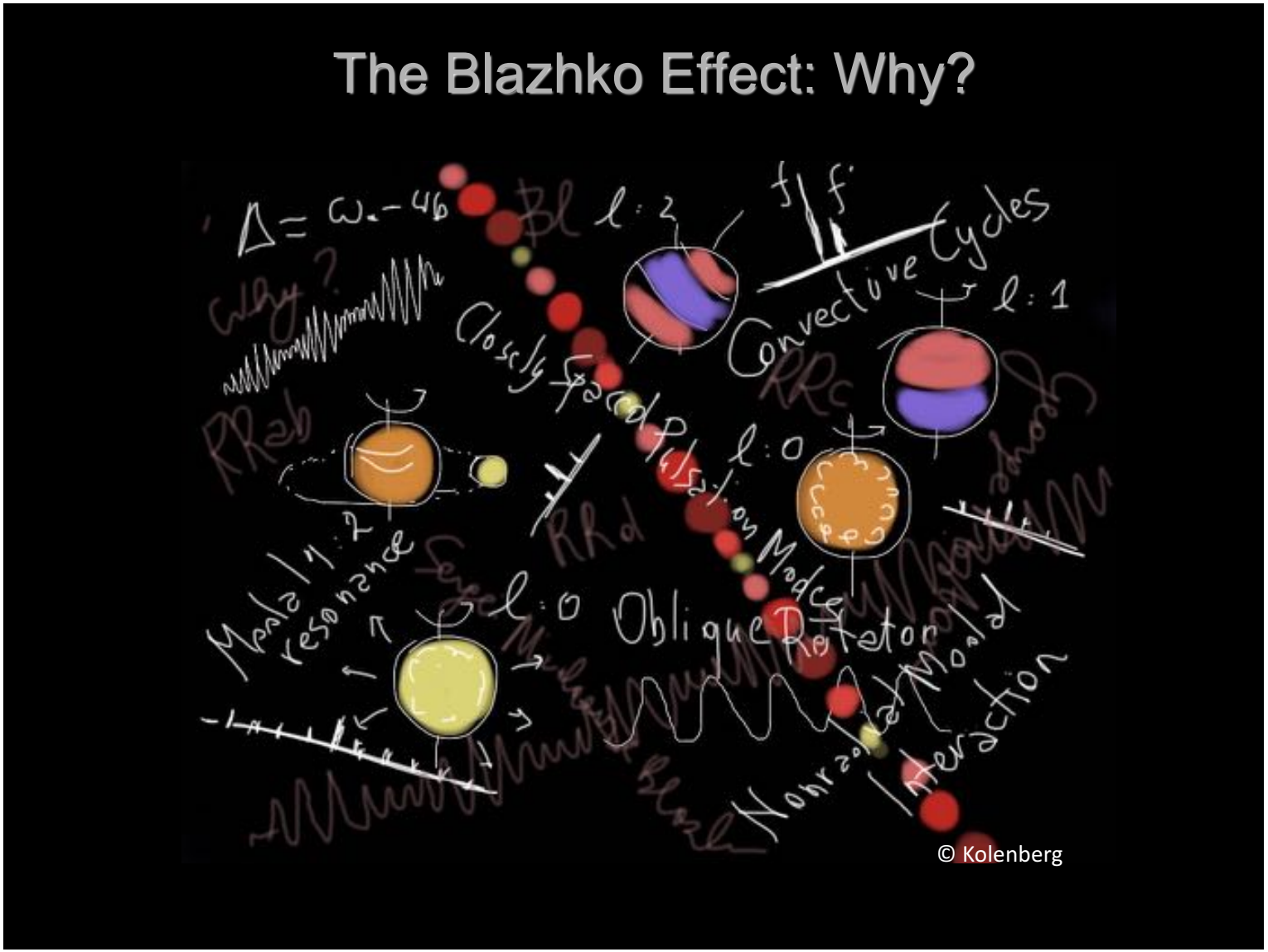

Brightness vs. Time

## Modulation
## Blazhko effect

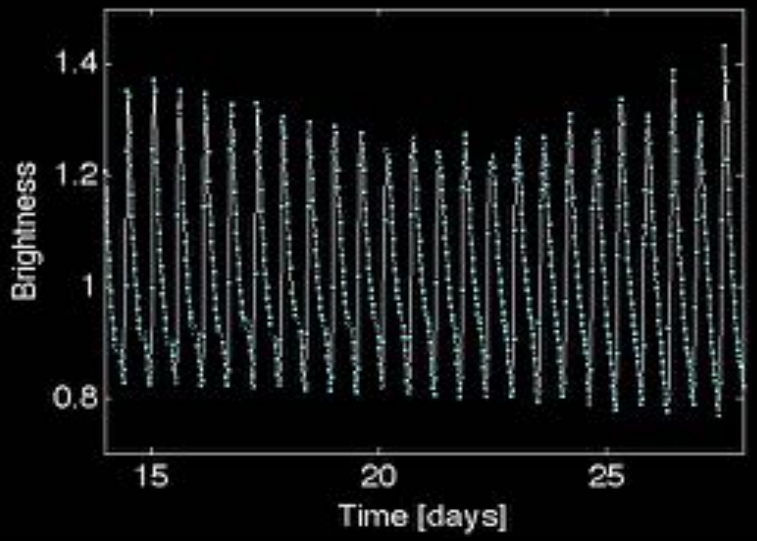


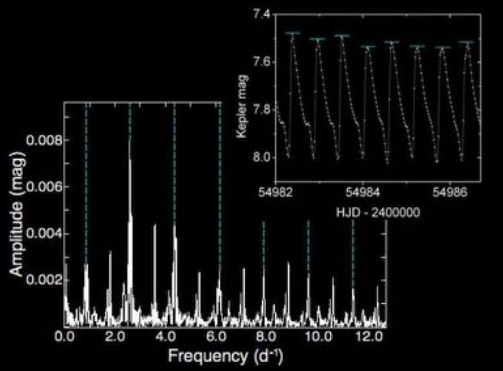
Amplitude vs. Frequency



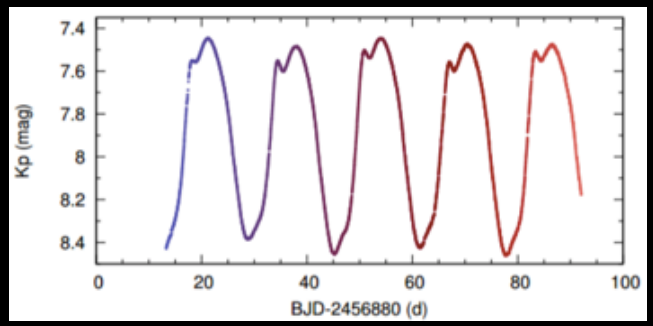

The Blazhko Effect: Why?
Convective Cycles
Closely Spaced Pulsation Modes
Oblique Rotator
Nonradial Modal Interaction
© Kolenberg

## Period doubling



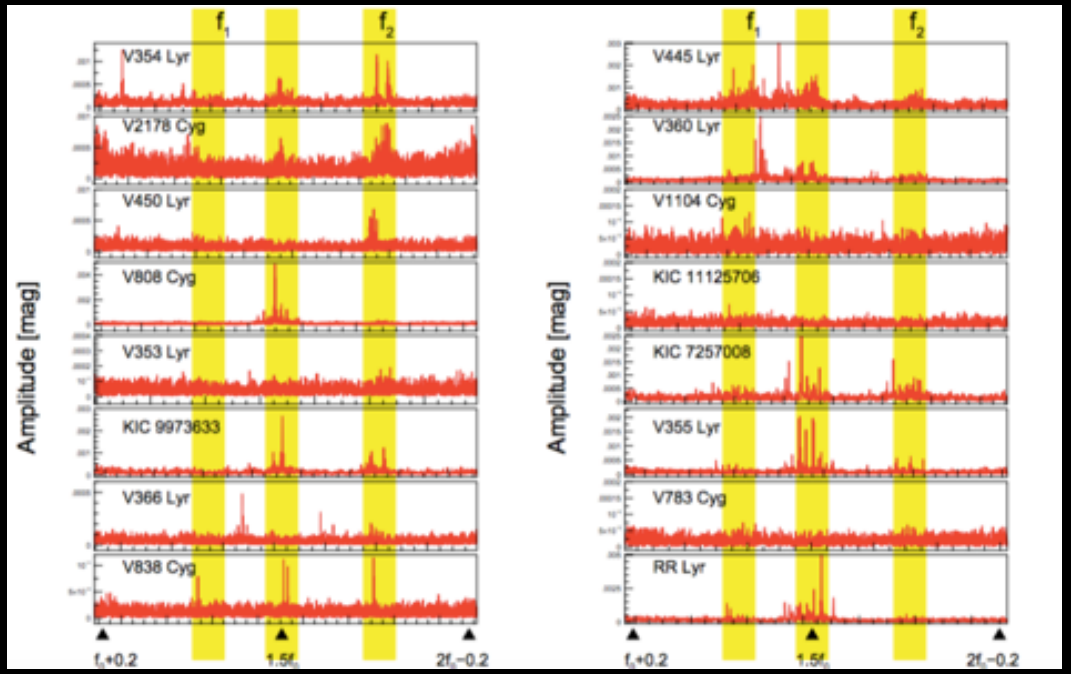




*Kolenberg et al. 2010, ApJ 713, 198*
*Benkö et al. 2010, MNRAS 409, 1585*



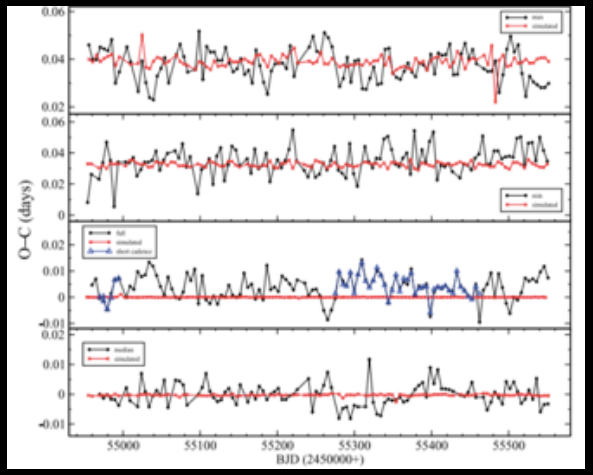

*Plachy et al. 2017, MNRAS 465, 173*

## Low-amplitude additional modes

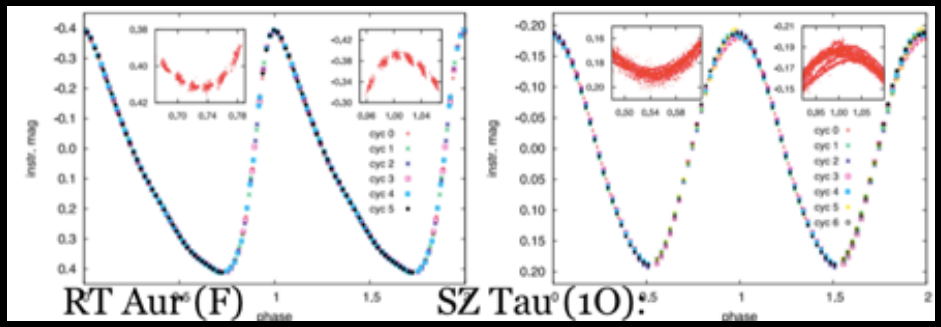



*Szábó et al. 2015, EPJWC (here for RRab stars)*

## Other instabilities

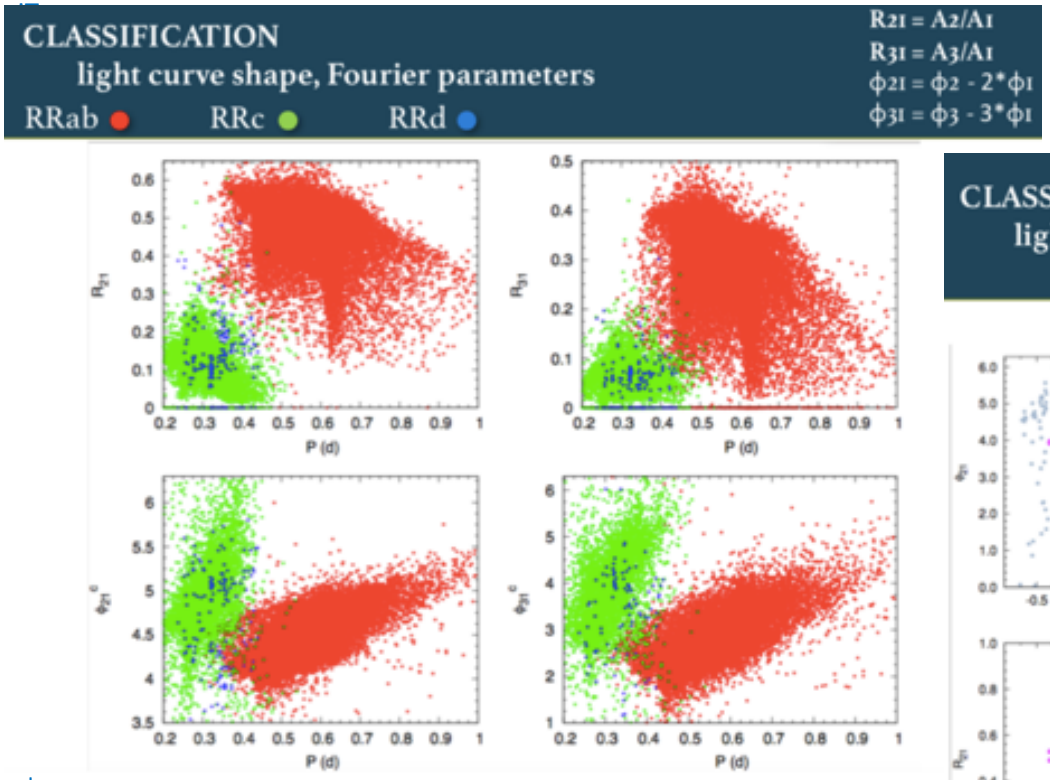



*Derekas et al. 2012, MNRAS, 425, 1312*

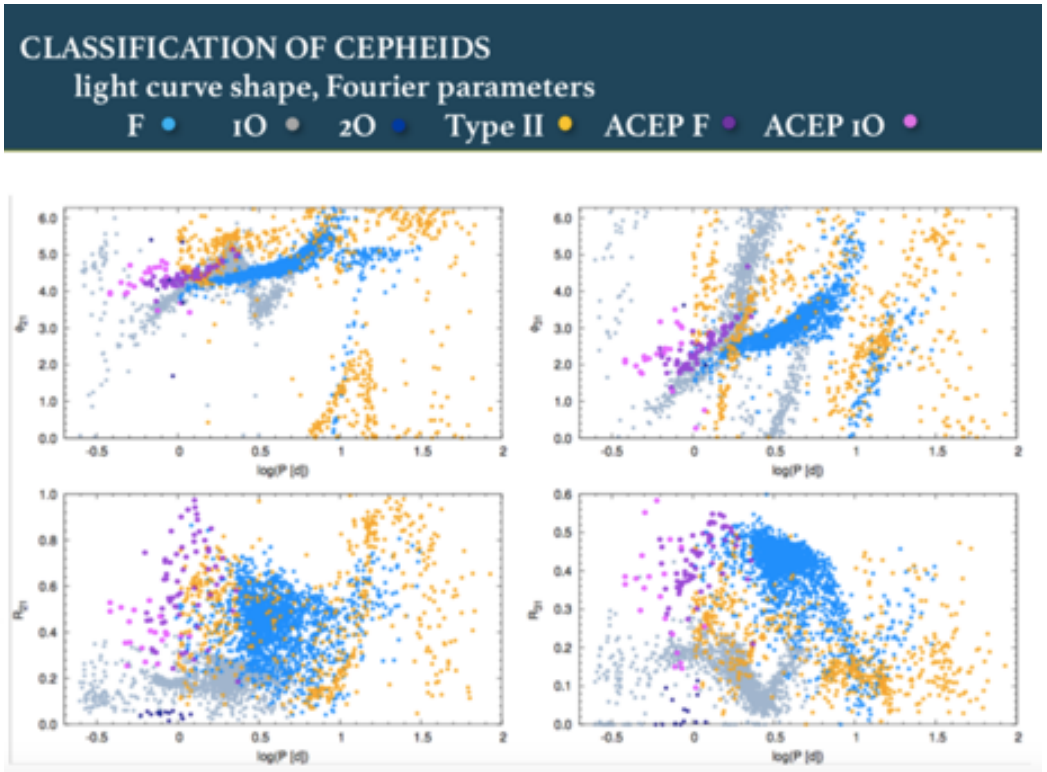



*Evans et al. 2015, MNRAS, 446, 4008*

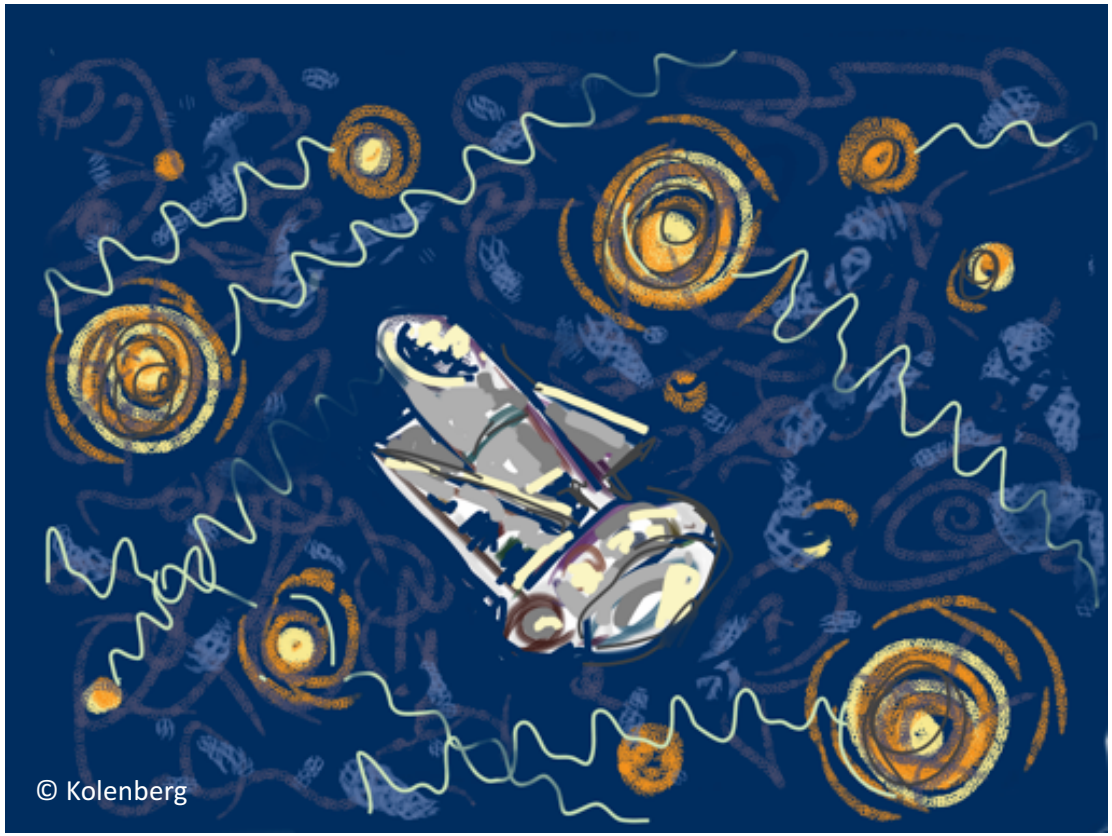
## Light curve & Fourier decomposition





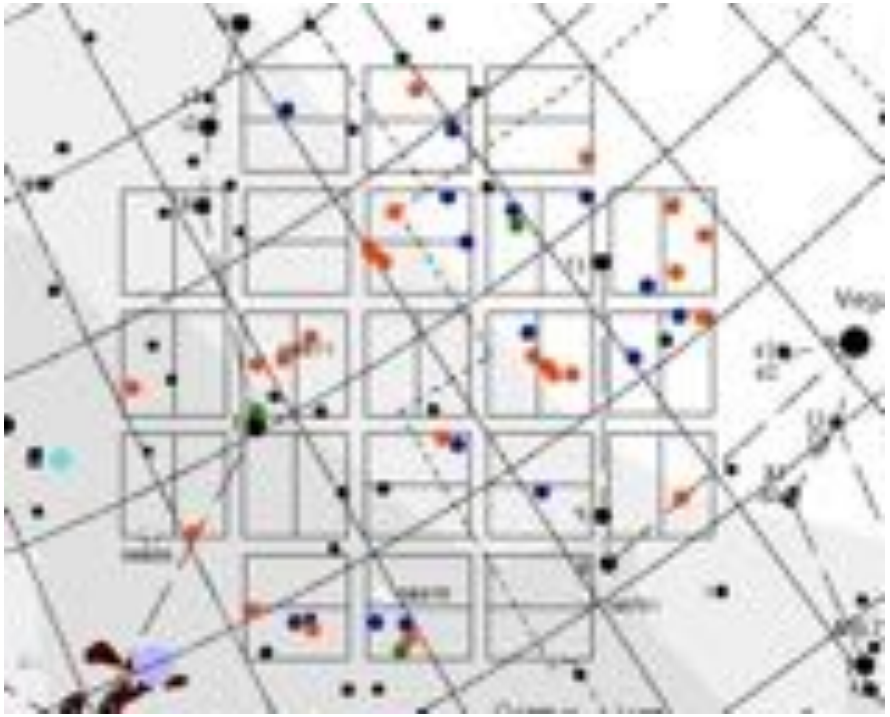



The Space Photometry revolution: MOST, CoRoT, **Kepler**, …



# KASC RR Lyrae working group

RRab
RRab - BL
RRc



Data analysis

Modelling

Ground-based follow-up

# KASC RR Lyrae working group

Additional RR Lyraes in the Kepler field?

**Data analysis**

Individual Blazhko RR Lyrae stars - non-Blazhko stars

Additional frequencies found in RRab, RRc and RRab-BL stars!

…higher radial overtones!, nonradial modes?

**Modelling**

Hydrodynamical modelling

Period doubling

Testing of Blazhko models

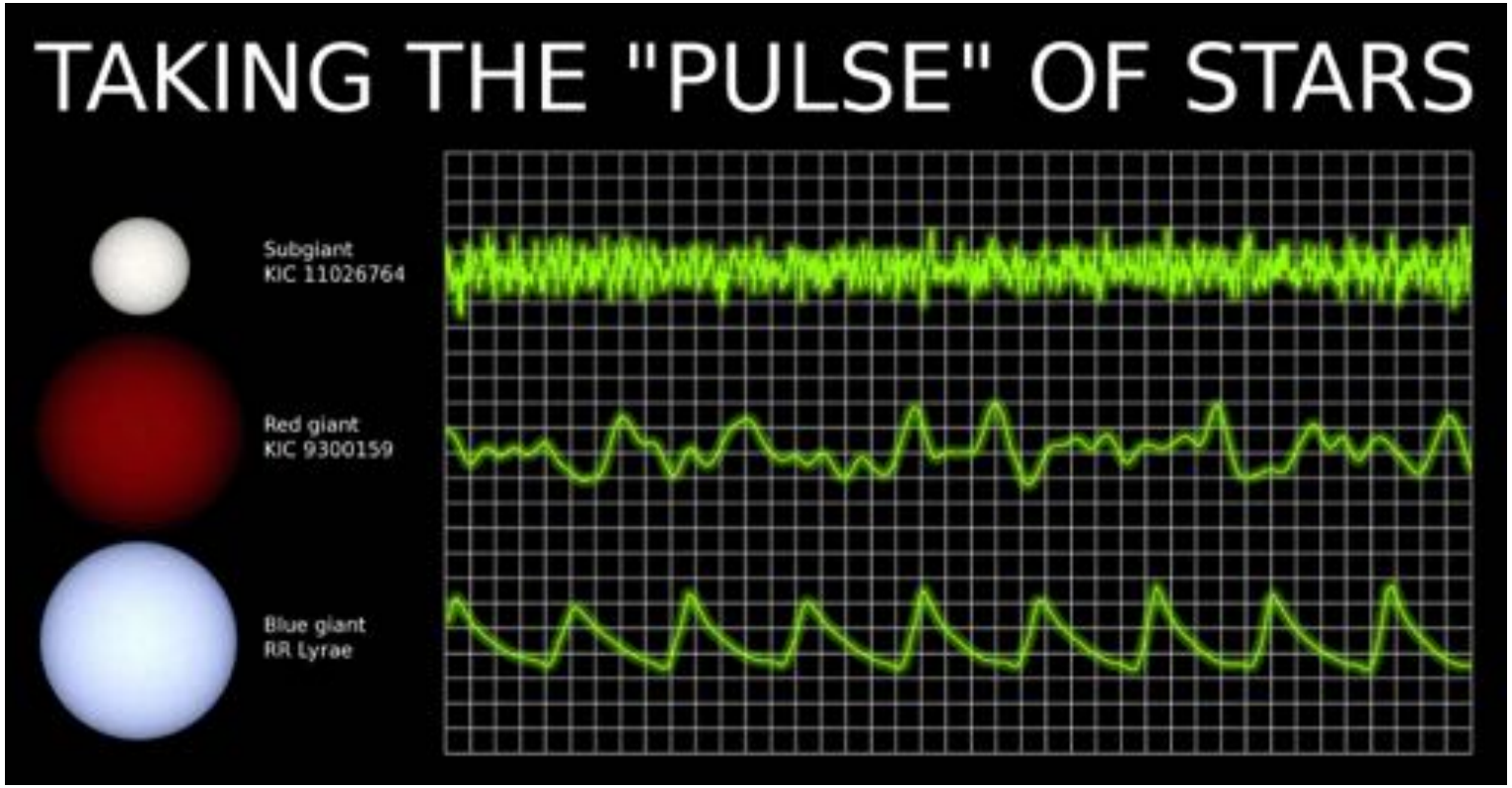
Exploring radial resonance models for the Blazhko effect

**Ground-based follow-up**

Multicolor photometric observations

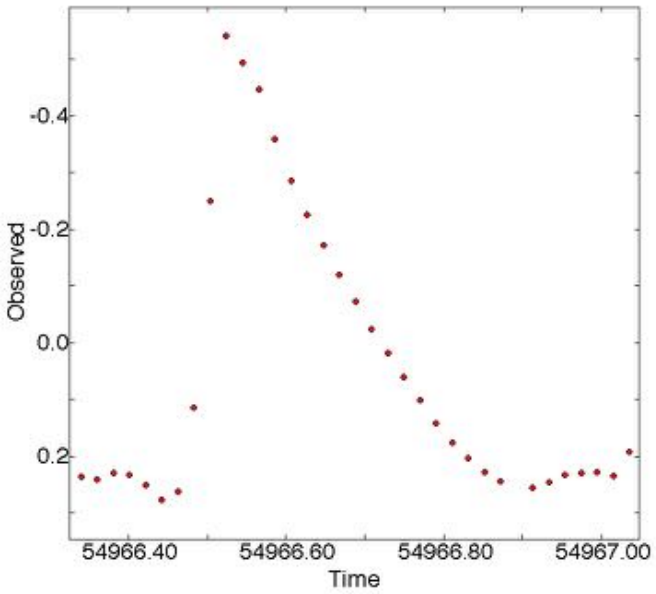
High-resolution spectroscopy of all targets

Time-series spectroscopy

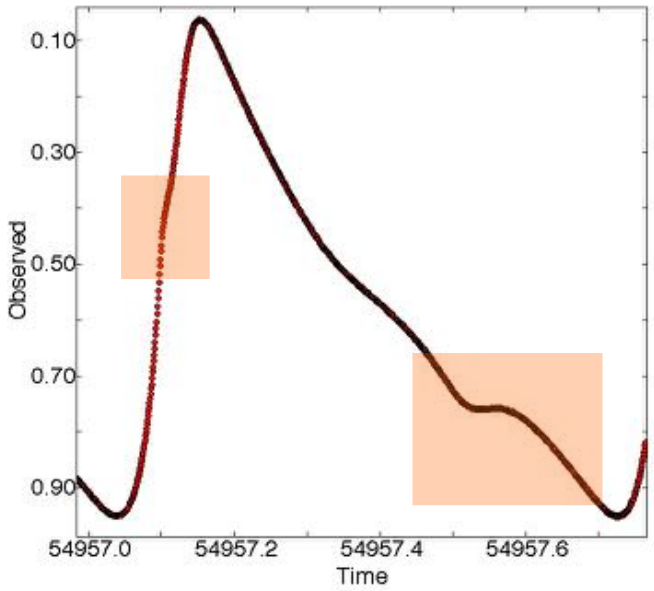

TAKING THE "PULSE" OF STARS
Subgiant
KIC 11026764
Red giant
KIC 9300159
Blue giant
RR Lyrae

# RR Lyrae star

## Long Cadence versus Short Cadence

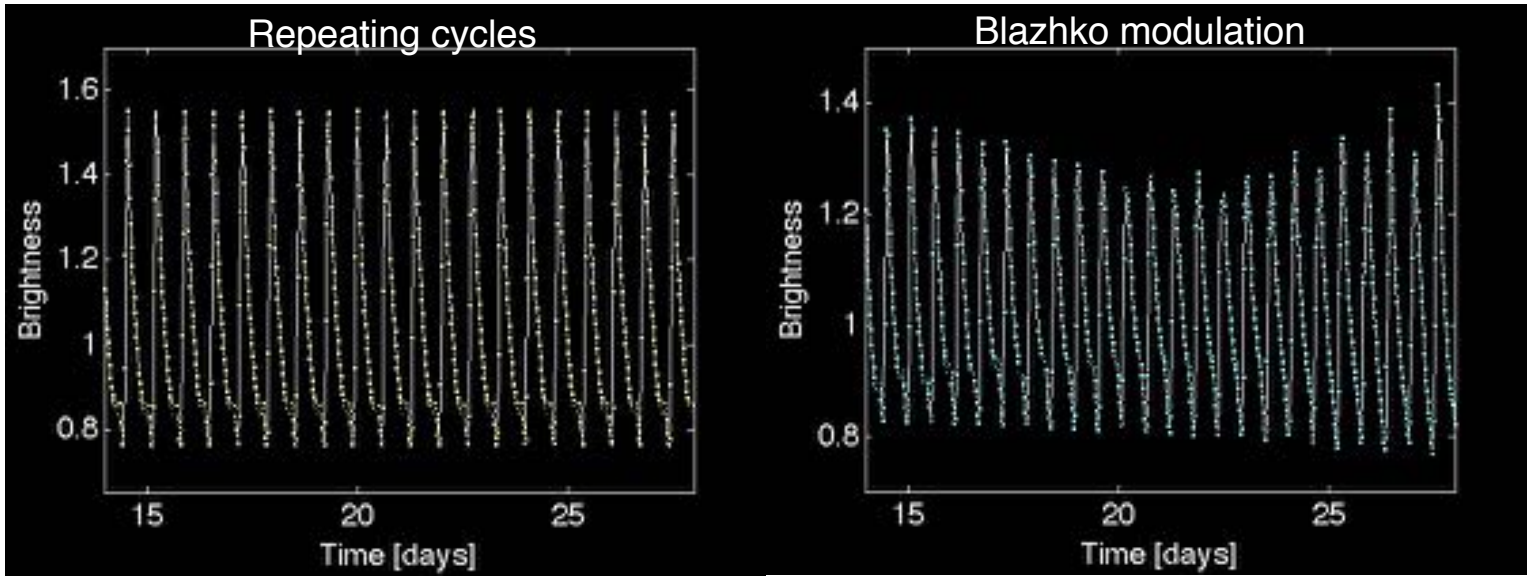



*~ 30 min*



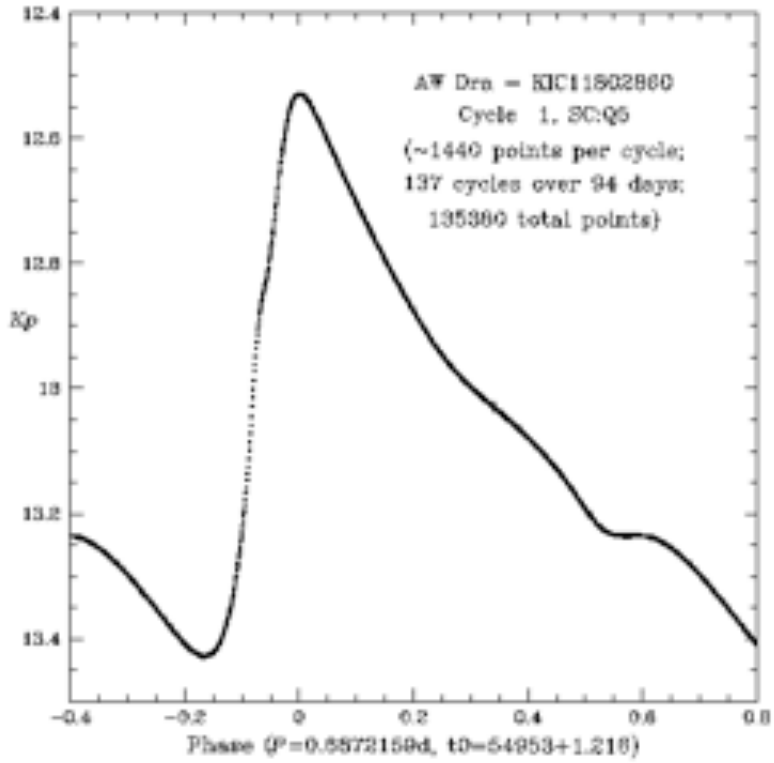

*~ 1 min*

# Typical Kepler Long Cadence Data



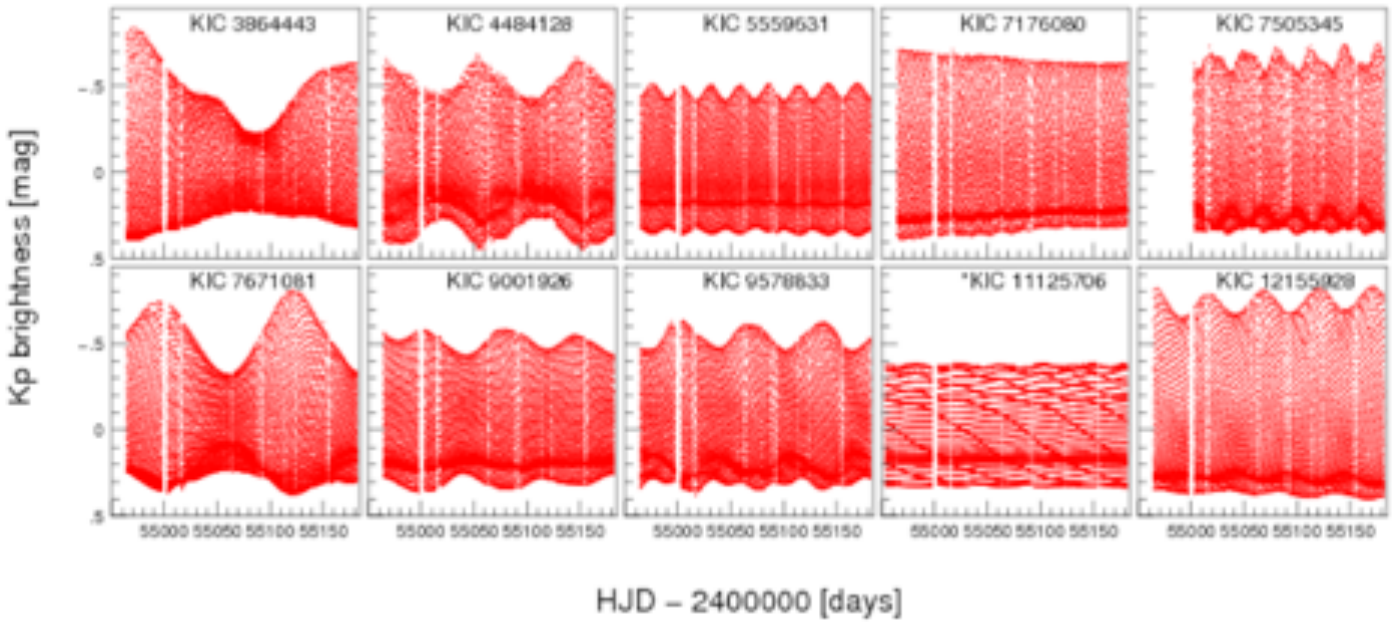

*Kolenberg et al. 2010, ApJ 713, 198*
*Benkö et al. 2010, MNRAS 409, 1585*

# Kepler's non-Blazhko RR Lyrae stars

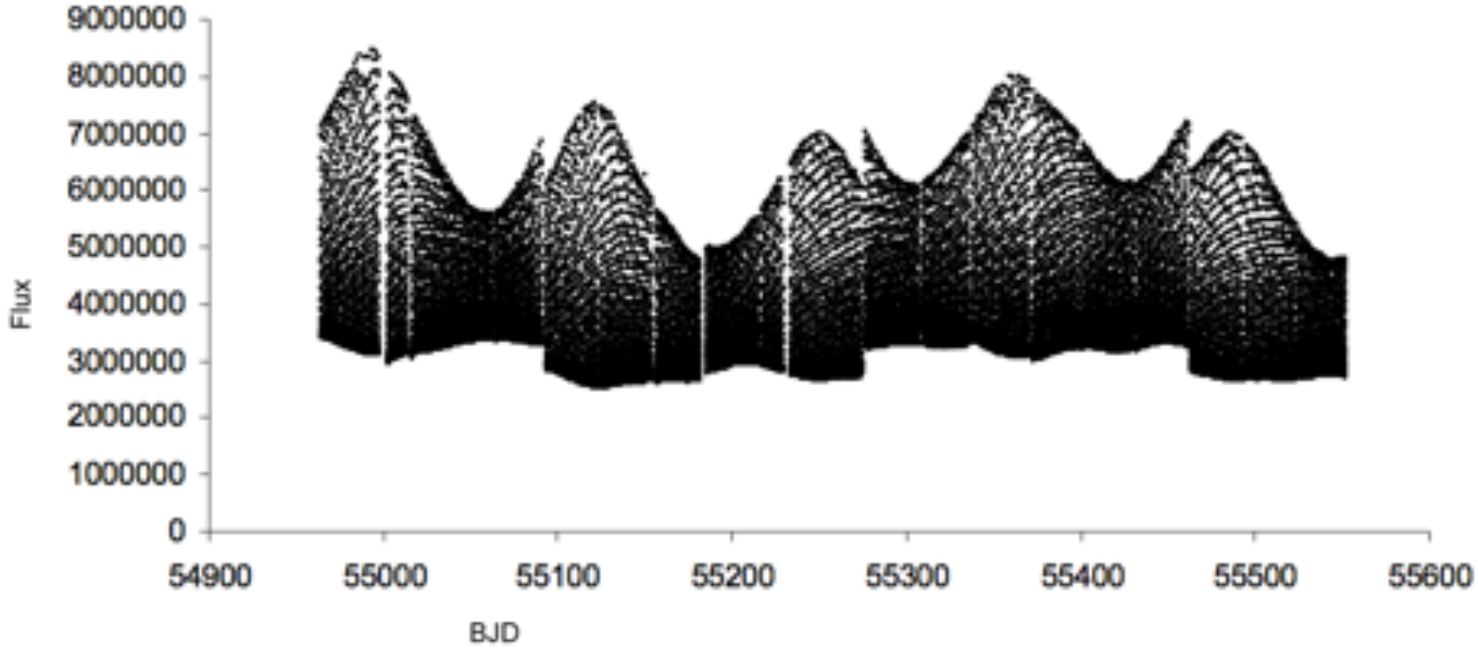



*Nemec et al. 2011, MNRAS 417, 1022*

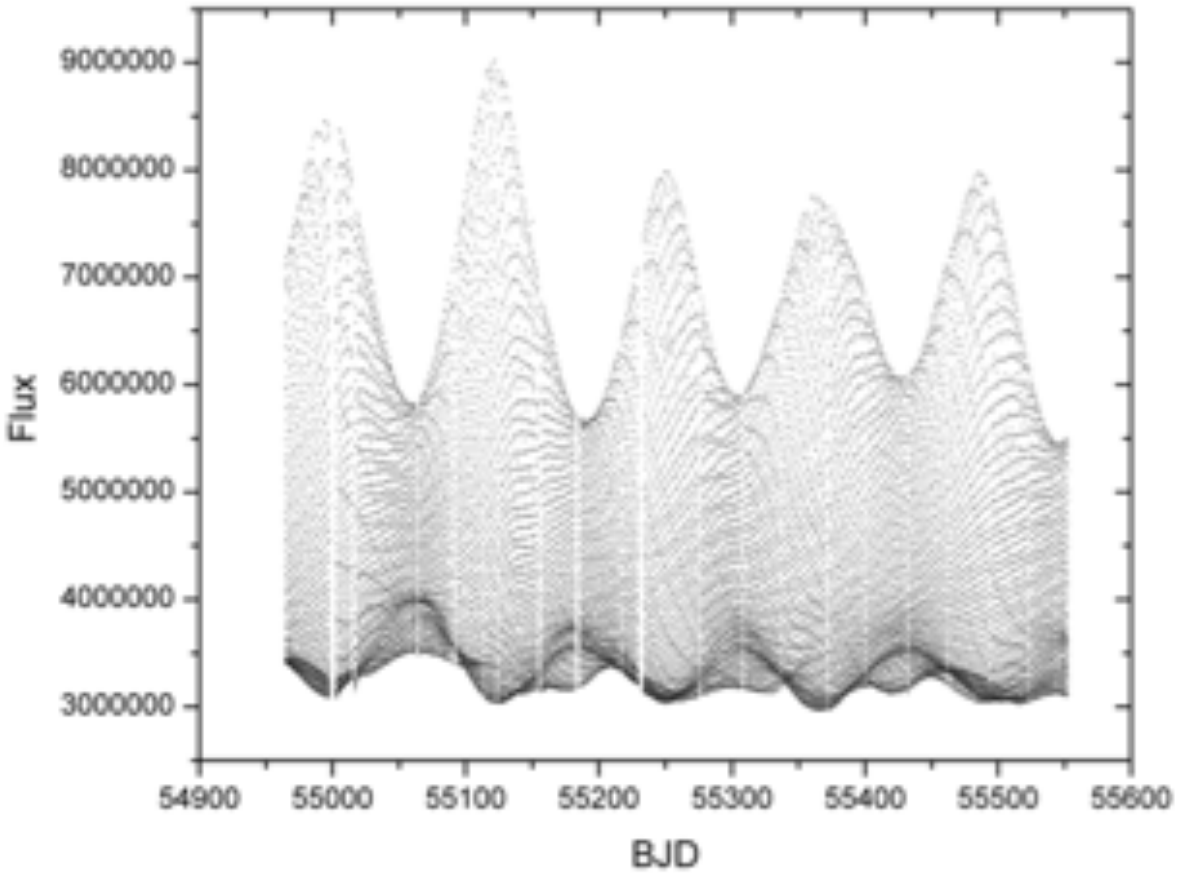
# Kepler's Blazhko Zoo



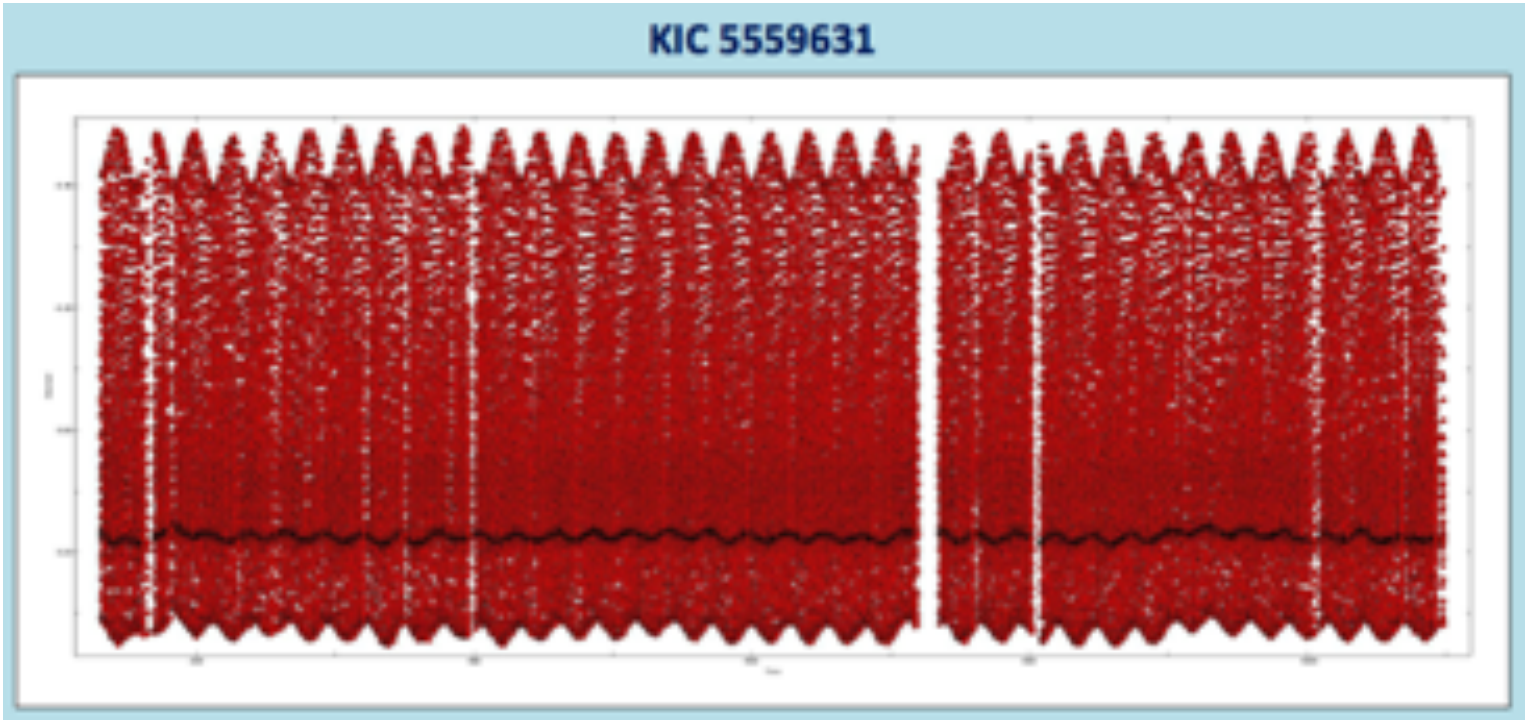

*Benkö et al. 2010, MNRAS 409, 1585*




*Celik et al. 2012*

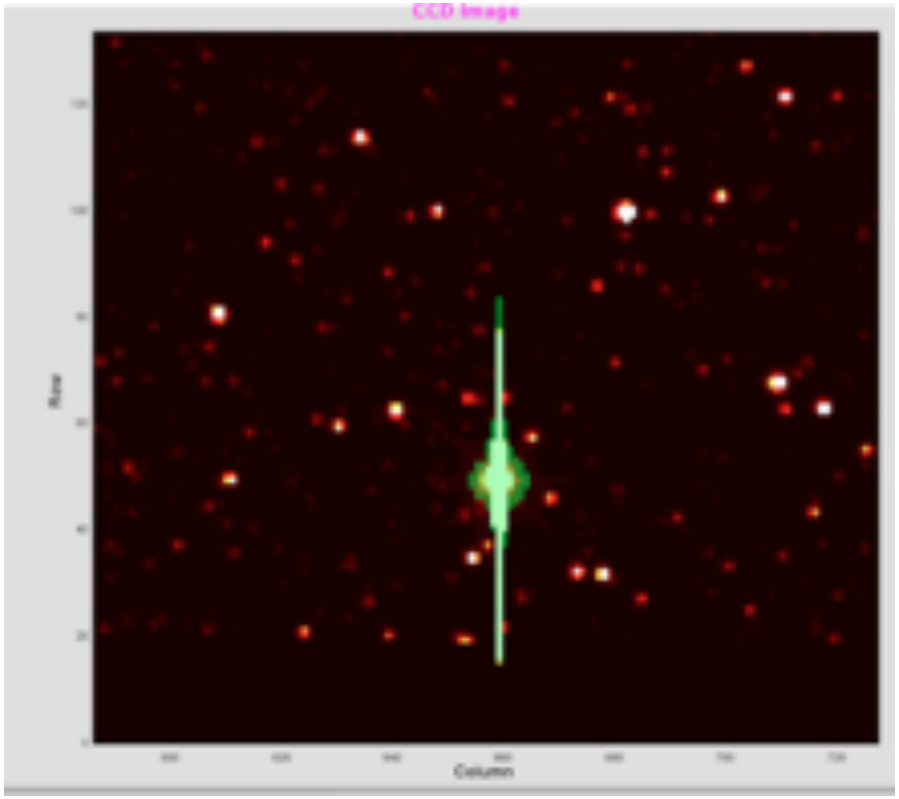


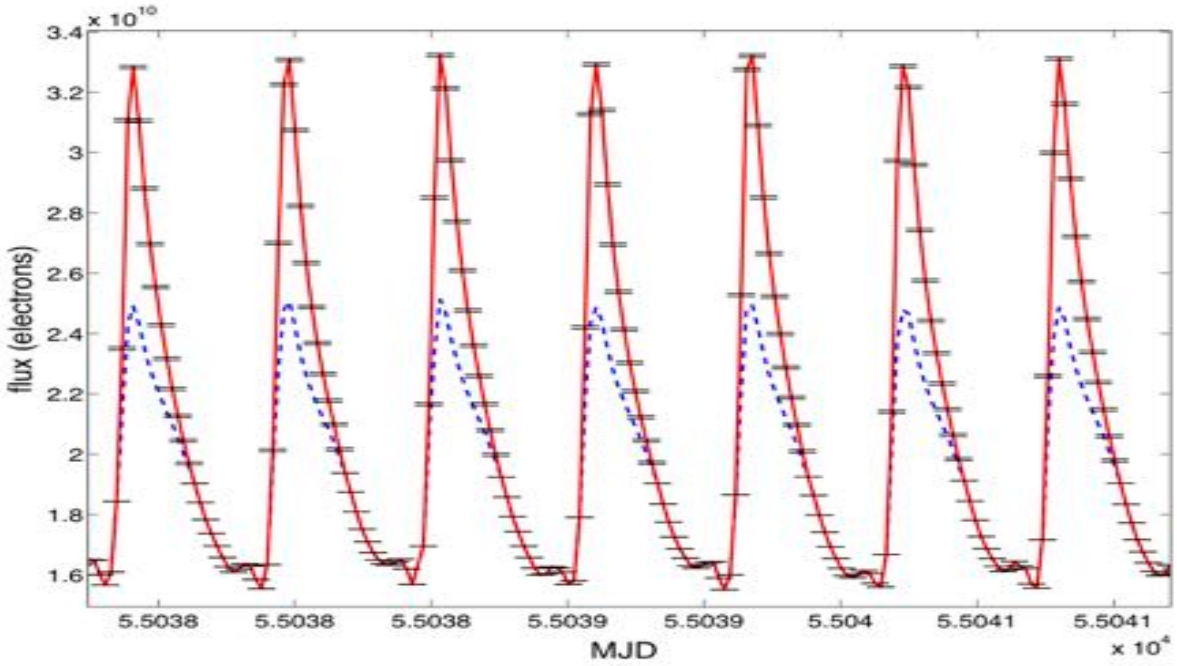

*Celik et al. 2012*



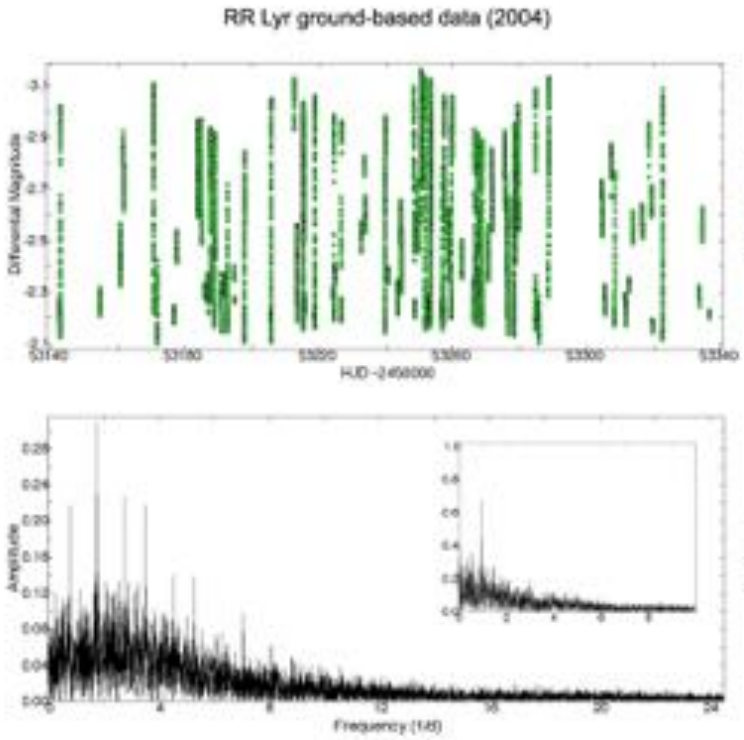

*Speagle, Kolenberg, & Benkö 2013*

# RR Lyr in the Kepler field (!)

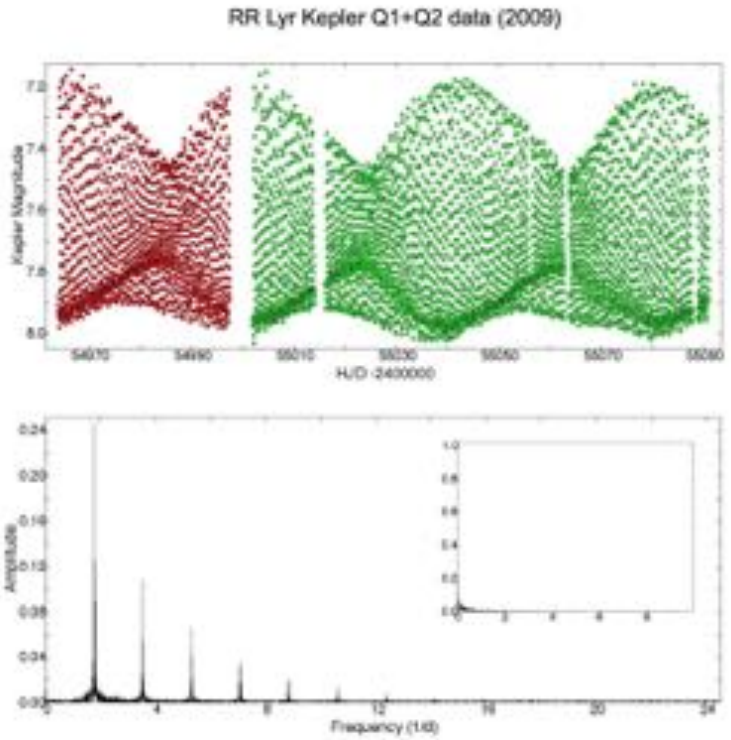





*Custom apetrure by Steve Bryson (NASA Ames)*

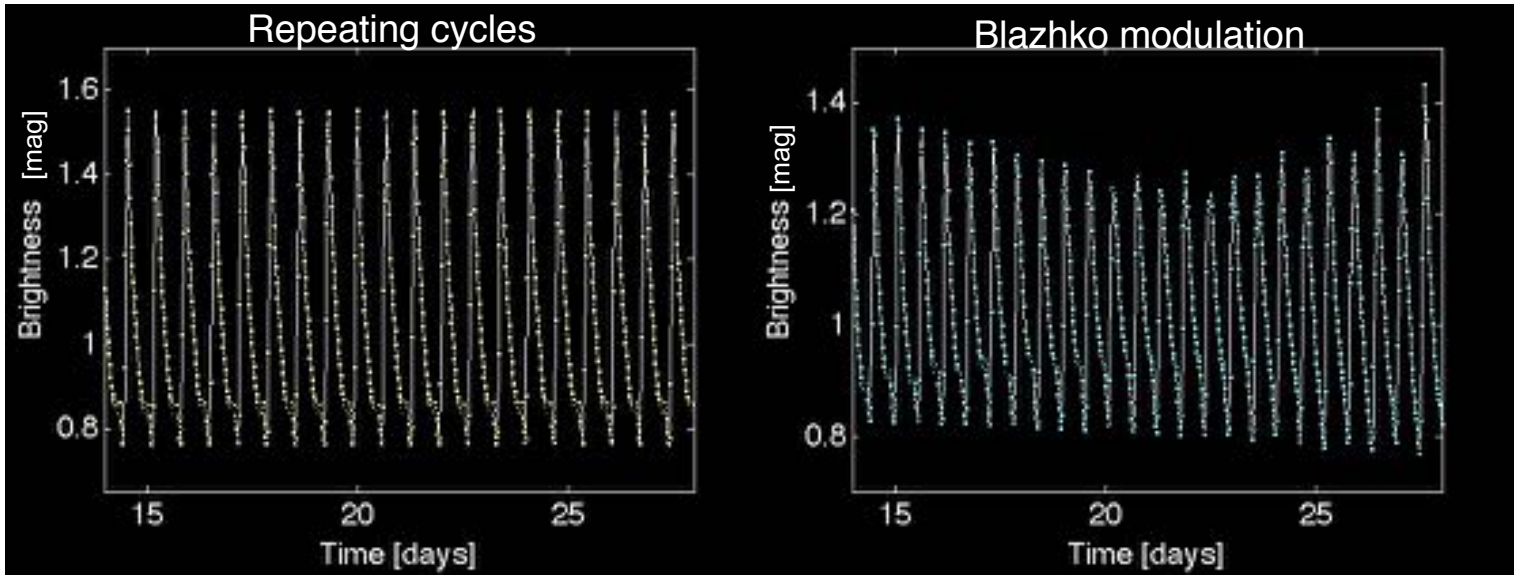



*Kolenberg et al. 2006, A&A 459, 577*

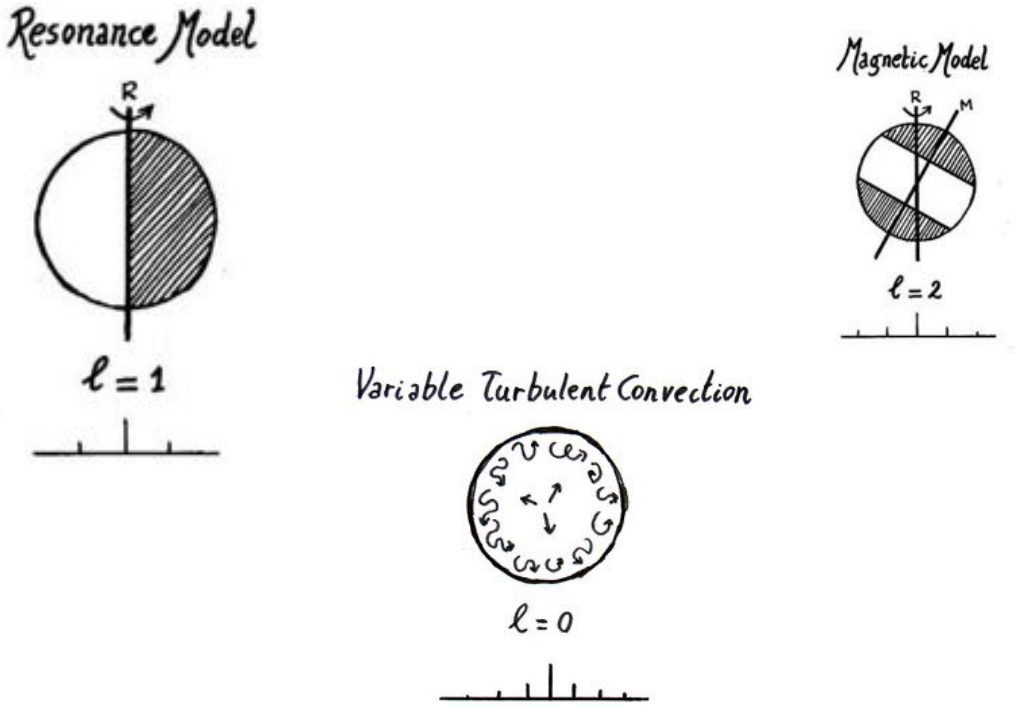


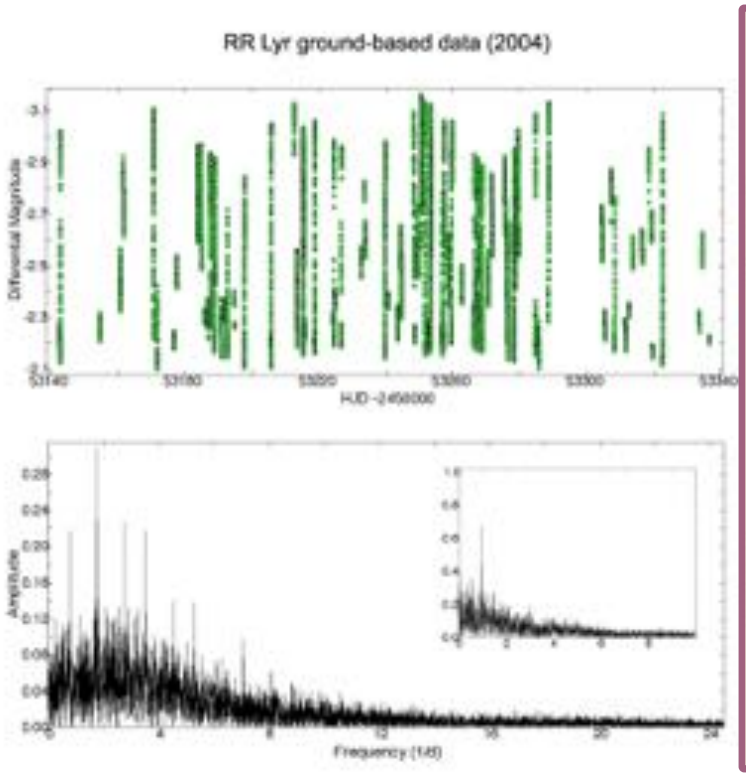

*Kolenberg et al. 2011, MNRAS 411, 878*

# Why do some stars do it and others don‘t?

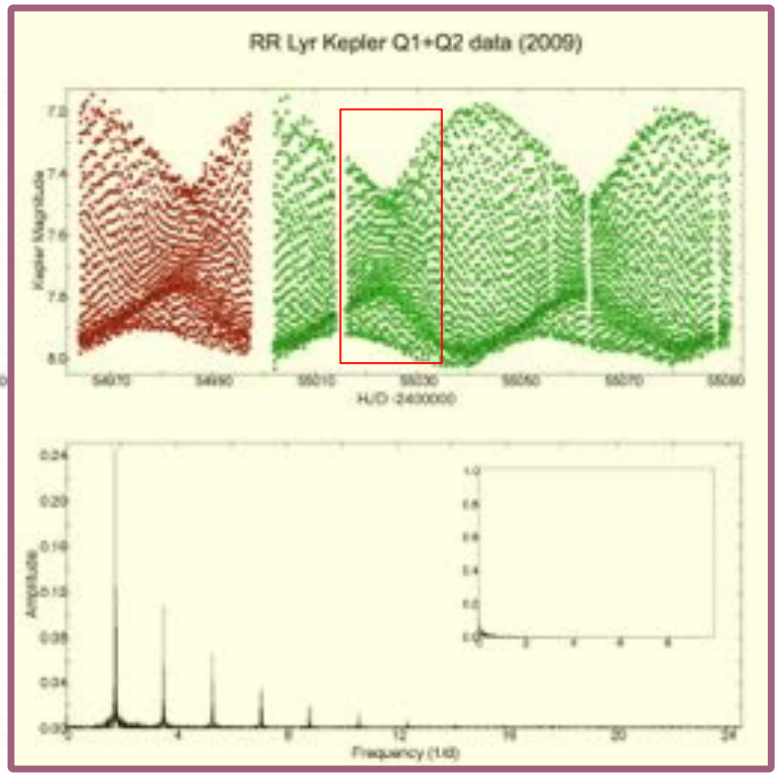


# Explanations for the Blazhko Effect

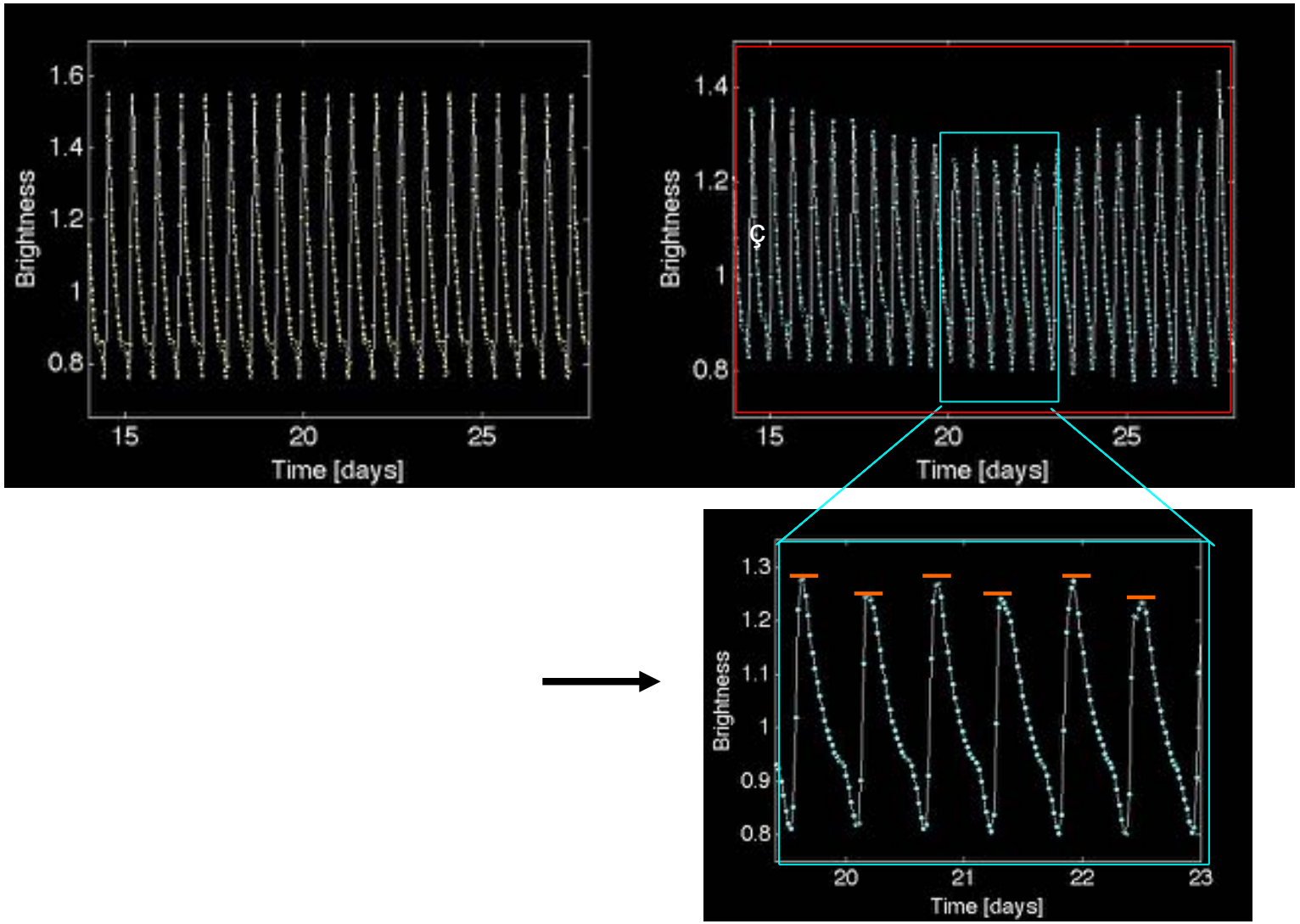


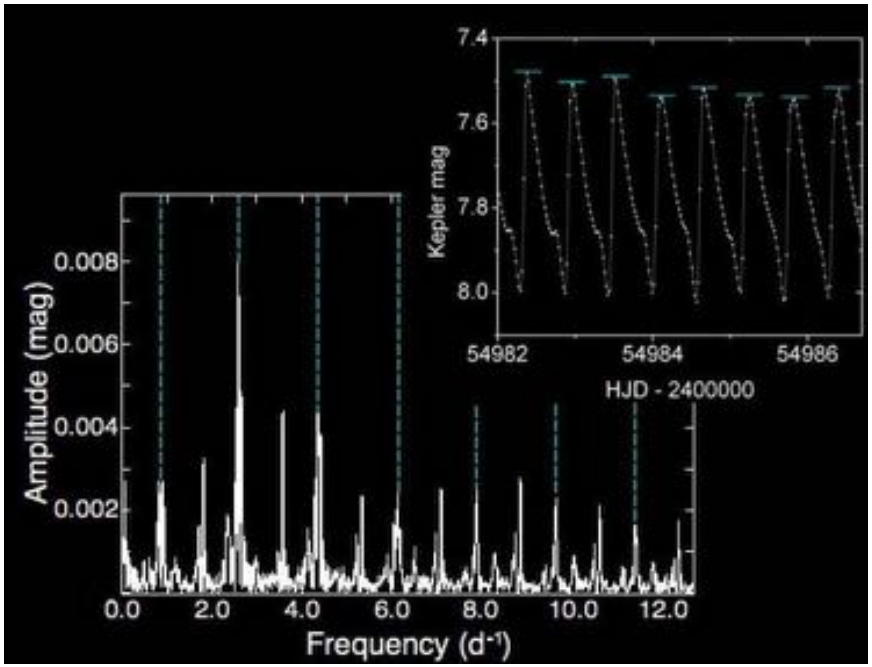



*Kolenberg et al. 2006, A&A 459, 577*



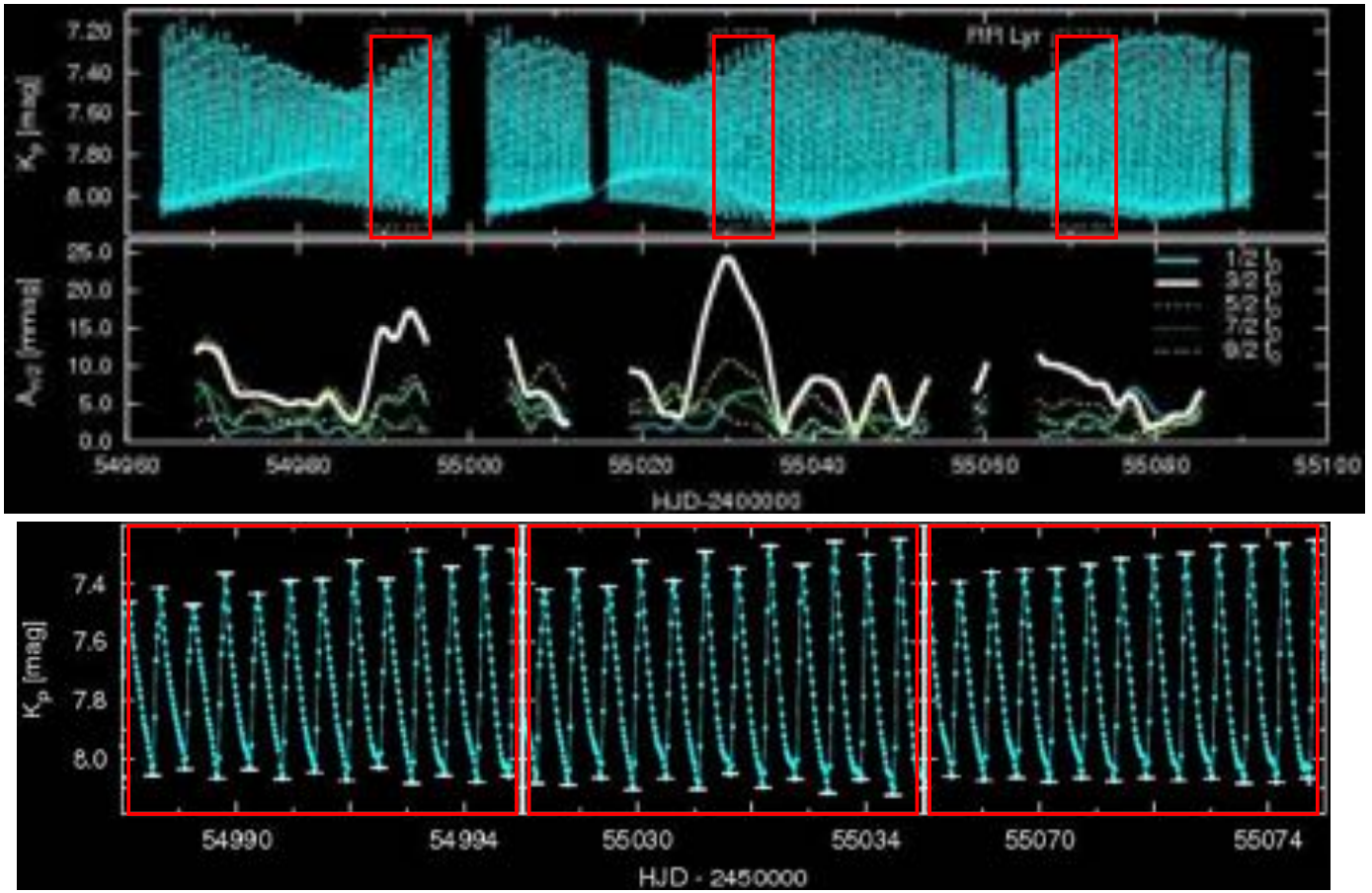

*Kolenberg et al. 2011, MNRAS 411, 878*


Brightness
Time [days]
Brightness
Time [days]
Brightness
Time [days]



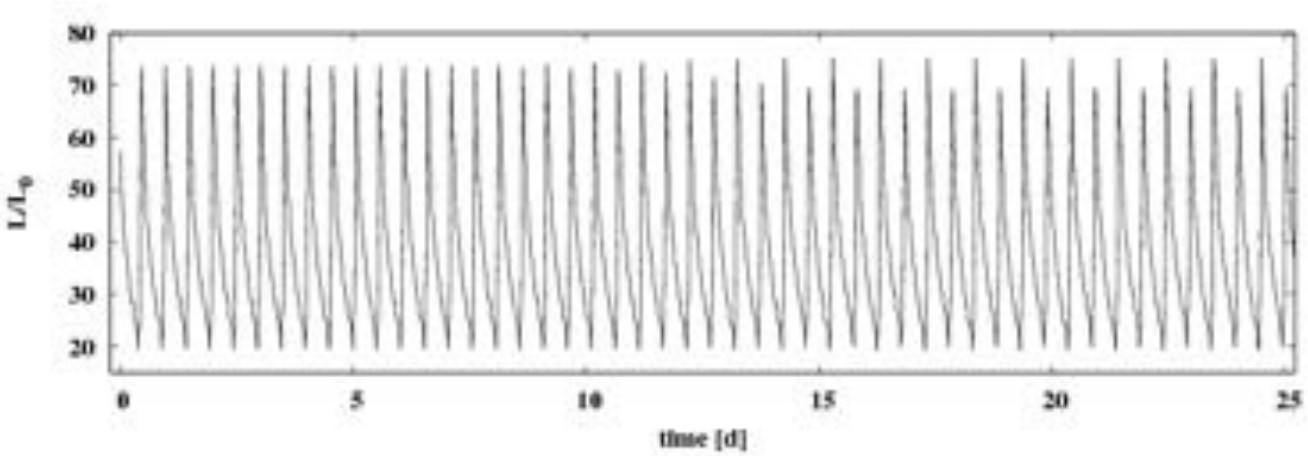

*Kolenberg et al. 2010, ApJ 713, 198*
*Szabó et al. 2010, MNRAS, 409, 1244*

# Period doubling in RR Lyr (Q1+Q2)




*Szabó et al. 2010 MNRAS, 409, 1244*

# Hydrocode showing the onset of period doubling




*Szabó et al. 2010, MNRAS 409, 1244*

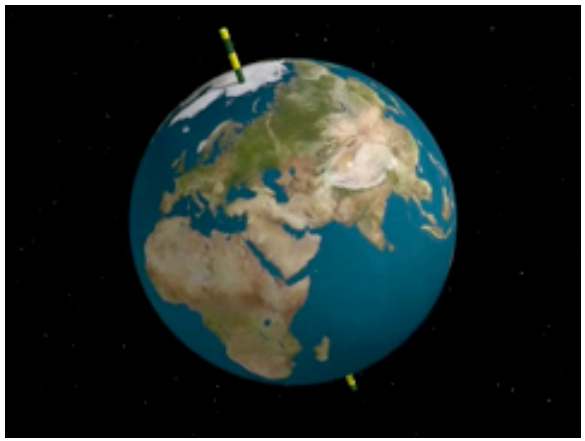
**9:2 resonance between fundamental mode and 9th overtone**

**Radial mode resonances, period doubling and the Blazhko effect**
*Kolláth, Molnár & Szabó 2011, MNRAS 414, 1111*

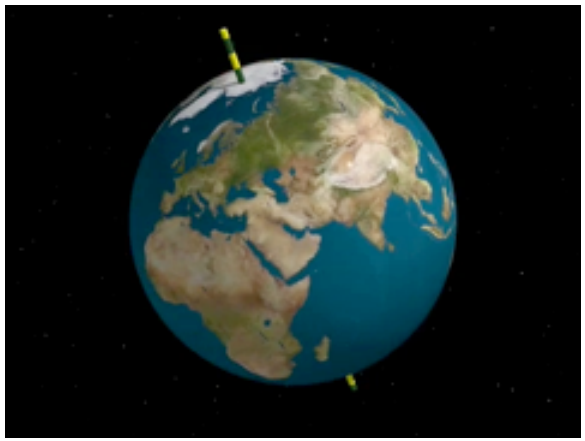
**Only Blazhko RR Lyrae stars show period doubling**

**New model**
*Buchler & Kolláth, 2011, ApJ 731, 24*

# Why was period doubling not seen before?

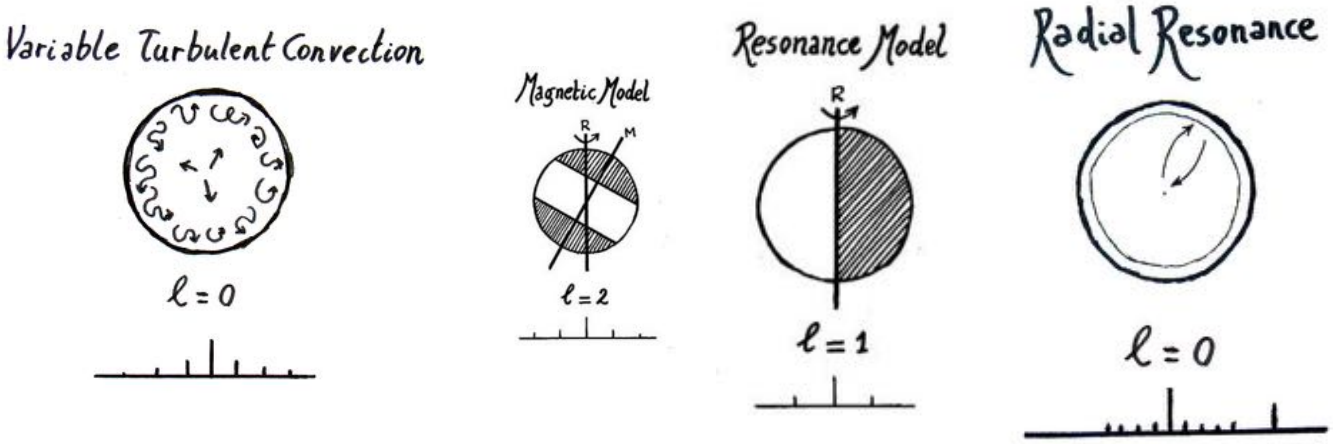


## Why was period doubling not seen before?



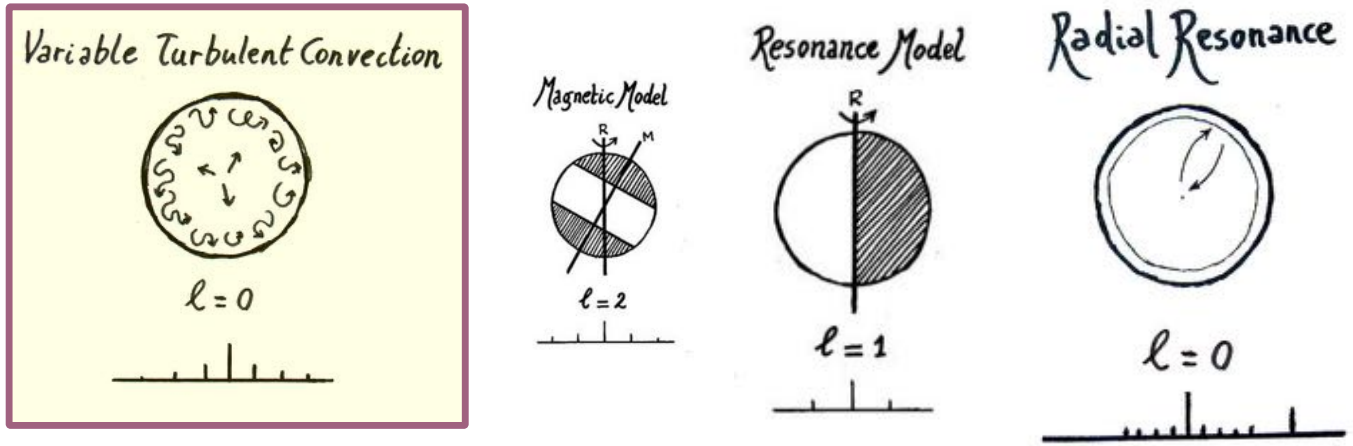
**“terrestrial exclusion principle”**

# Explanations for the Blazhko Effect



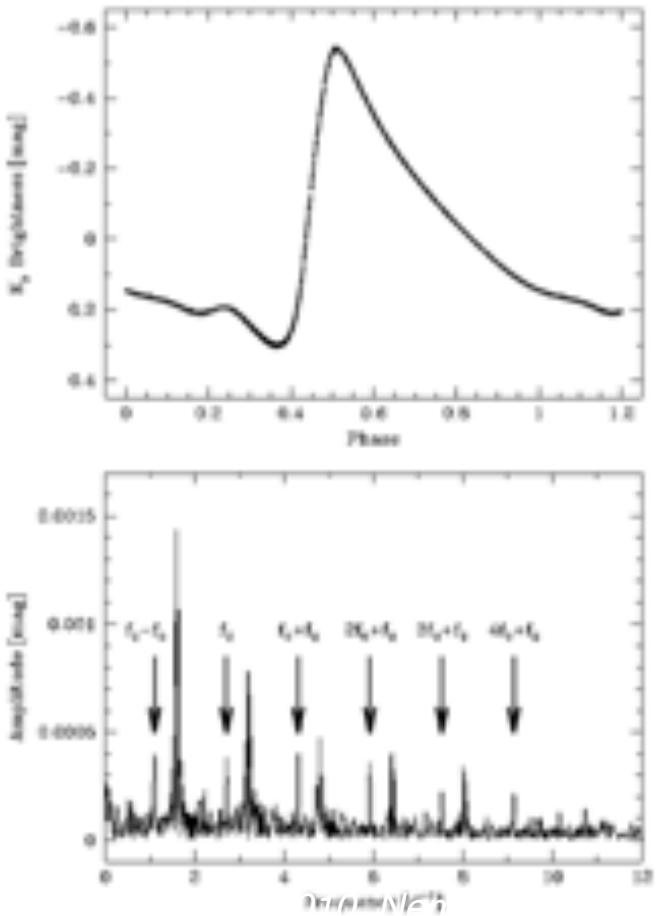

2011

# Explanations for the Blazhko Effect

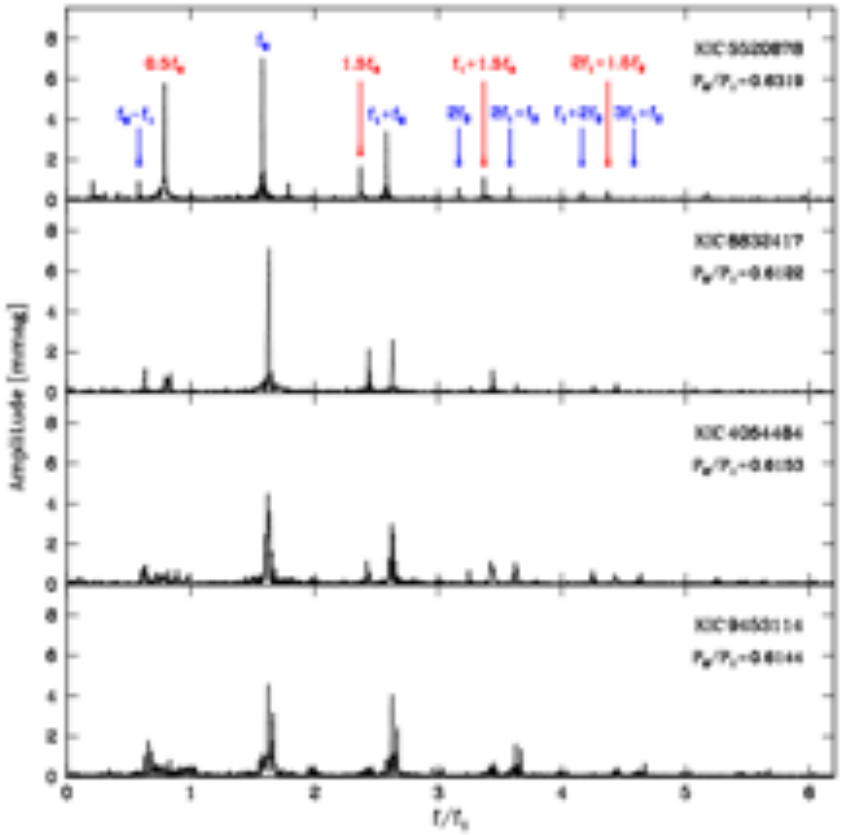



*Molnár & Kolláth 2010, JPhCS 218, 2027*
*Smolec et al. 2011, MNRAS 414, 2950*

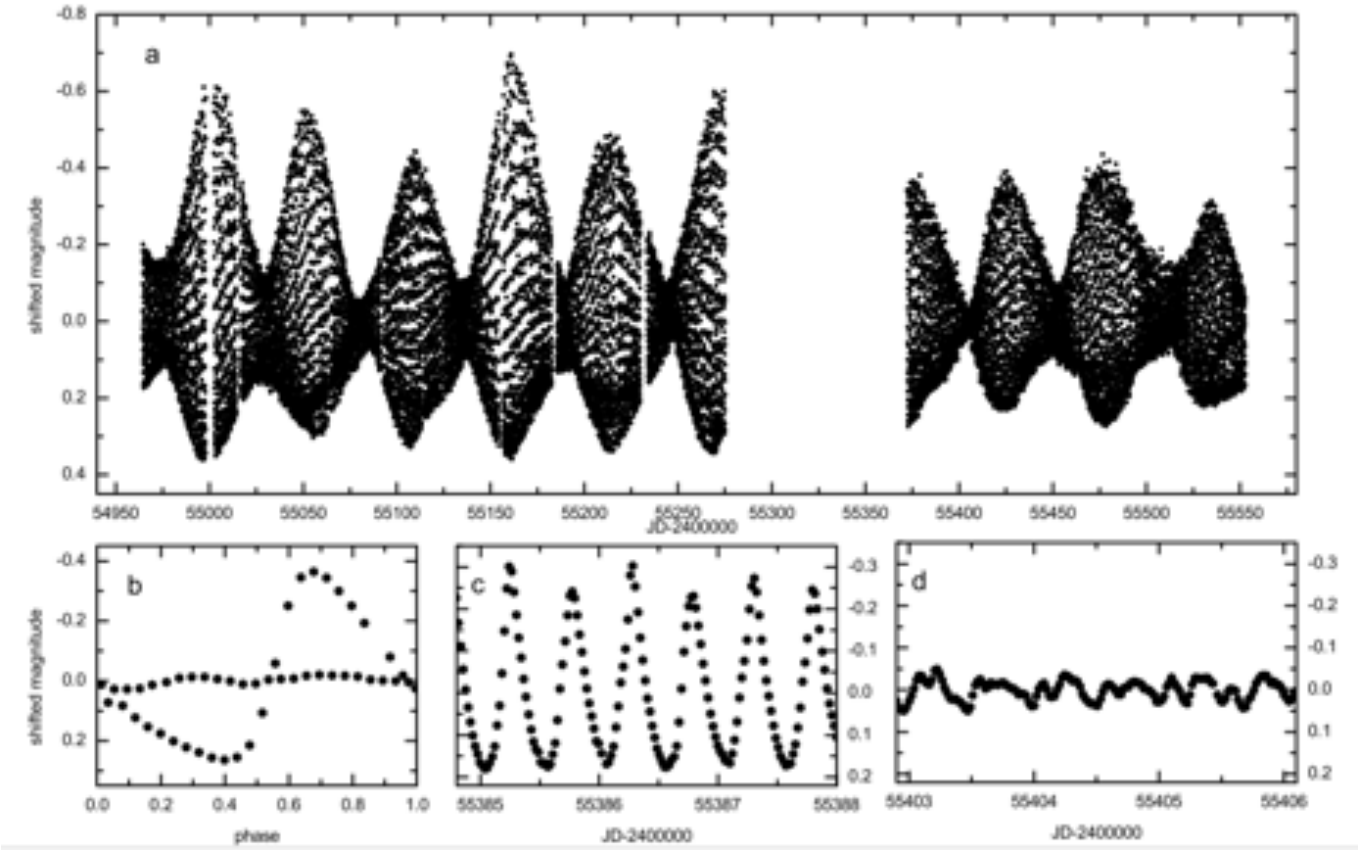
# RR02 stars – new double mode stars



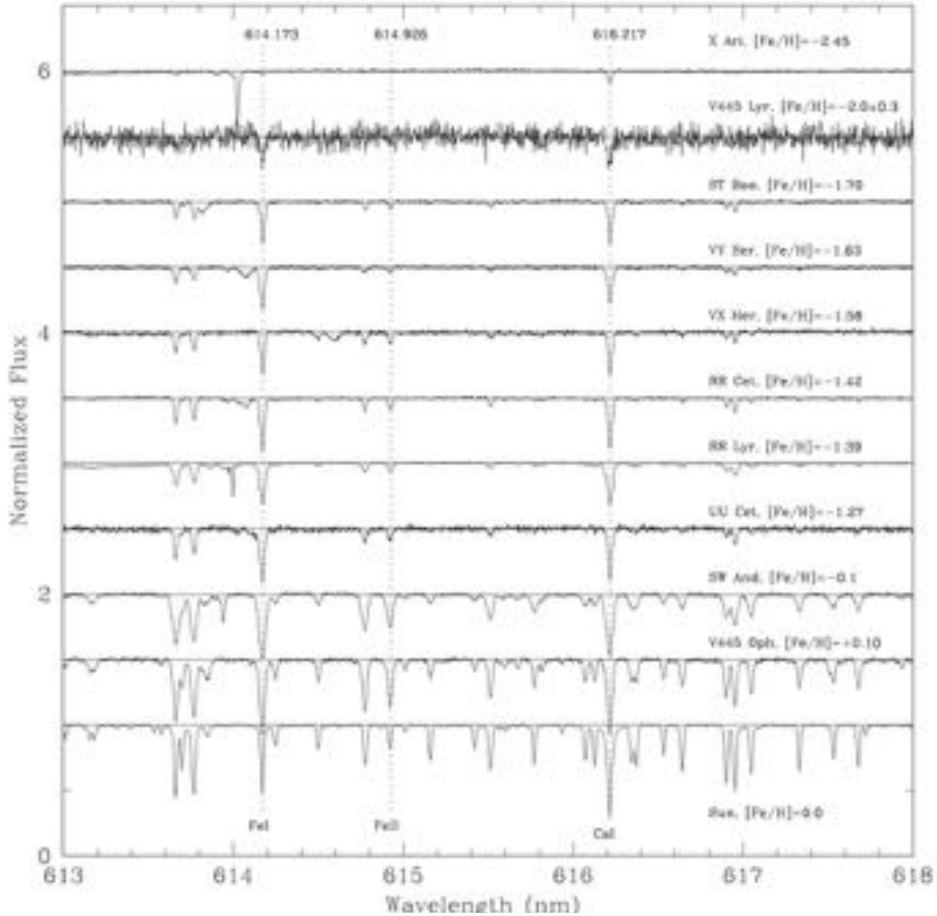
# RRc stars – puzzling additional mode



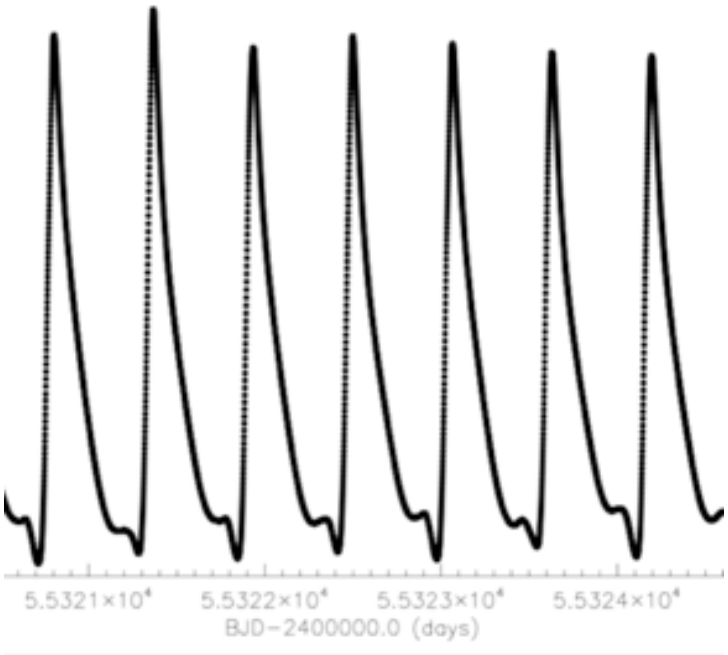
# Crazy Star

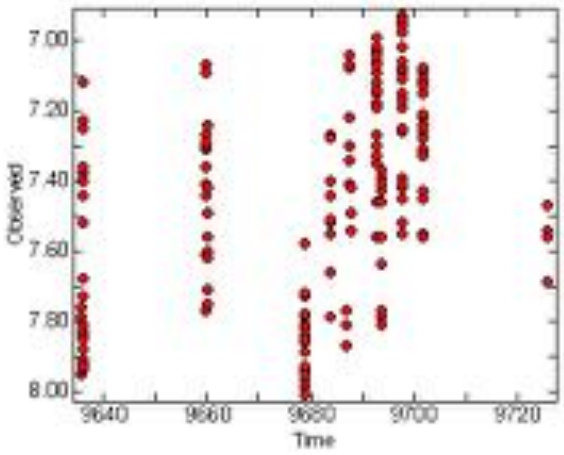

a
shifted magnitude
JD-2400000
b
shifted magnitude
phase
c
JD-2400000
d
JD-2400000

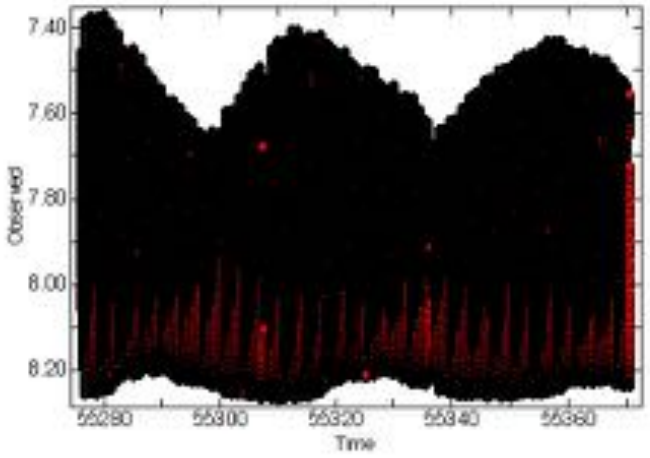
# Spectroscopic parameters

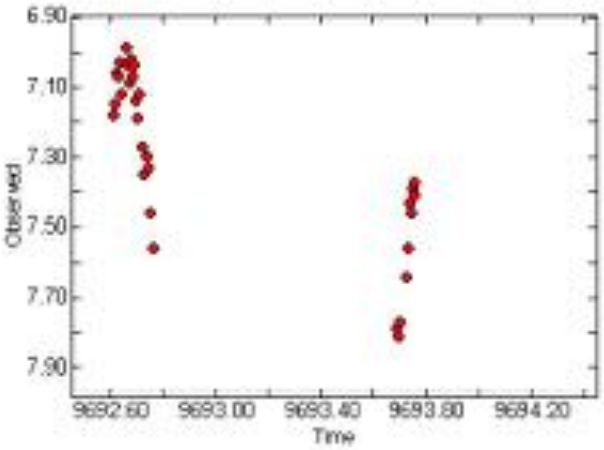


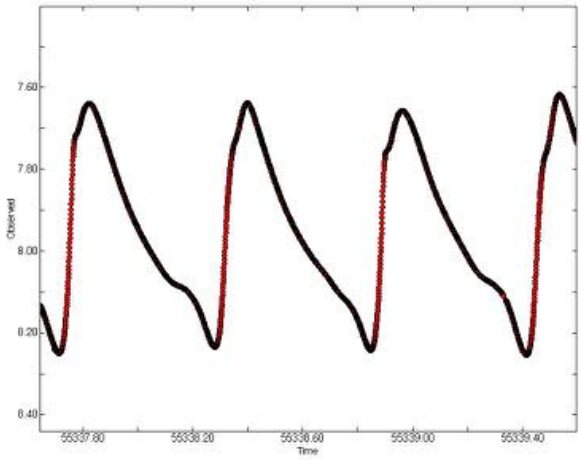
# RR Lyr in short cadence



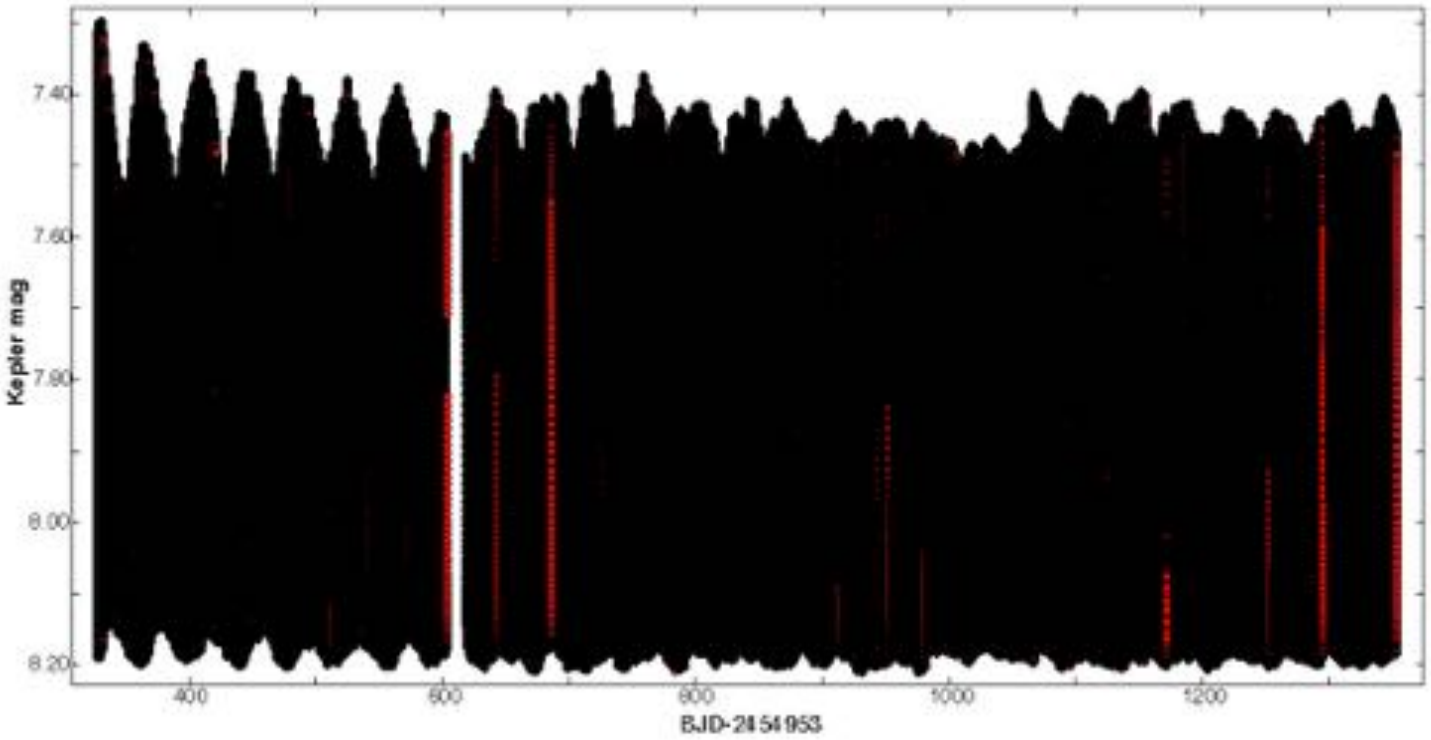

7.00
7.20
7.40
7.60
7.80
8.00
Observed
9640
9660
9680
9700
9720
Time

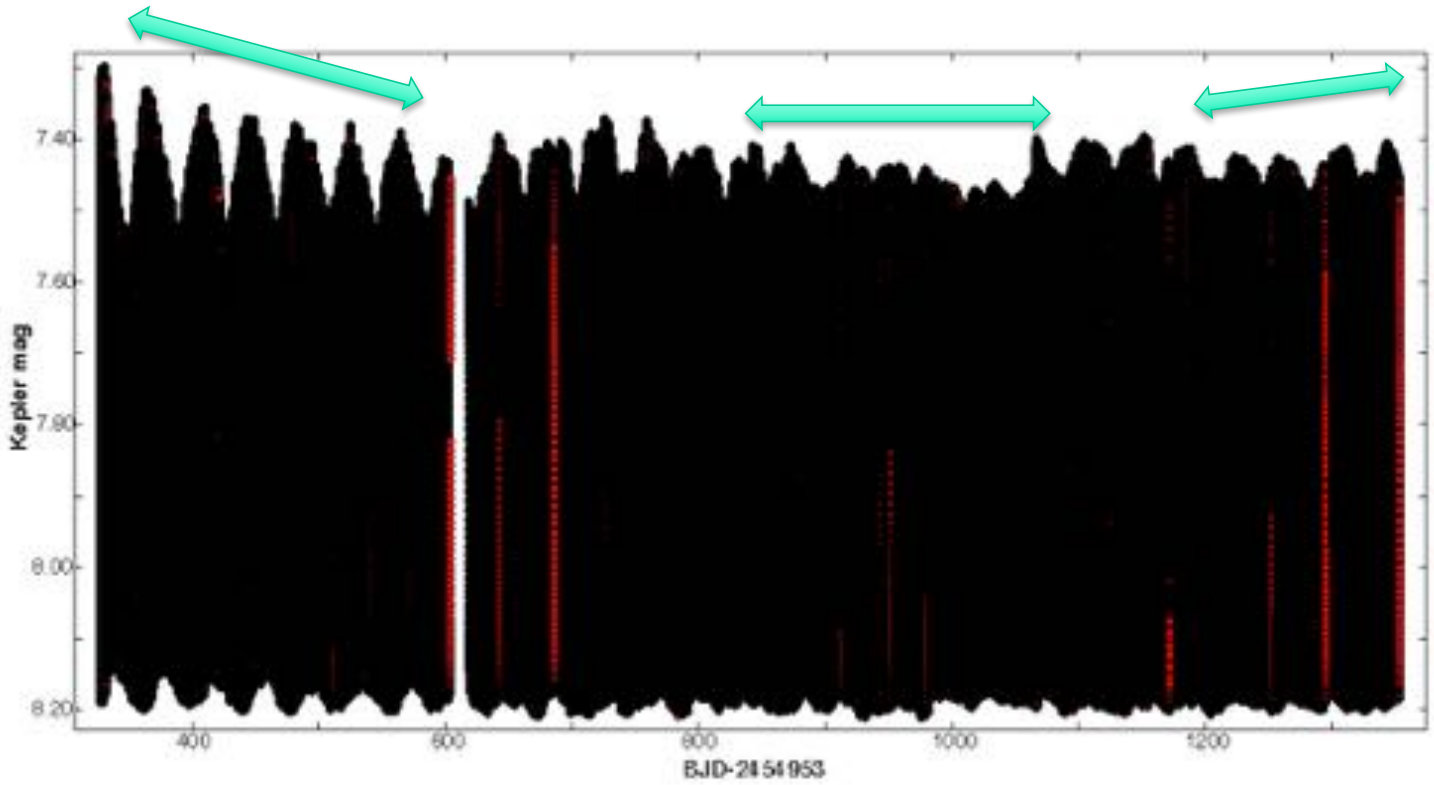

7.40
7.60
7.80
8.00
8.20
Observed
55280
55300
55320
55340
55360
Time

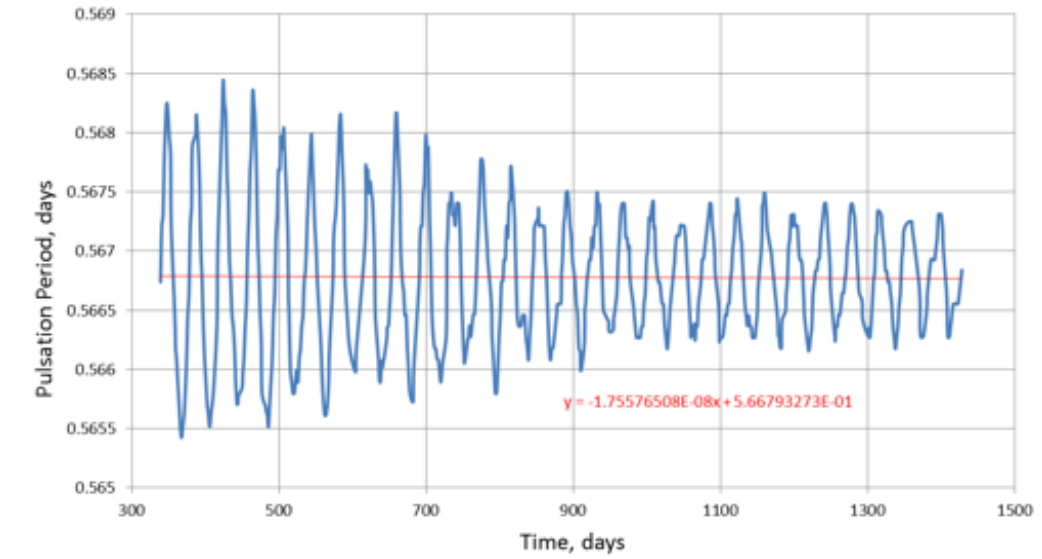

6.90
7.10
7.30
7.50
7.70
7.90
Observed
9692.60
9693.00
9693.40
9693.80
9694.20
Time


7.60
7.80
8.00
8.20
8.40
Observed
55337.80
55338.20
55338.60
55339.00
55339.40
Time

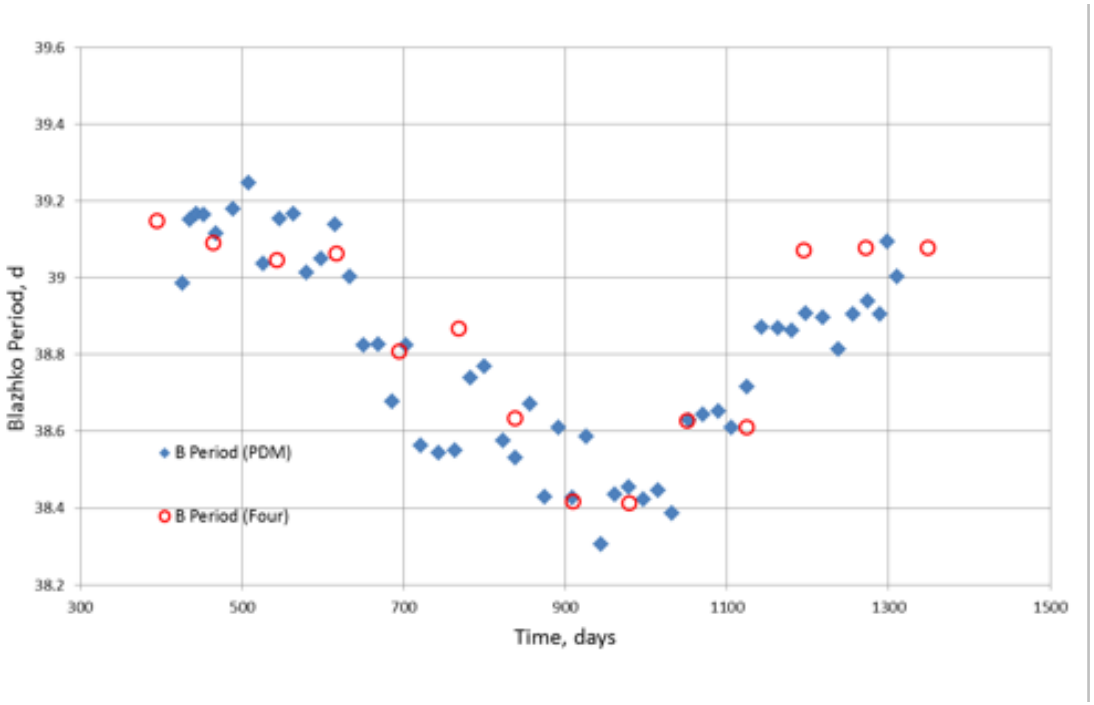
# A NEW ERA


7.40
7.60
7.80
8.00
8.20
Kepler mag
400
600
800
1000
1200
BJD-2454953


7.40
7.60
7.80
8.00
8.20
Kepler mag
400
600
800
1000
1200
BJD-2454953

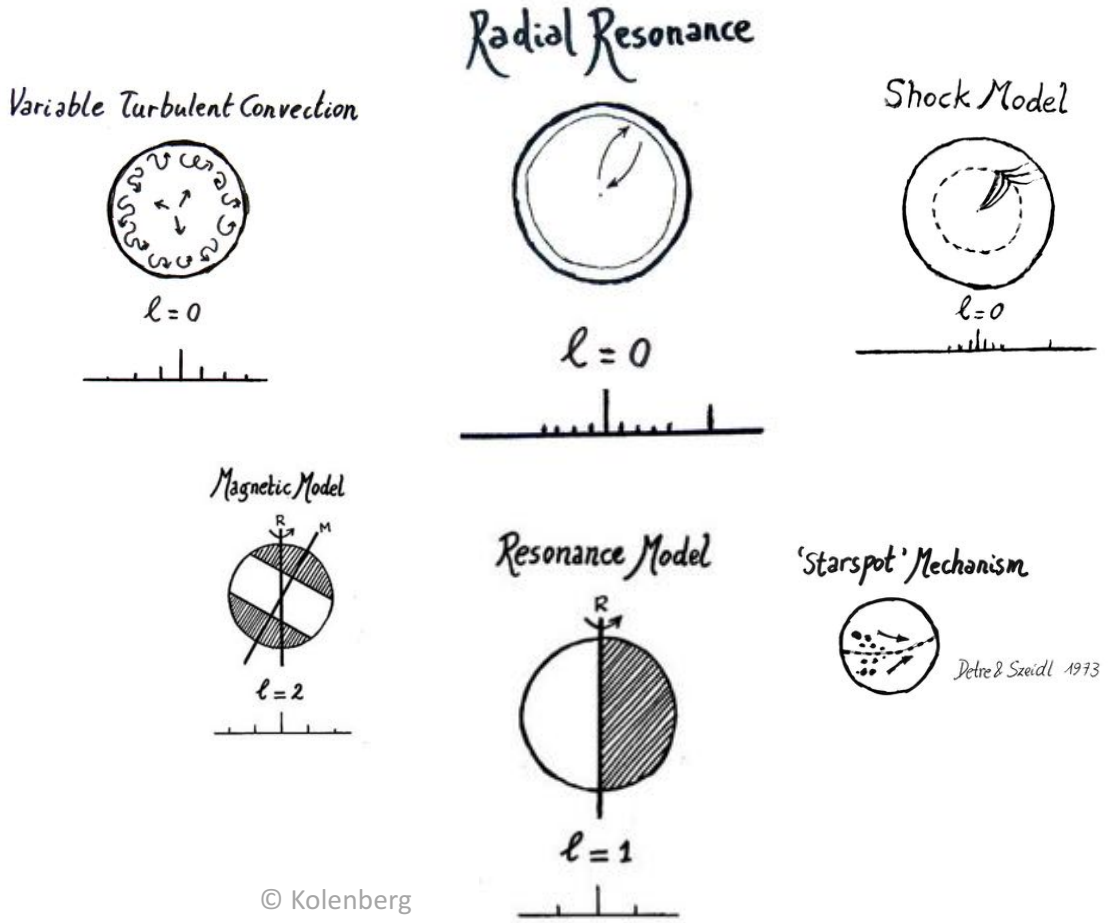



Stellingwerf, Nemec, Moskalik (2013)




Stellingwerf, Nemec, Moskalik (2013)

# Explanations for the Blazhko Effect

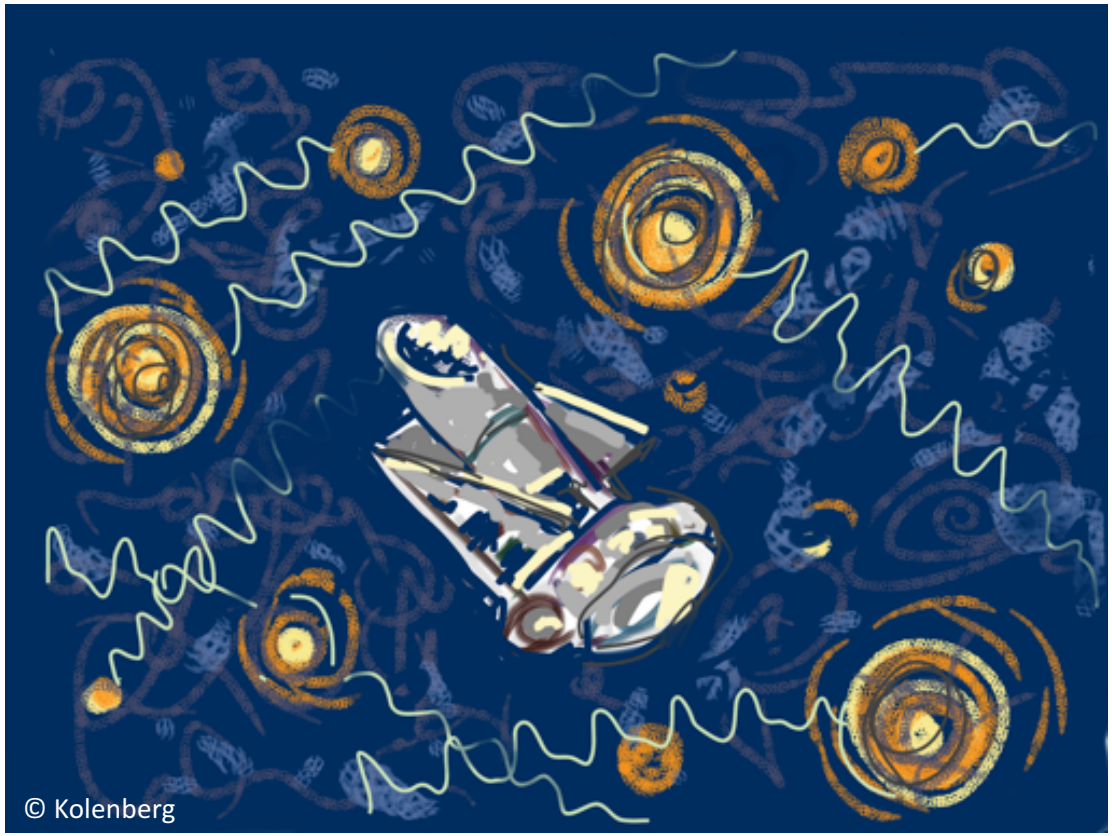


# Setting the scene

Modulation

Period doubling

Additional modes




Unusual period ratios

Instabilities

# Setting the scene

Modulation

Period doubling

Additional modes

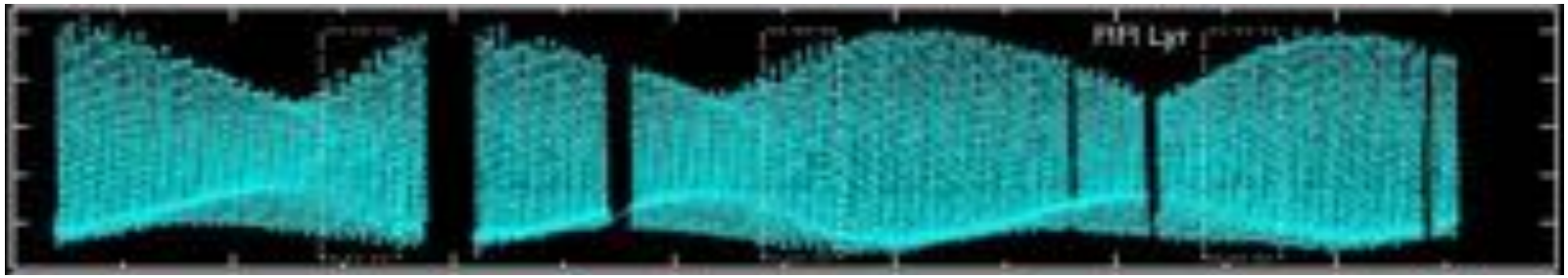

Unusual period ratios

Instabilities

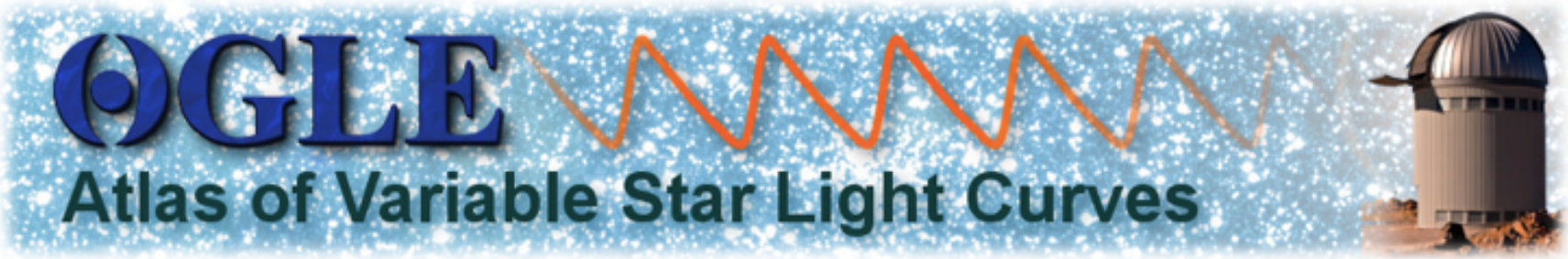
Link with physical parameters?

Effect on, e.g., distance determination?

High-precision space photometry

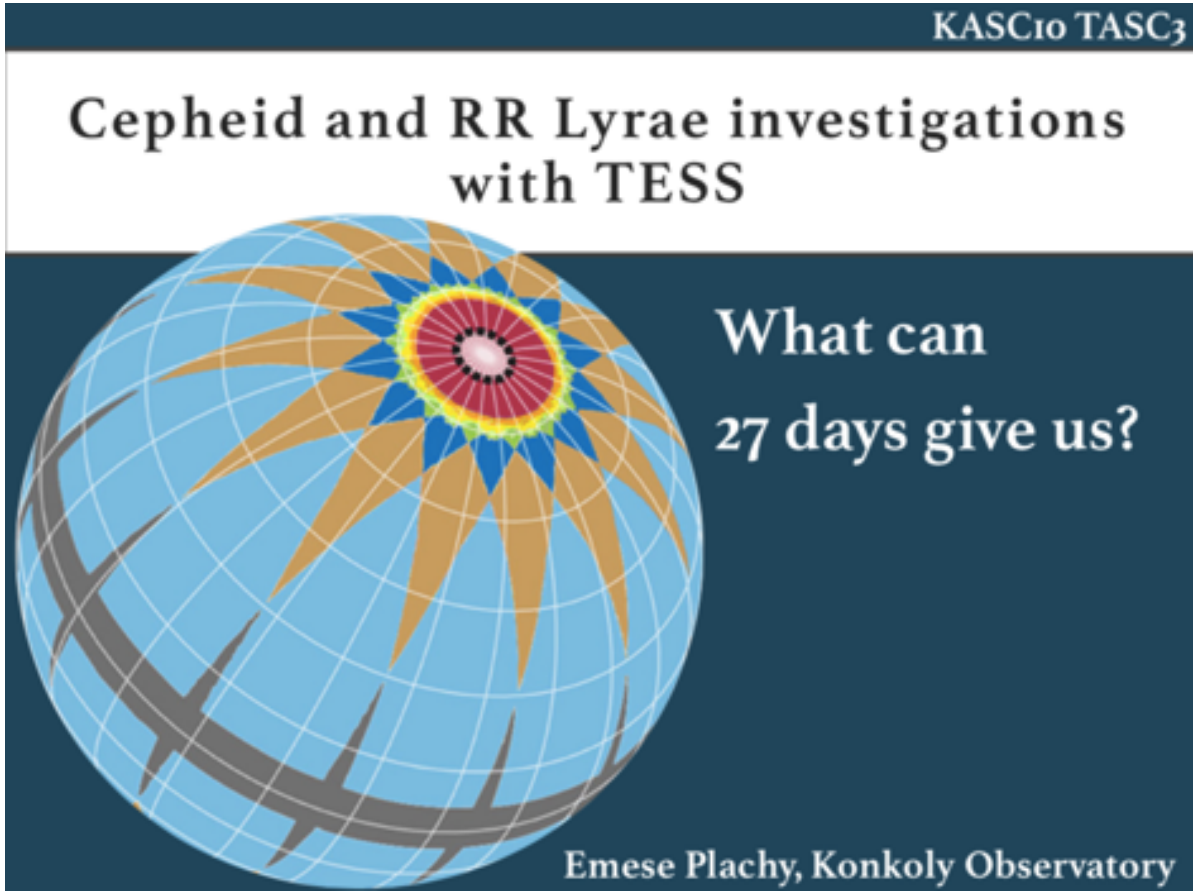



Ground-based photometry of many stars over many years




→ statistics

# Setting the scene



## WHAT COULD 27 DAYS GIVE US?

### DETECTION
- period doubling in RR Lyraes and short period Cepheids
- additional/nonradial modes in RR Lyraes , short period Cepheids
- short period Blazhko modulation in RR Lyrae stars
- cycle-to-cycle variation in RR Lyraes , short period Cepheids

### DISCOVERY
- new RR Lyrae stars and short period Cepheids

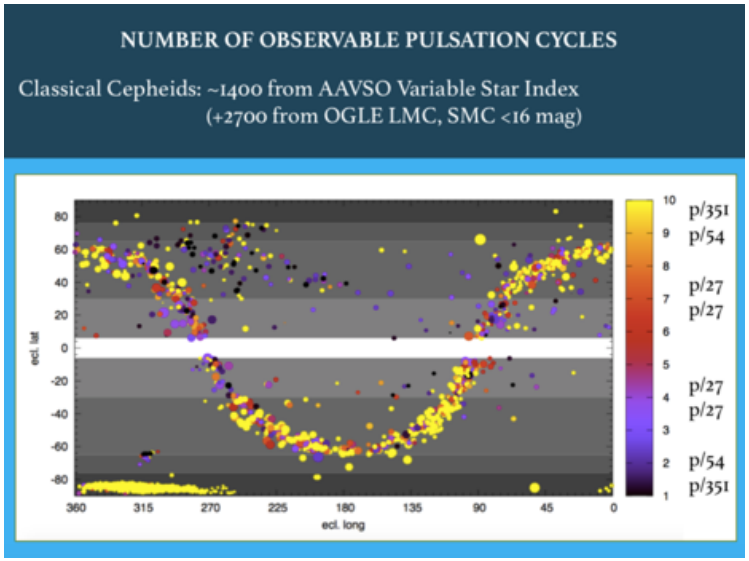
### VALIDATION
- Cepheid candidates
- RRc candidates

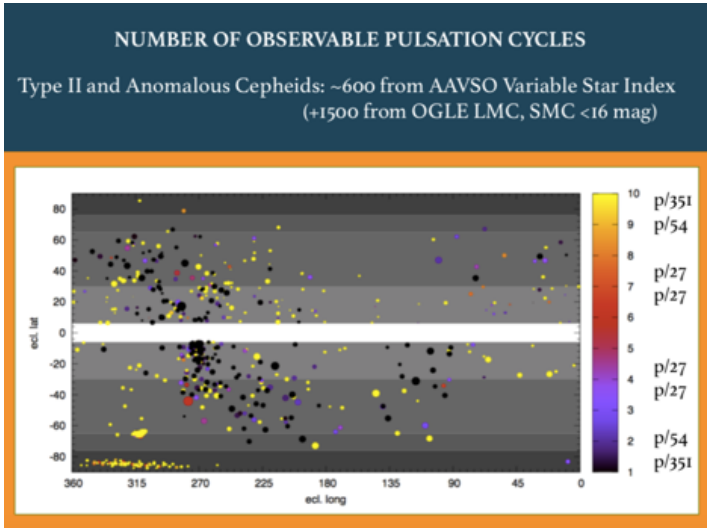
### RESOURCE FOR POPULATION STUDIES
- metallicity, Oosterhoff groups, distribution of modes

Emese Plachy (2017)

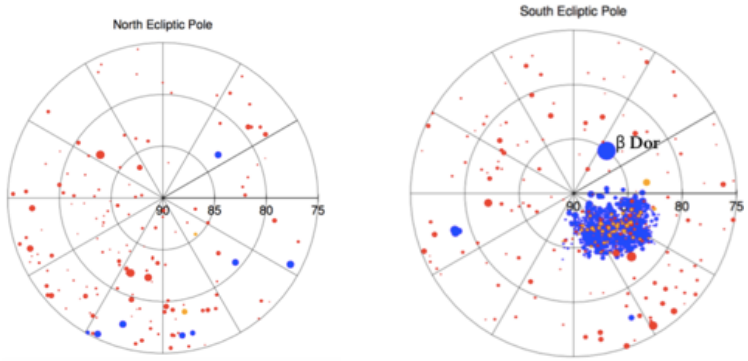
# Setting the scene

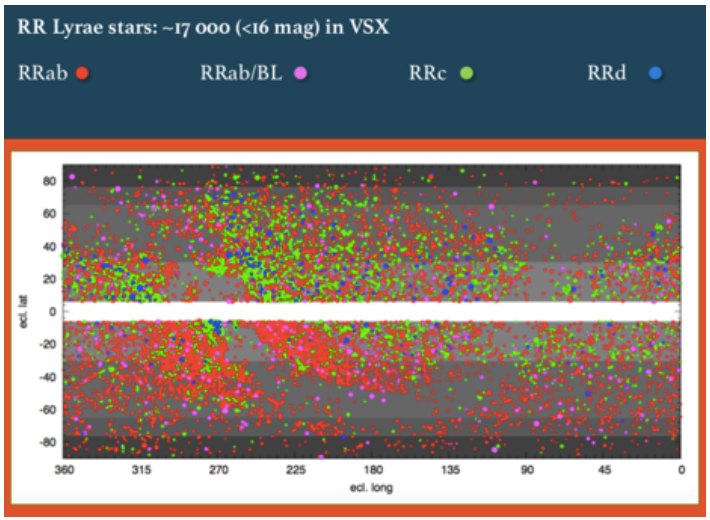
TESS yield predictions




© Emese Plachy (2017)




*Large area covered! All Cepheids in the Galaxy …*

trien Kolenberg

eting – 1

EVS2019 – E

**TESS Classical Pulsators**
**First Light Papers in preparation**

TESS observations of Cepheid stars: first light results

Emese Plachy,[1,2] András Pál,[1] László Molnár,[1,2] Attila Bódi,[1,3,2] Pál Szabó,[1,2] R. I. Anderson,[1] A. Bellinger,[1] J. M. Benkő,[1] A. Bhardwaj,[1] M. Ebadi,[1] K. Gazeas,[1] A. Hasanzadeh,[1] M. J. Kalaee,[1] M. Jurkovic,[1] P. Kervella,[1] K. Kolenberg,[1] P. Mikołajczyk,[1] N. Nardetto,[1] J. M. Nemec,[1] H. Netzel,[1] C–C. Ngeow,[1] D. Ozuyar,[1] J. Pascual-Granado,[1] V. Ripepi,[1] M. Skarka,[1] R. Smolec,[1] Á. Sódor,[1] L. Szabados,[1] R. Szabó,[1] and TESS Team members

First results on RR Lyrae stars with the TESS space telescope

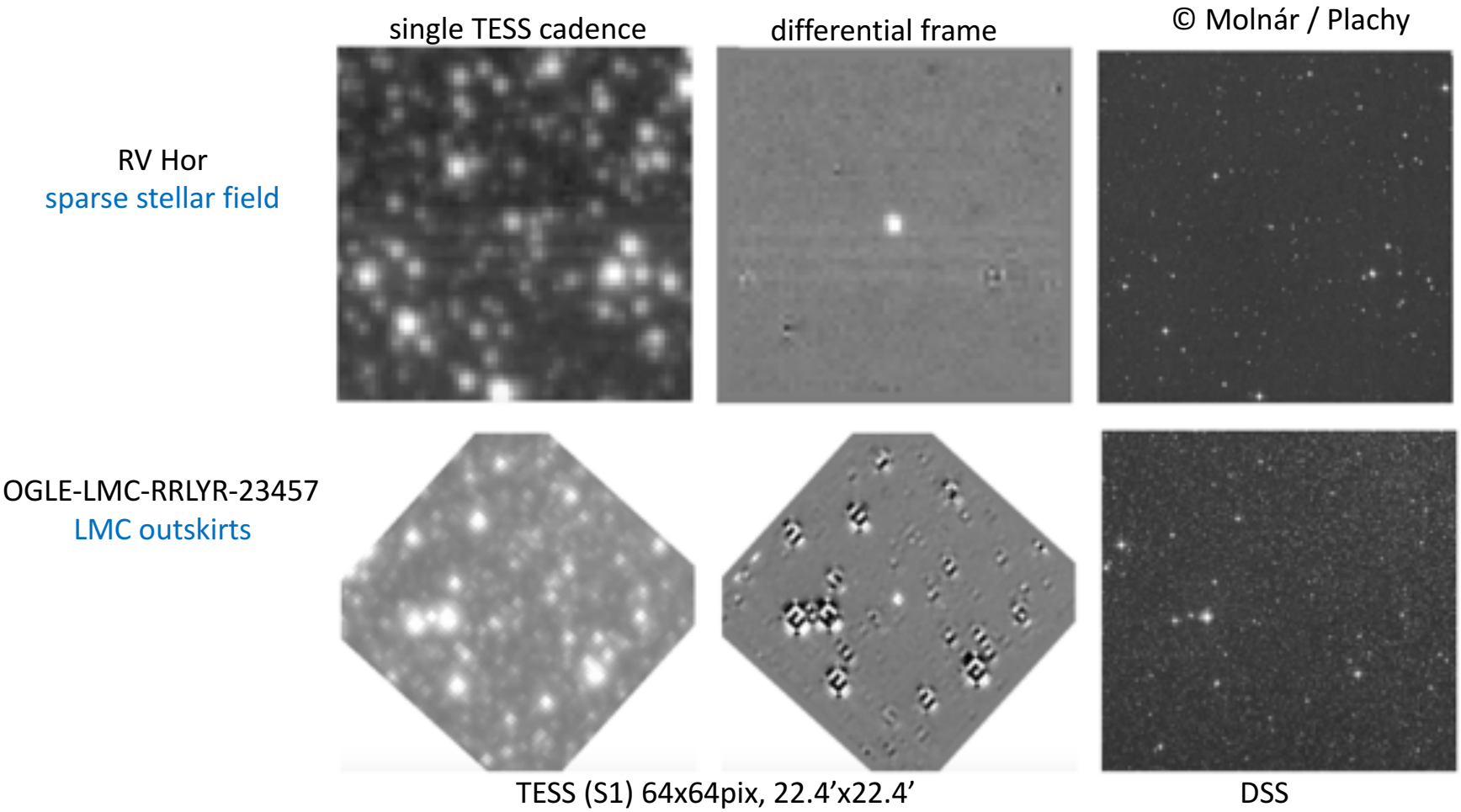
L. Molnár,[1,2] A. Pál,[1,3,4] J. M. Benkő,[1] A. Bhardwaj,[1] A. Bódi,[1] M. Ebadi,[5] F–J. Hambsh,[5] A. Hasanzadeh,[6,7] K. Kolenberg,[6,7] J. M. Nemec,[6,7] H. Netzel,[6,7] C–C. Ngeow,[6,7] Z. Prudil,[6,7] M. Skarka,[6,7] R. Smolec,[1] Á. Sódor,[1] J. Pepper,[1] E. Plachy,[1] P. Szabó,[1] R. Szabó,[1] and TESS Team members

# Target Selection

”Good data”: photometric precision & enough observed pulsation cycles

→ brightness, pulsation period and location in the sky determine selection

# TESS photometry – opportunities and challenges



# First highlights: Cepheids

- Sectors 1 to 5
- Classical Cepheids:
  - 10 fundamental mode
  - 3 first-overtone mode
  - 2 double mode
- Type II Cepheids: 3
- Anomalous Cepheids: 7

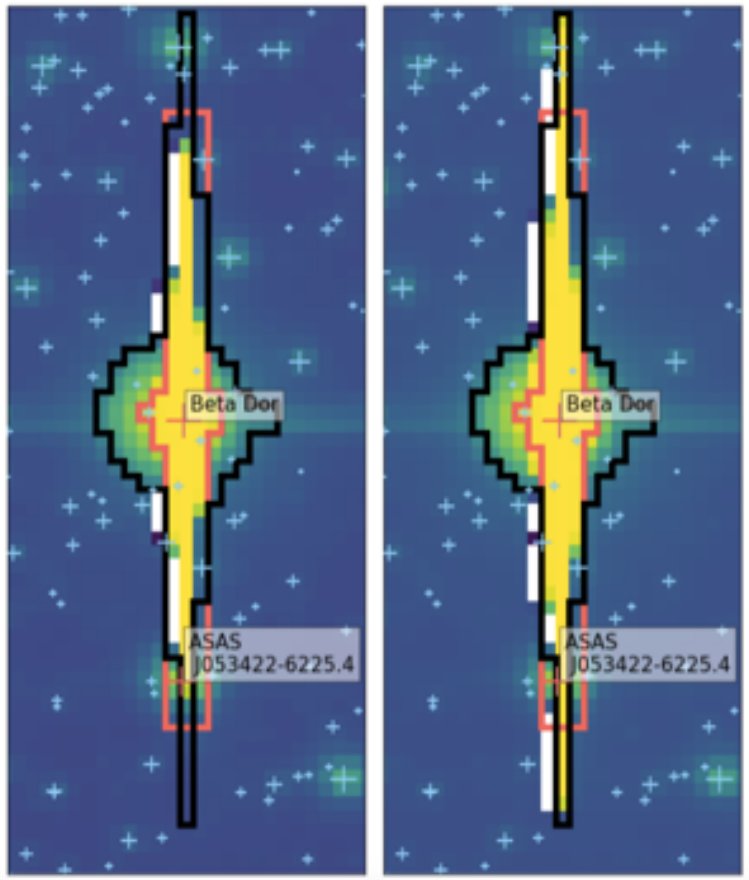
*…from fields with different stellar densities in the Galaxy and the Magellanic Clouds*

3 SC light curves: bright classical Cepheid **β Dor** (CVZ), 2 anomalous Cepheids: **XZ Cet** in S3, **UY Eri** in S4

TESS SPOC data products for SC data, differential photometric pipeline based on FITSH
(see Pál Szabó's poster and Andras Pal's presentation)

**Goal: investigate pulsation behavior and influence of data quality on the results**

# TESS photometry – opportunities and challenges

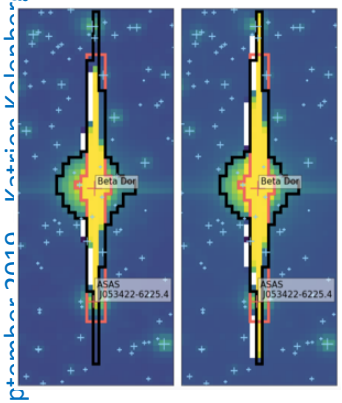



custom pixel mask
SPOC pixel mask

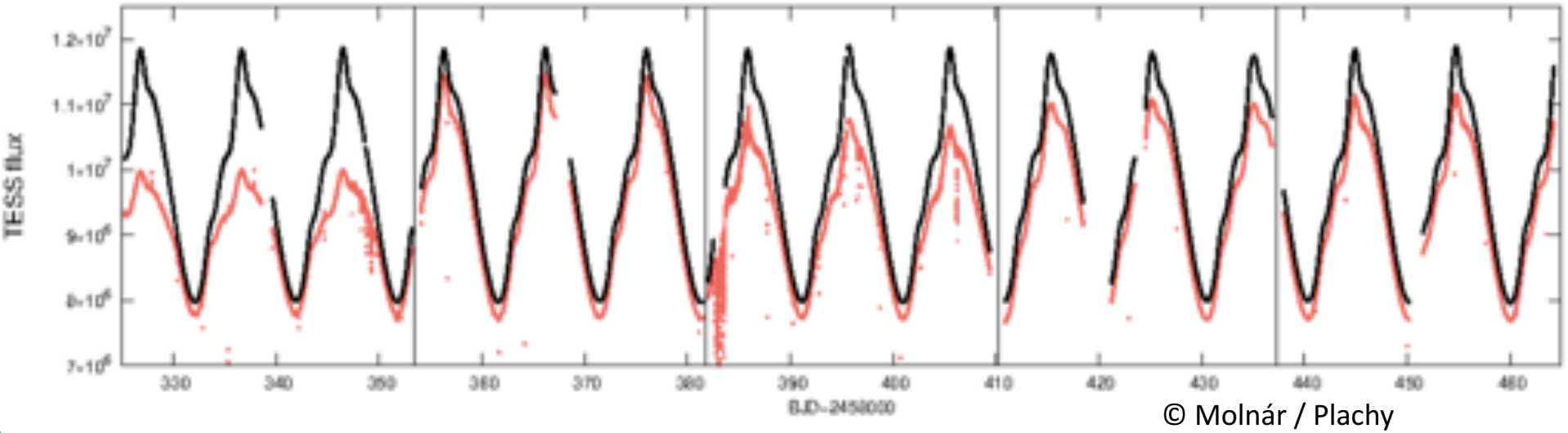
minimum light

maximum light

© Molnár / Plachy

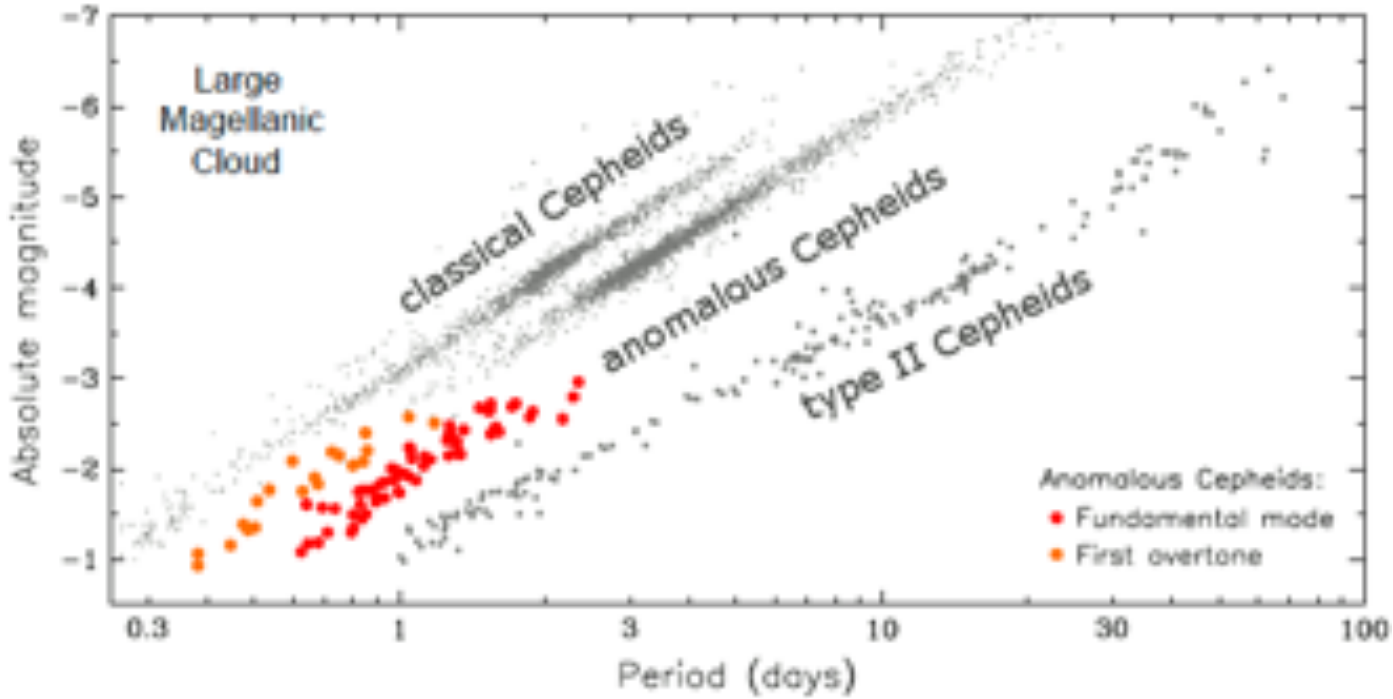



β Dor: fundamental mode pulsator, P = 9.842 d



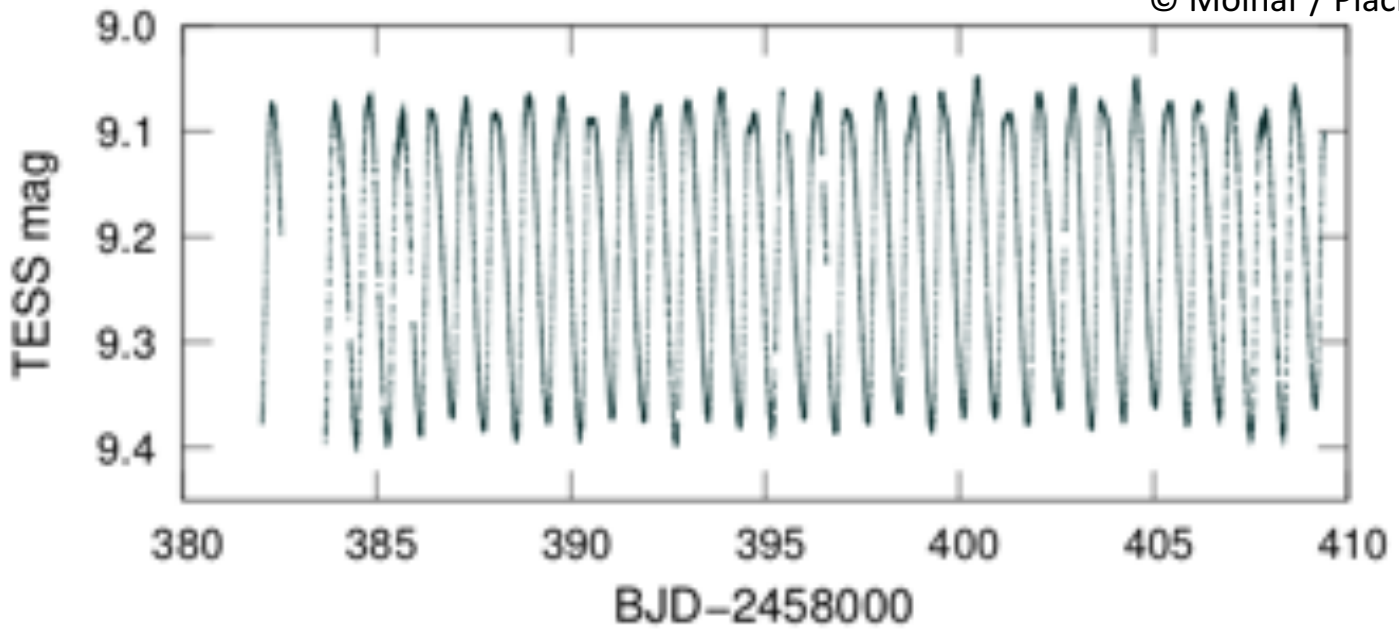

© Molnár / Plachy

# First highlights: Cepheids



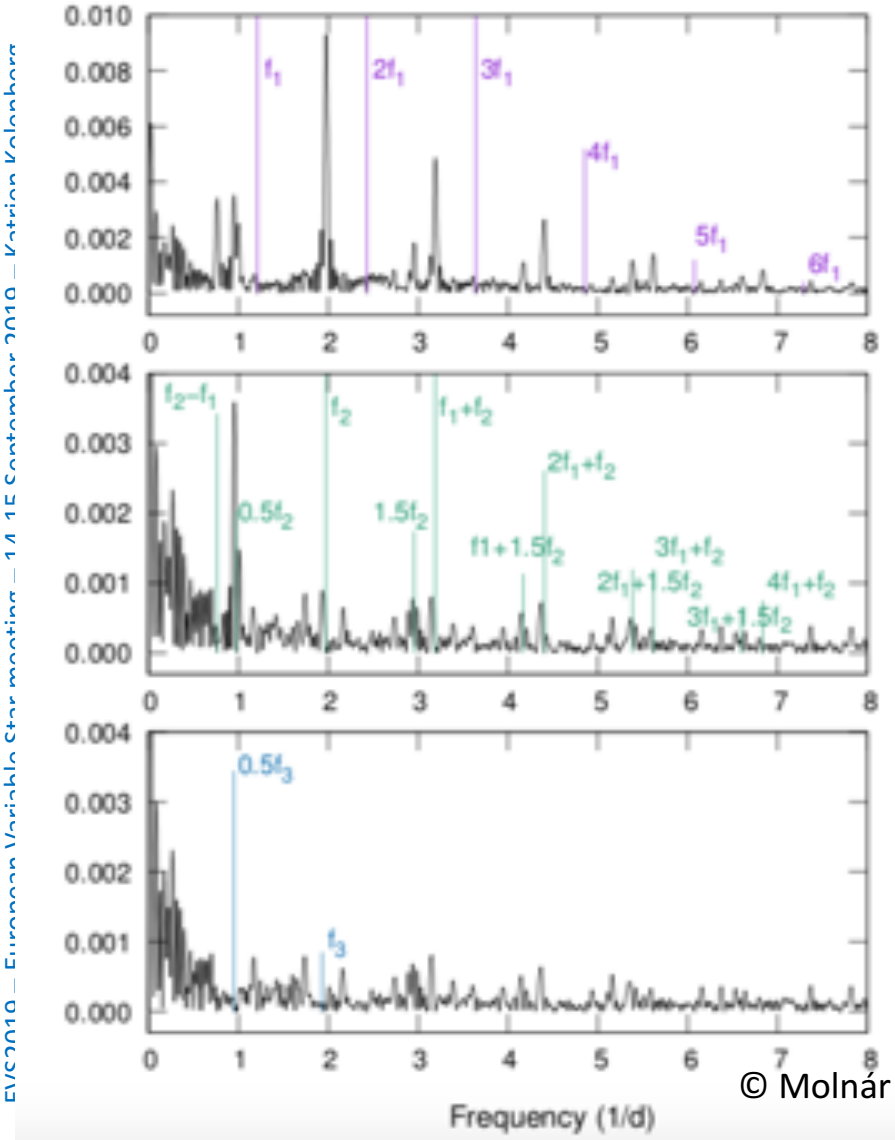
Galactic Anomalous and Type II Cepheids






XZ Cet: first anomalous Cepheid (AC) found in the Galactic field

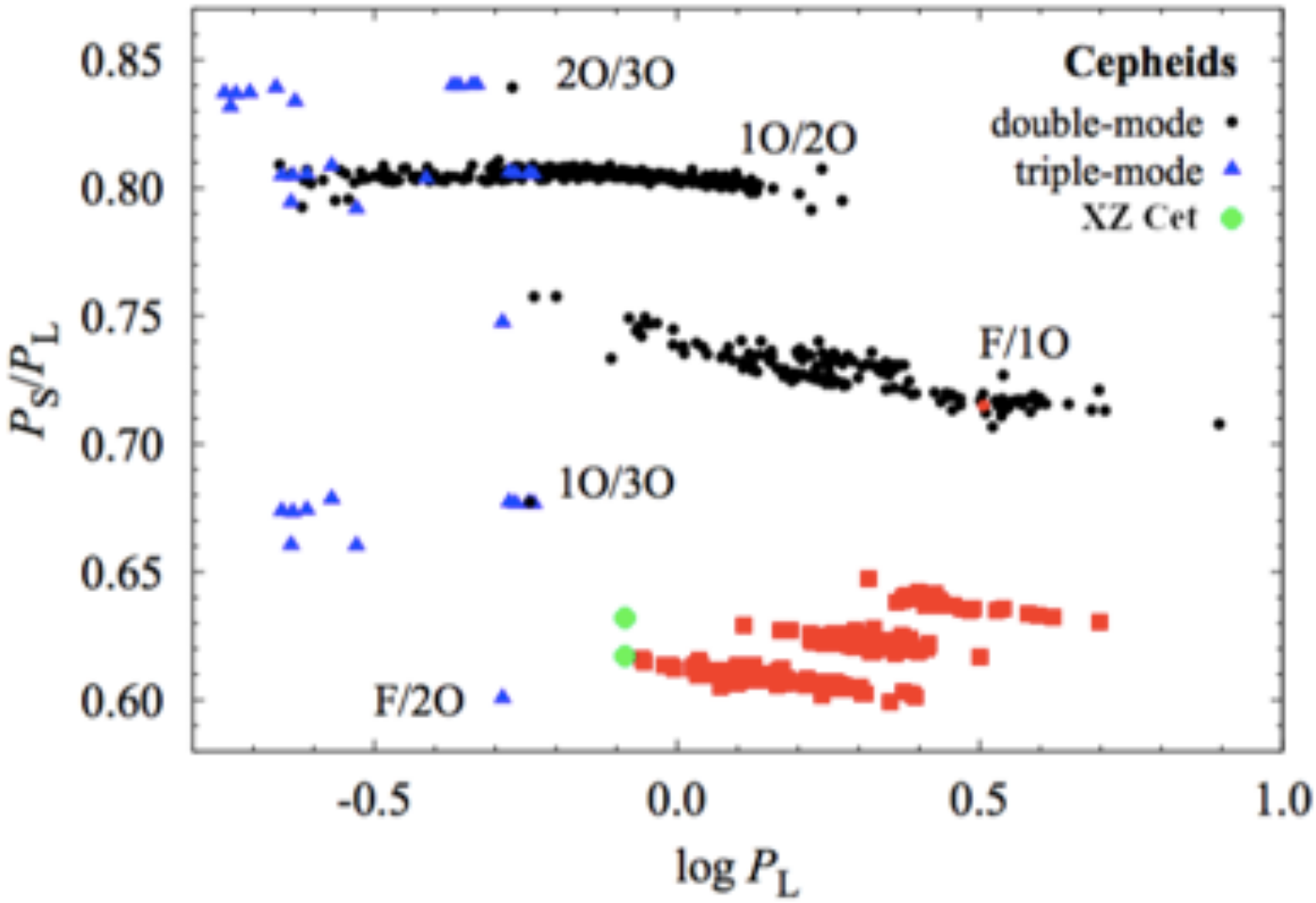
# First highlights: Cepheids



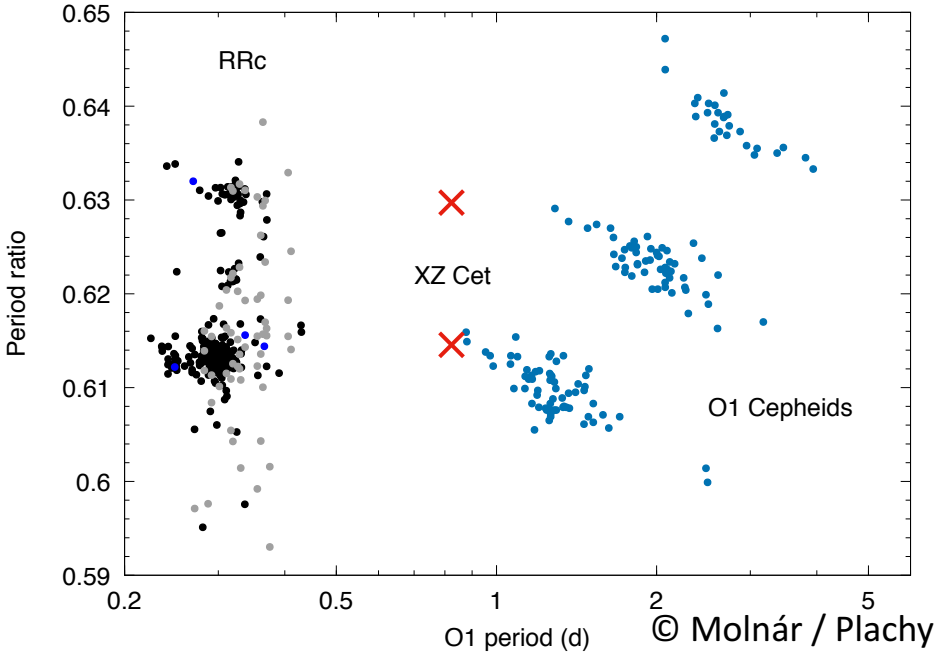

XZ Cet short cadence TESS data

© Molnár / Plachy

# First highlights: Cepheids



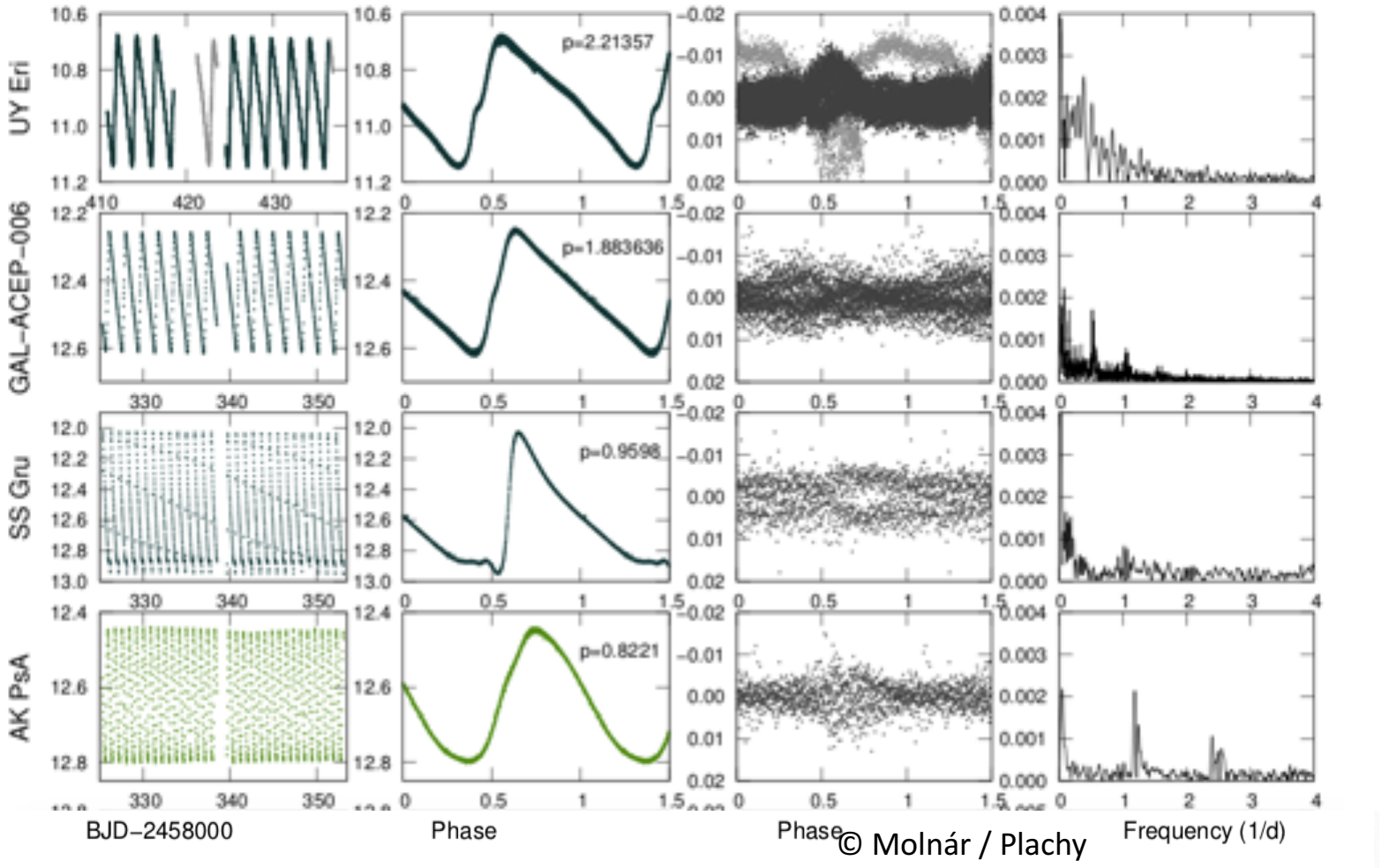
# First highlights: Cepheids



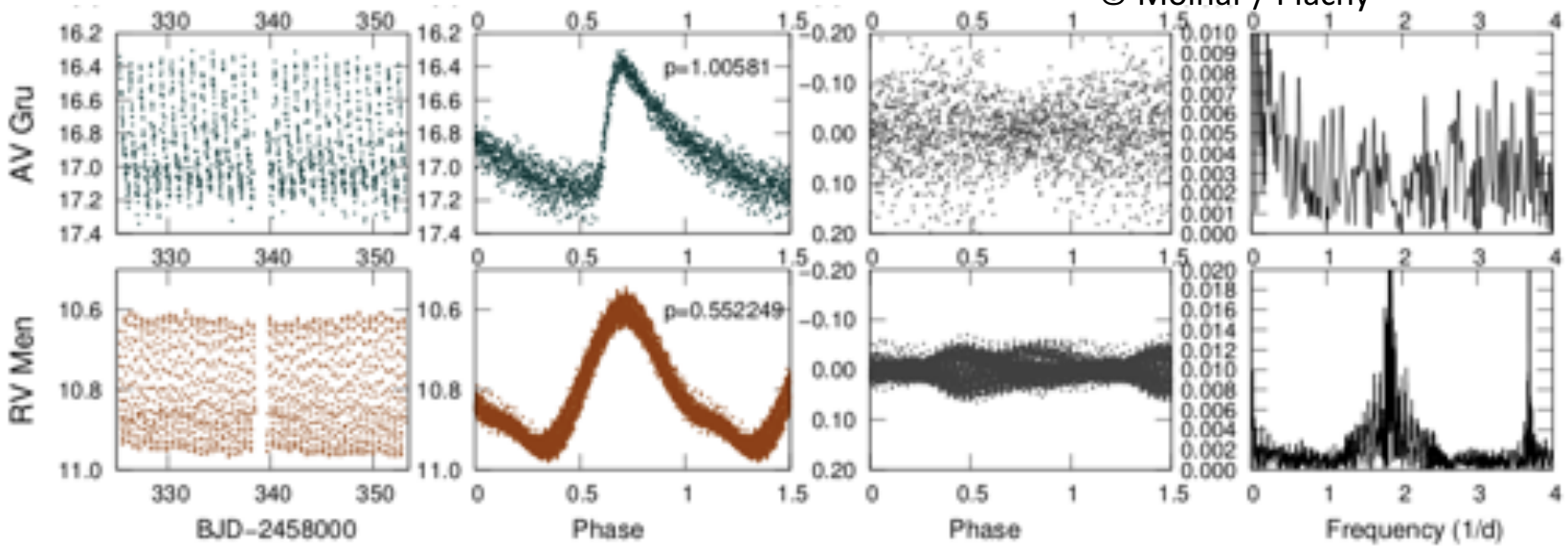

Overtone Petersen diagram for the fX modes, XZ Cet, the anomalous Cepheid fits right in, so the $f_x$ or $f_{0.61}$-type modes are common along three groups now: RRc, O1 DCEP, and O1 ACEP.

Analysis of TESS data of 10 additional short-period Cepheid candidates





# First highlights: Cepheids



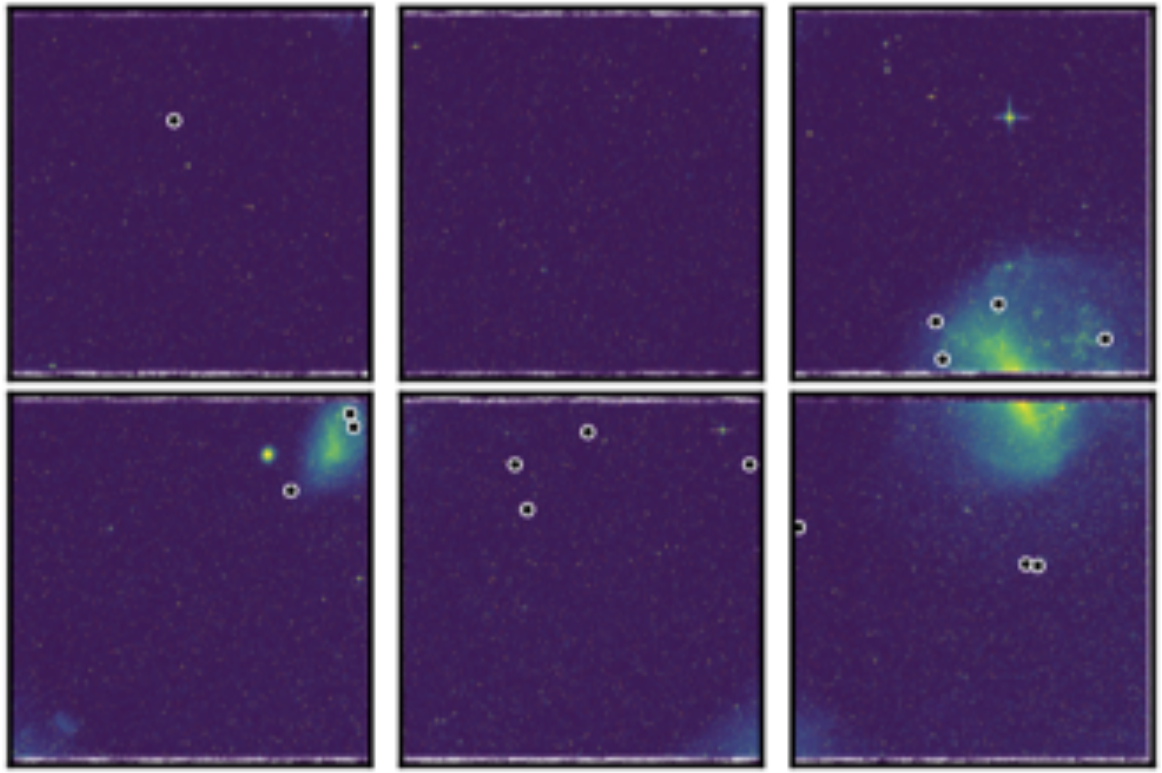

**RV Men:** Cepheid imposter (probably a rotational variable) with a large amplitude and a relatively stable light curve shape

Confusion in classification
between subtypes
& resemblance to other variables
(rotational variables, binaries)

Period doubling
can also resemble primary and secondary eclipses

# First highlights: Cepheids

Cepheids in the Magellanic Clouds

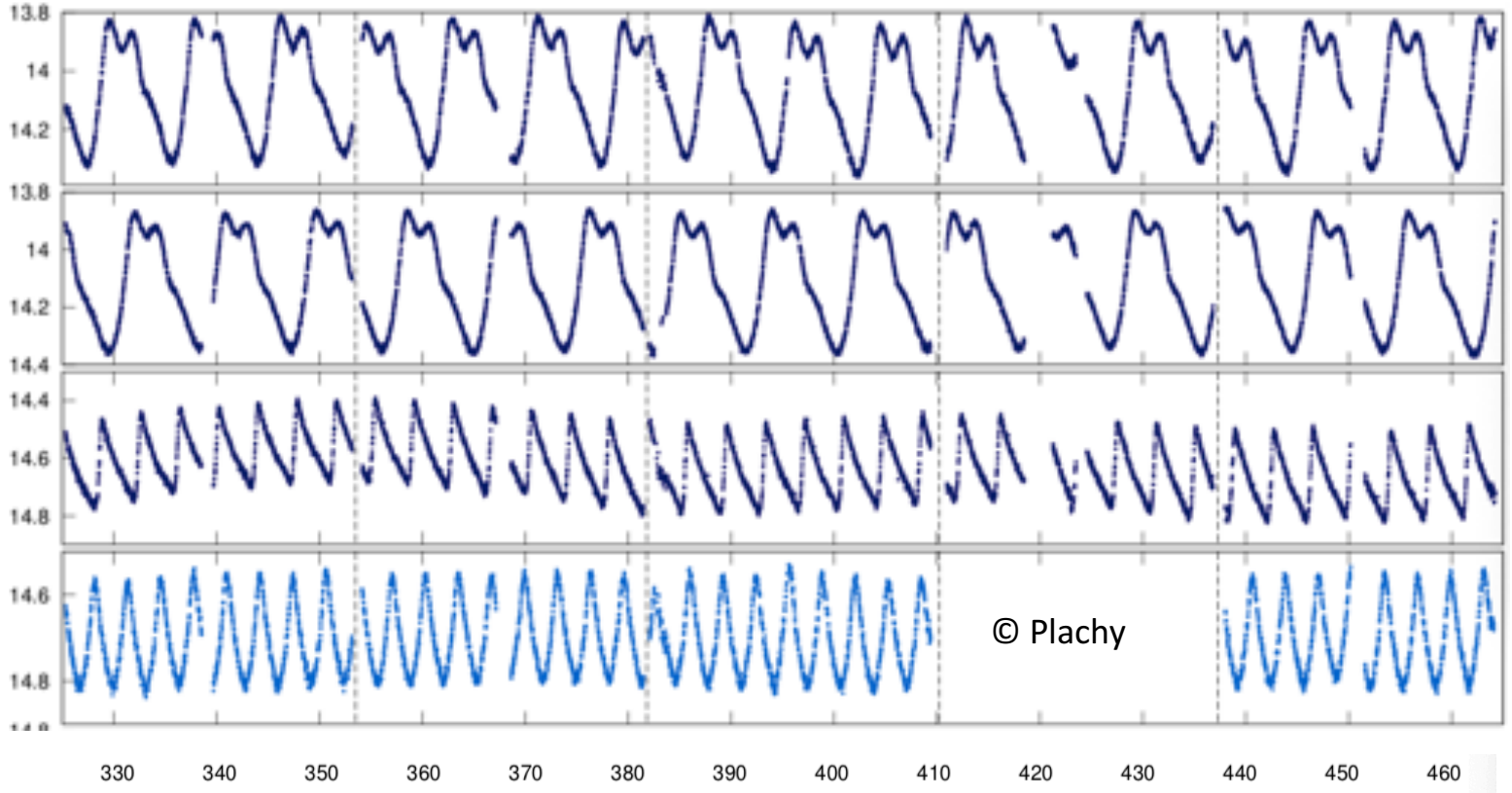


© Molnár / Plachy

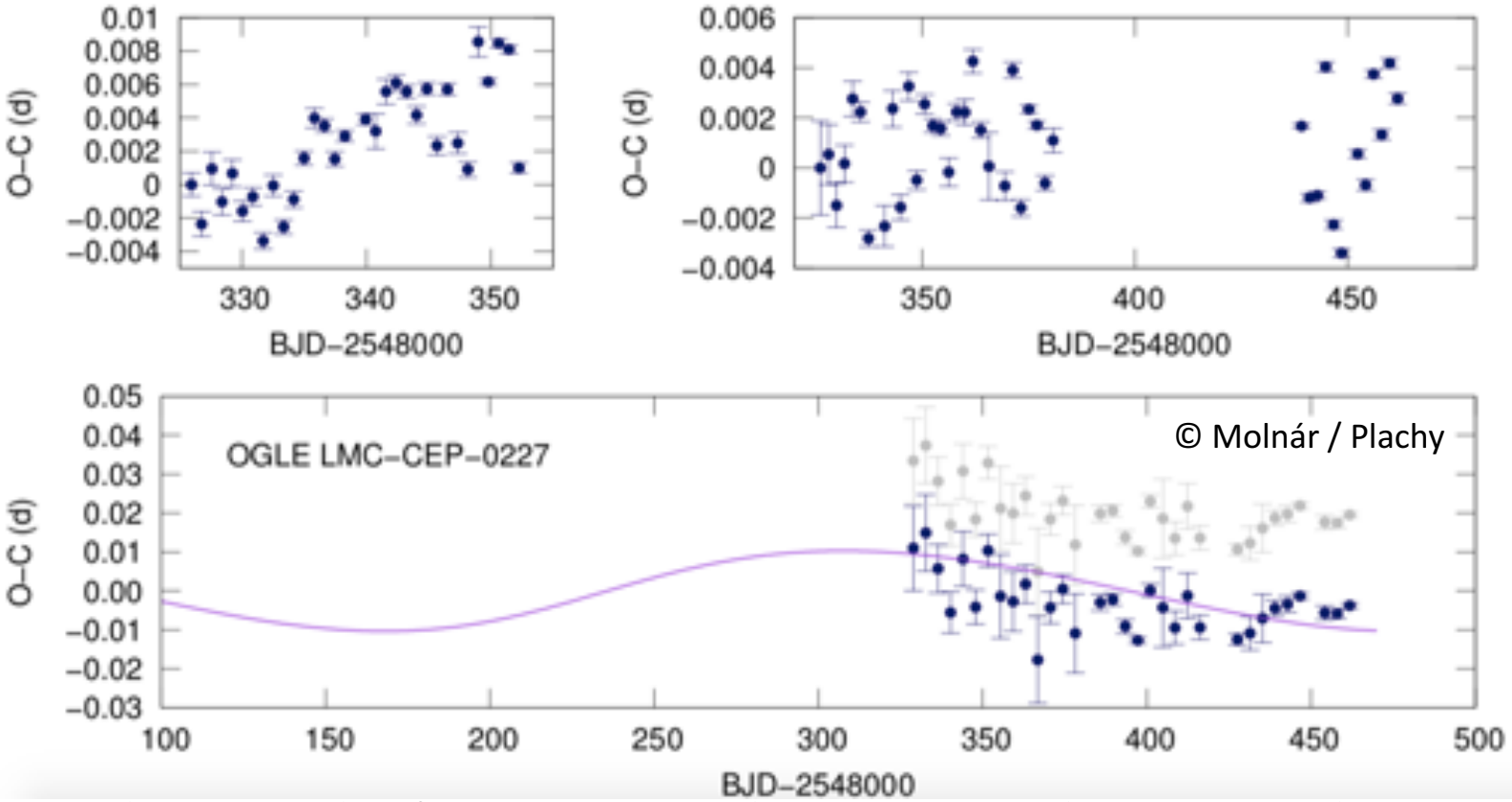
A variety of targets in LMC, SMC and Bridge

# First highlights: Cepheids

Cepheids in the Magellanic Clouds



# First highlights: Cepheids




Cepheid O-Cs: unclear if scatter is instrumental or intrinsic jitter, makes detecting LITE harder. We can confirm CEP-0227 because we have an ephemeris for it, and probably see contribution from a secular period change term too.

## First highlights: RR Lyraes

- Sectors 1 and 2
- RR Lyrae targets for this study: SIMBAD and Gaia DR2 catalogs (not exhaustively)
  - < 12.5-13.0 mag in TESS passband for Camera 1-3
  - < 14.0 mag in TESS passband for Camera 4
  - Targets with severe systematics or contamination discarded

*…from fields with different stellar densities*

3 SC light curves: **ST Pic** in S1+S2, **BV Aqr** in S1, **RU Scl** in S2

TESS SPOC data products for SC data, FFI: differential photometric pipeline based on FITSH
(see Pál Szabó's poster and Andras Pal's presentation)

Ground-based data: KELT (Kilodegree Extremely Little Telescope) for 33 stars (Pepper et al. 2007, 2012), Wide-Angle Search for Planets (SuperWASP), Butters et al. 2010; Paunzen et al. 2014). **RU Scl** : data from Chile in 2017-2018 (Hambsch 2012).

Your data?

# Things to investigate for RR Lyraes with TESS

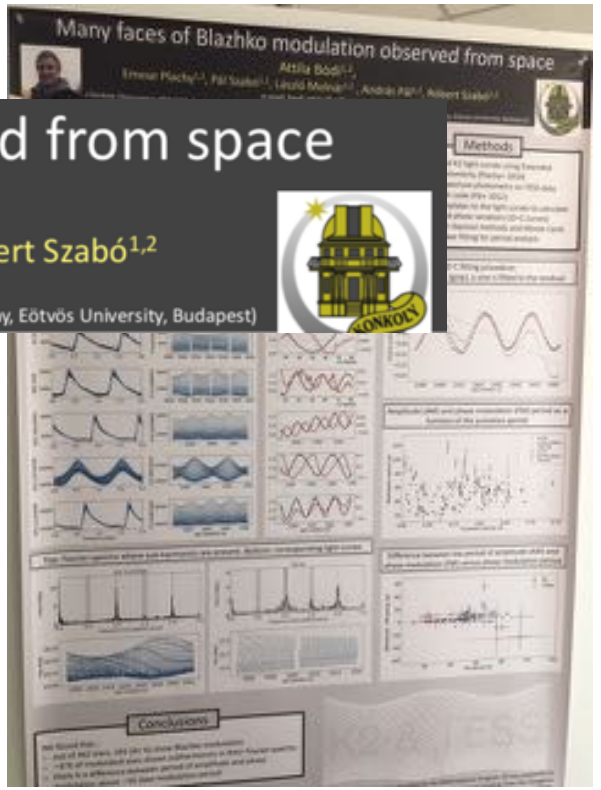
- Non-Blazhko stars? (or are all stars modulated?)
- Modulation properties
- Additional modes
- RRd stars
- Contamination
- Faint stars
- Different populations, different pulsation properties?

## Modulation properties

First highlights: RR Lyraes

# Many faces of Blazhko modulation observed from space

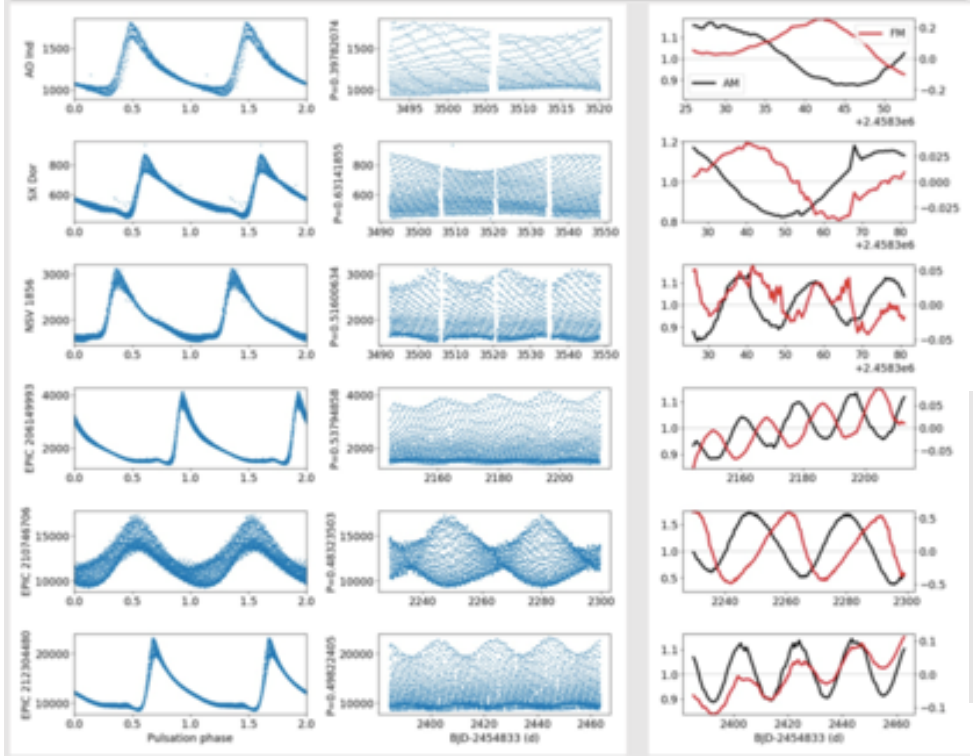
Attila Bódi[1,2],
Emese Plachy[1,2], Pál Szabó[1,2], László Molnár[1,2] , András Pál[1,3], Róbert Szabó[1,2]
e-mail: bodi.attila@csfk.mta.hu
([1]Konkoly Observatory, MTA CSFK, Budapest, [2]MTA CSFK Lendület Near-Field Cosmology Research Group, [3]Dept. of Astronomy, Eötvös University, Budapest)



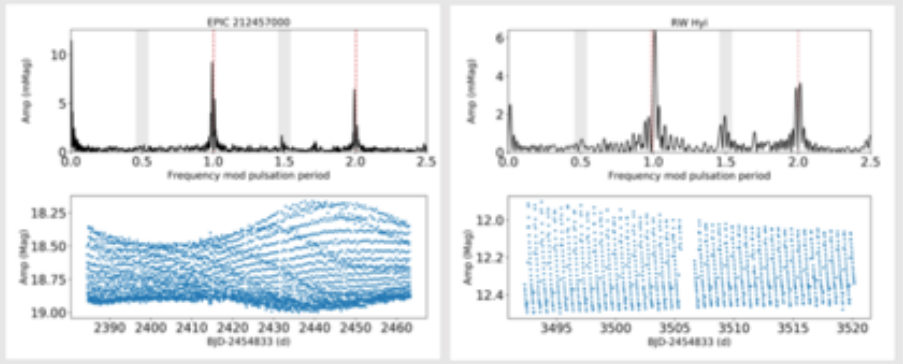
# Modulation properties

First highlights: RR Lyraes

Gallery of phase curves (left), light curves (middle) and amplitude-phase modulations




Top: Fourier-spectra where sub-harmonics are present. Bottom: corresponding light curves




## Conclusions

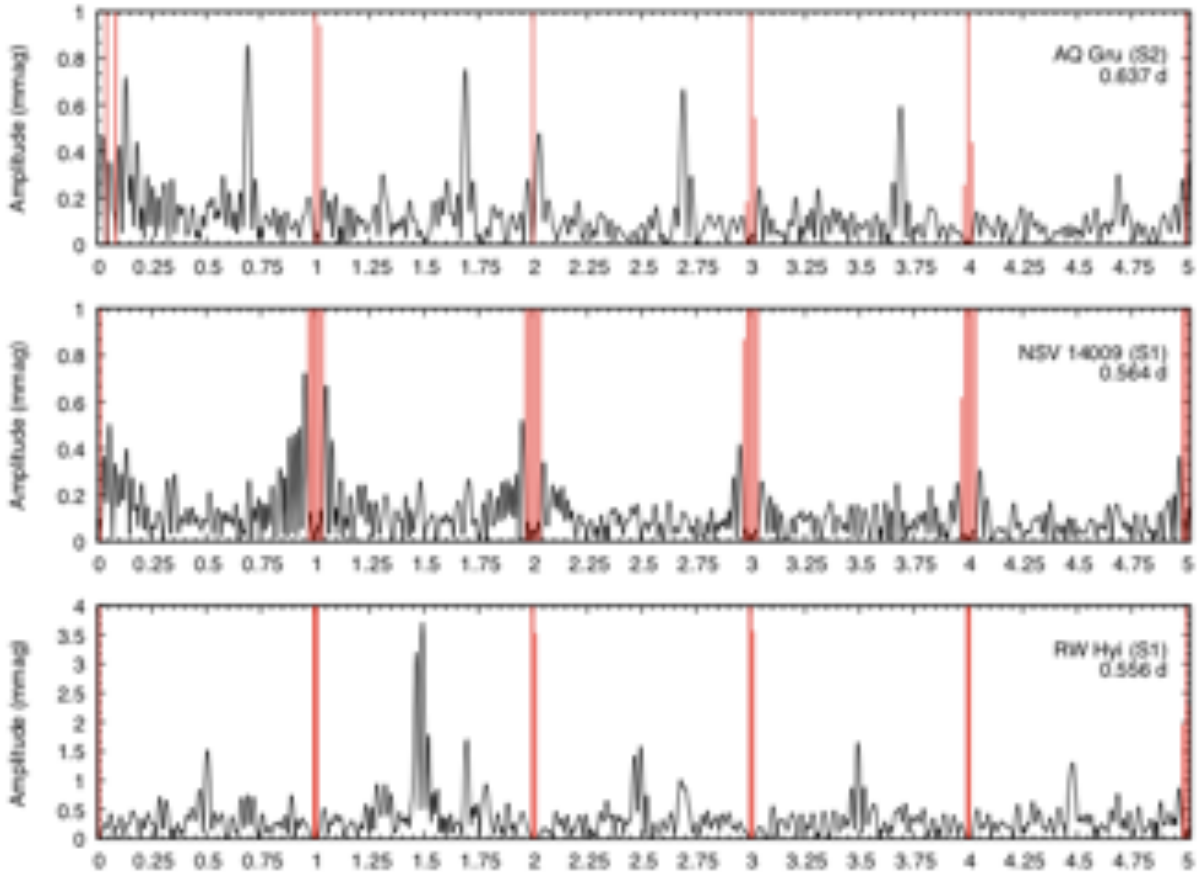
We found that...

- out of 462 stars, 191 (41 %) show Blazhko modulation
- ~8 % of modulated stars shows subharmonics in their Fourier-spectra
- there is a difference between period of amplitude and phase modulation above ~55 days modulation period

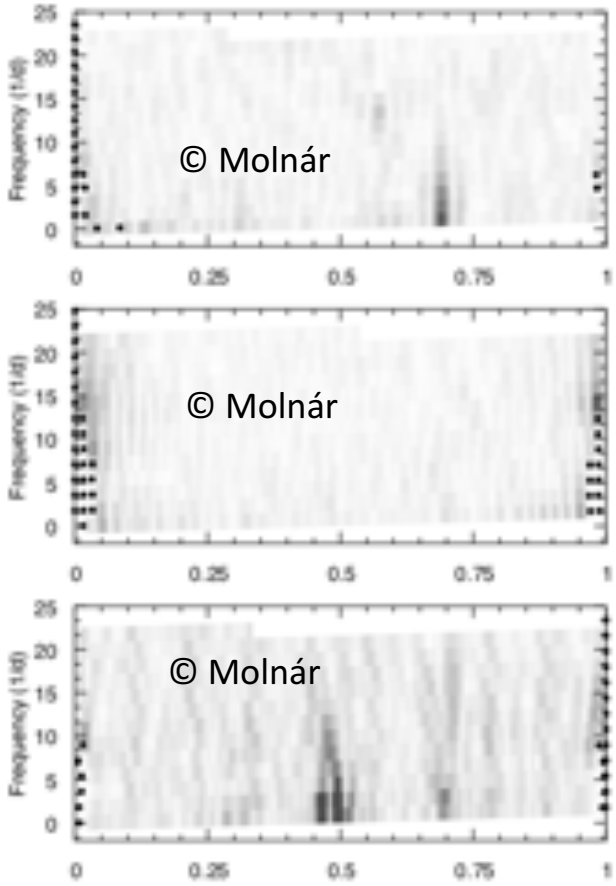
Many faces of Blazhko modulation observed from space

Attila Bódi[1,2],
Emese Plachy[1,2], Pál Szabó[1,2], László Molnár[1,2], András Pál[1,3], Róbert Szabó[1,2]
e-mail: bodi.attila@csfk.mta.hu
([1]Konkoly Observatory, MTA CSFK, Budapest, [2]MTA CSFK Lendület Near-Field Cosmology Research Group, [3]Dept. of Astronomy, Eötvös University, Budapest)

# Additional modes: Echelle diagrammes!

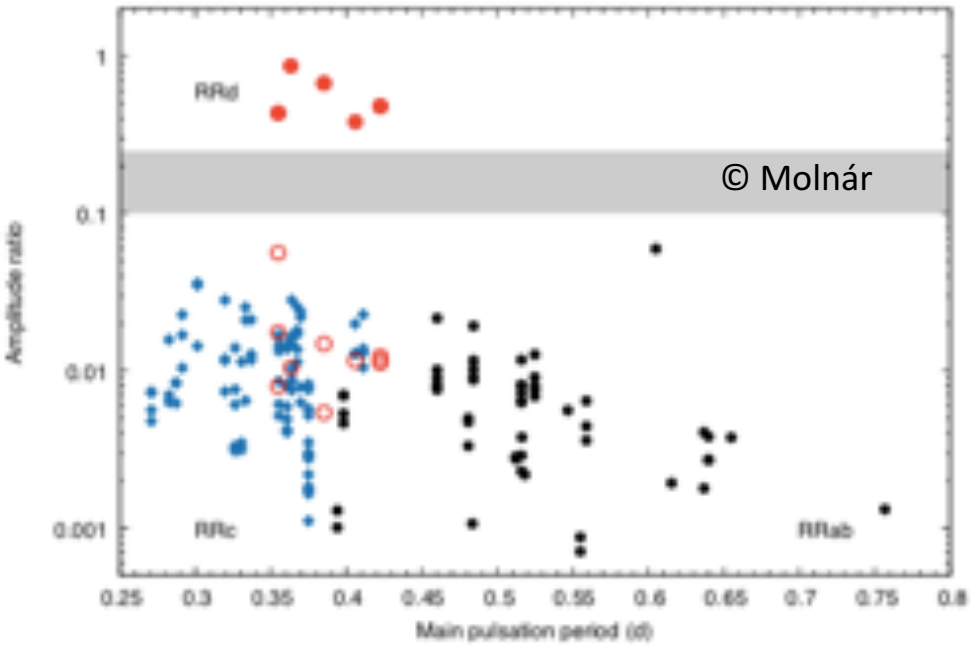


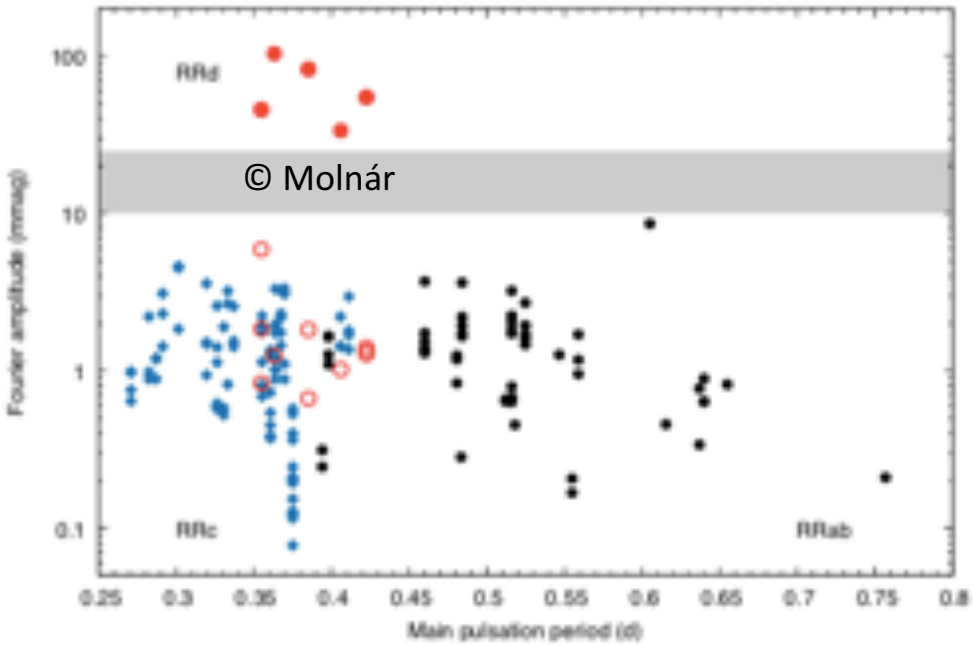

Normalized frequency




Frequency modulo $f_{puls}$

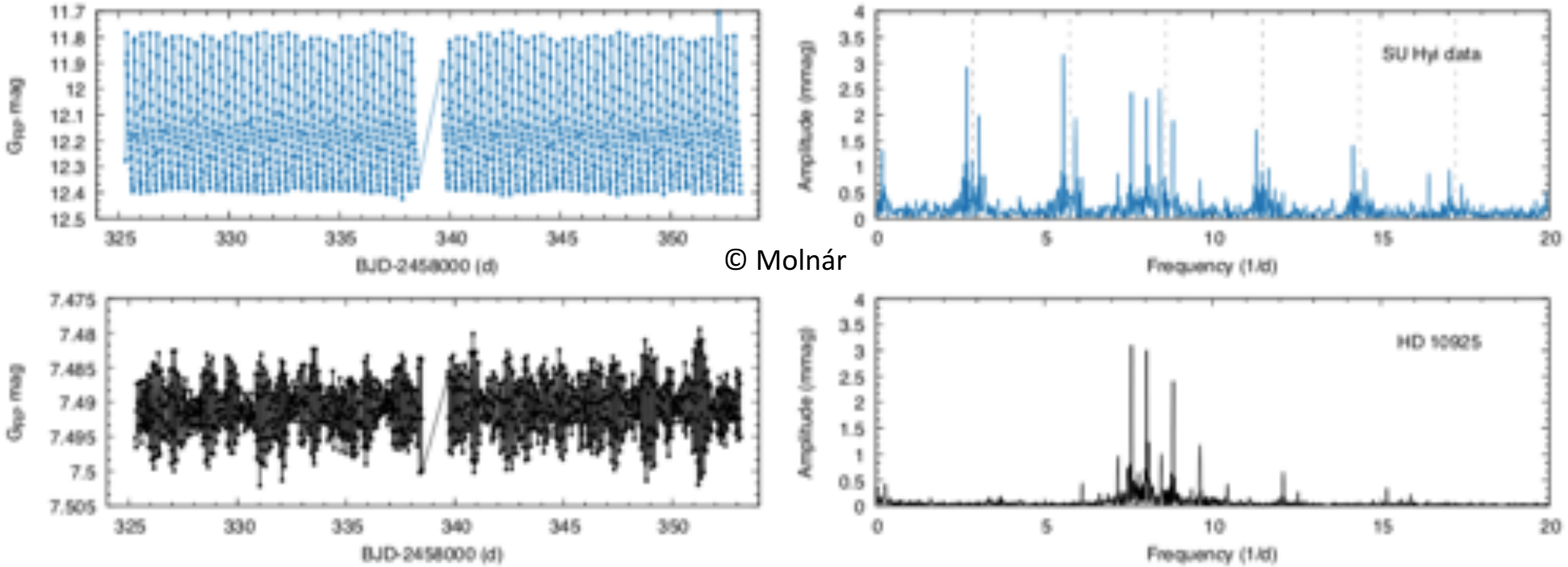
## RRd stars




Mind the gap!

## Contamination

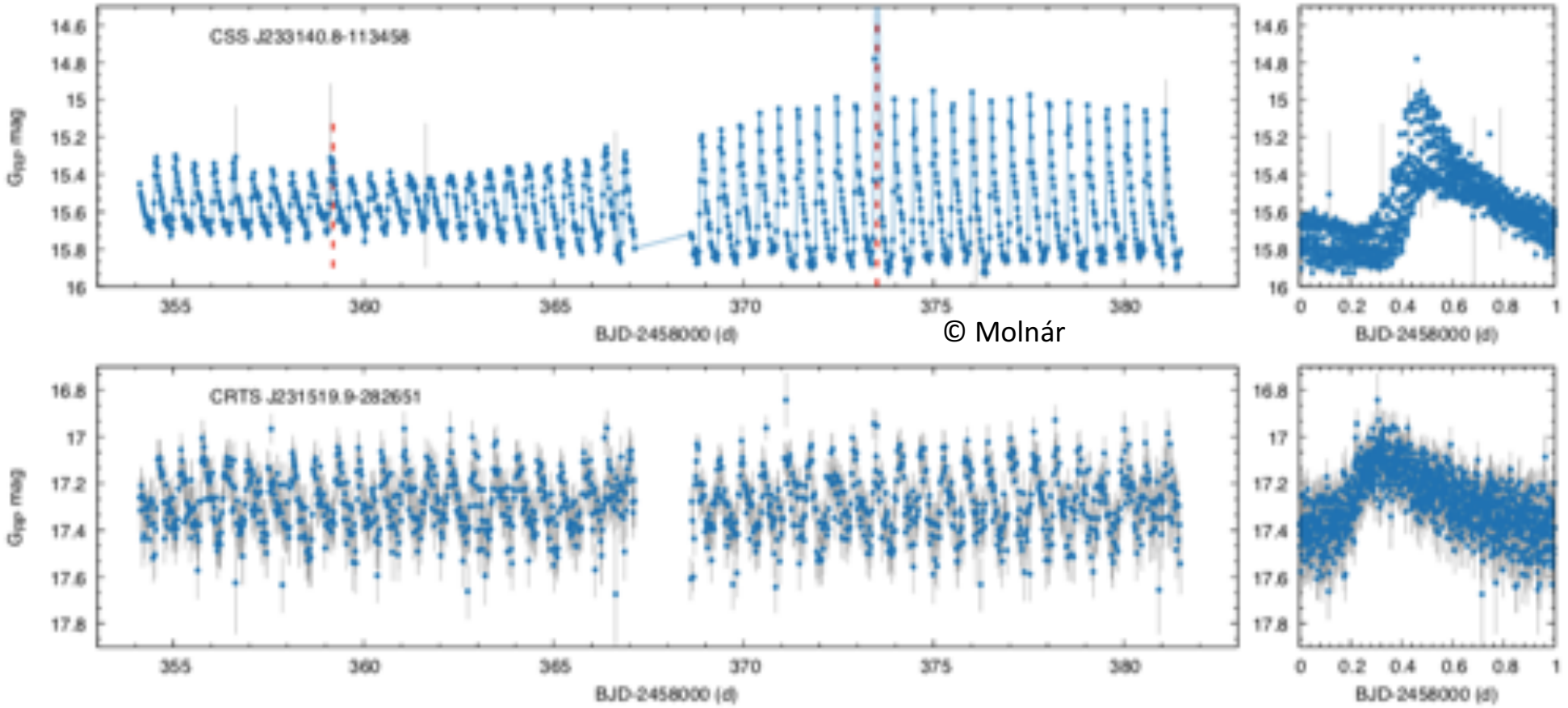



© Molnár

TESS RR Lyrae star data “contaminated” by a Delta Scuti

# Faint stars

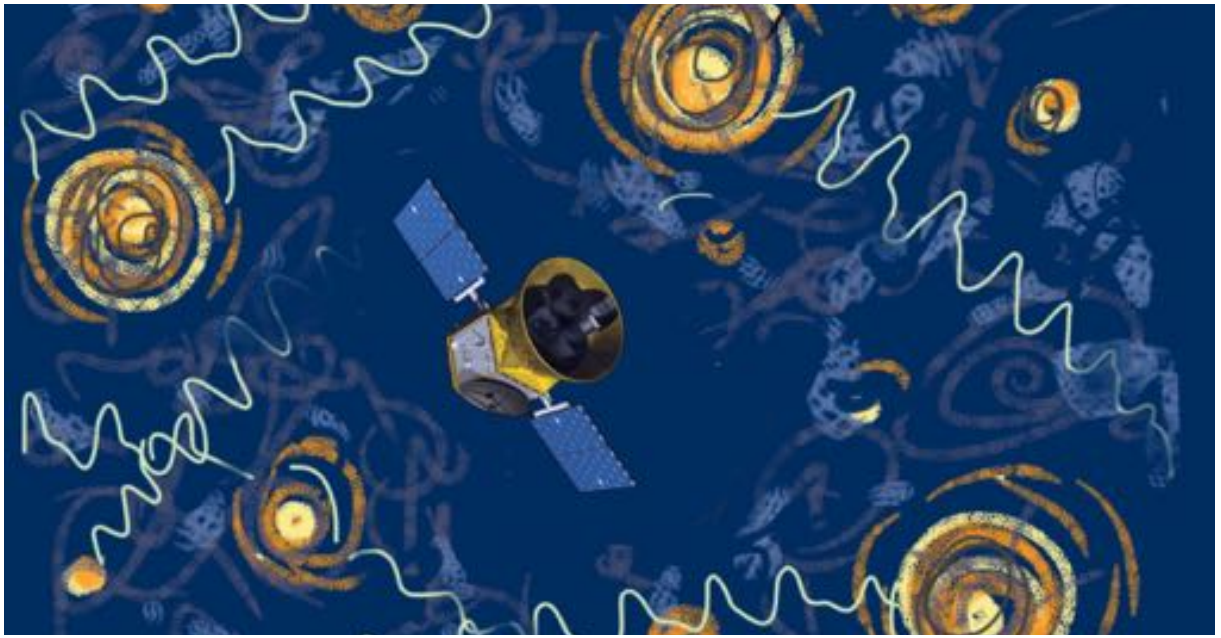
First highlights: RR Lyraes




© Molnár

Also asteroids going through! See László Molnár's poster.

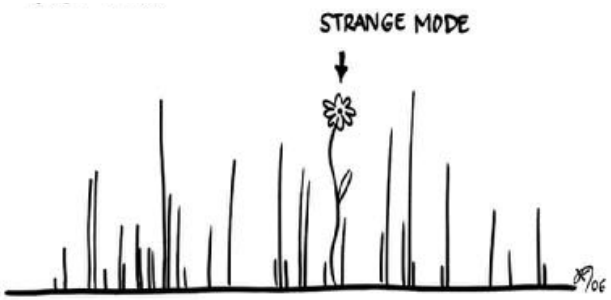
## Take-home message

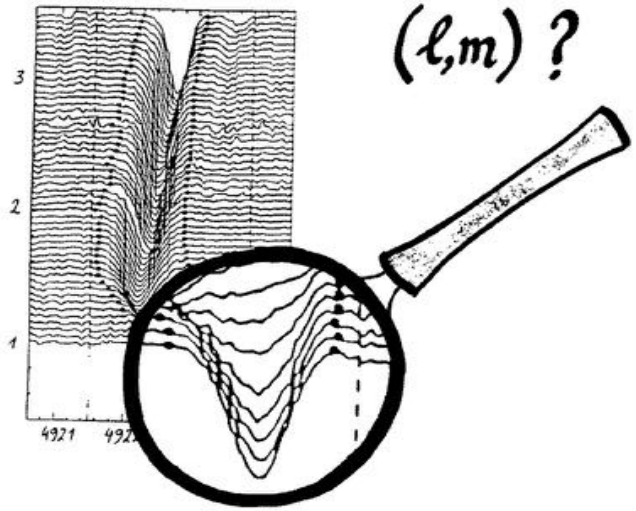


**With TESS we can start doing real asteroseismology of classical pulsators!**

Follow-up campaigns:

- multicolor photometry
- (time series) spectroscopy
- X-ray data?
- interferometry?



Follow-up campaigns:

- **multicolor photometry**
- **(time series) spectroscopy**
- X-ray data?
- interferometry?

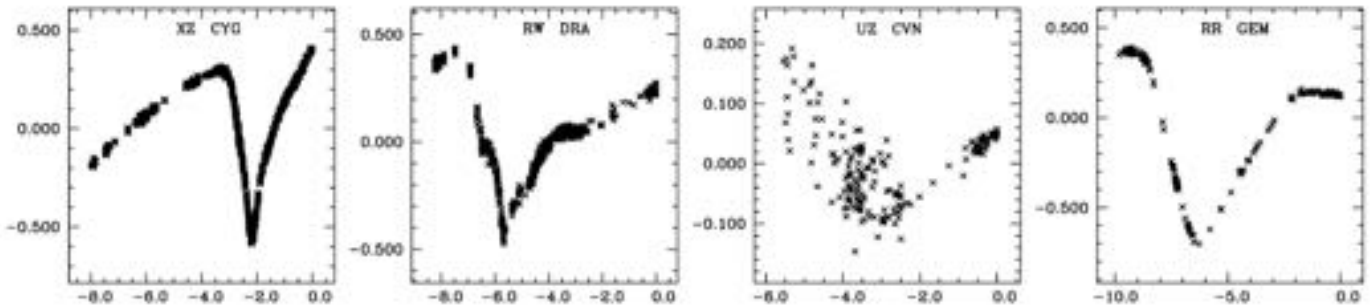
# RR Lyraes and Pro-Am


Dedicated ground-based observations for specific targets!

Loooong time base – slow evolution
Multicolor data supplement space mission data

Specific projects: photometry and spectroscopy
…some ideas…

# Binarity

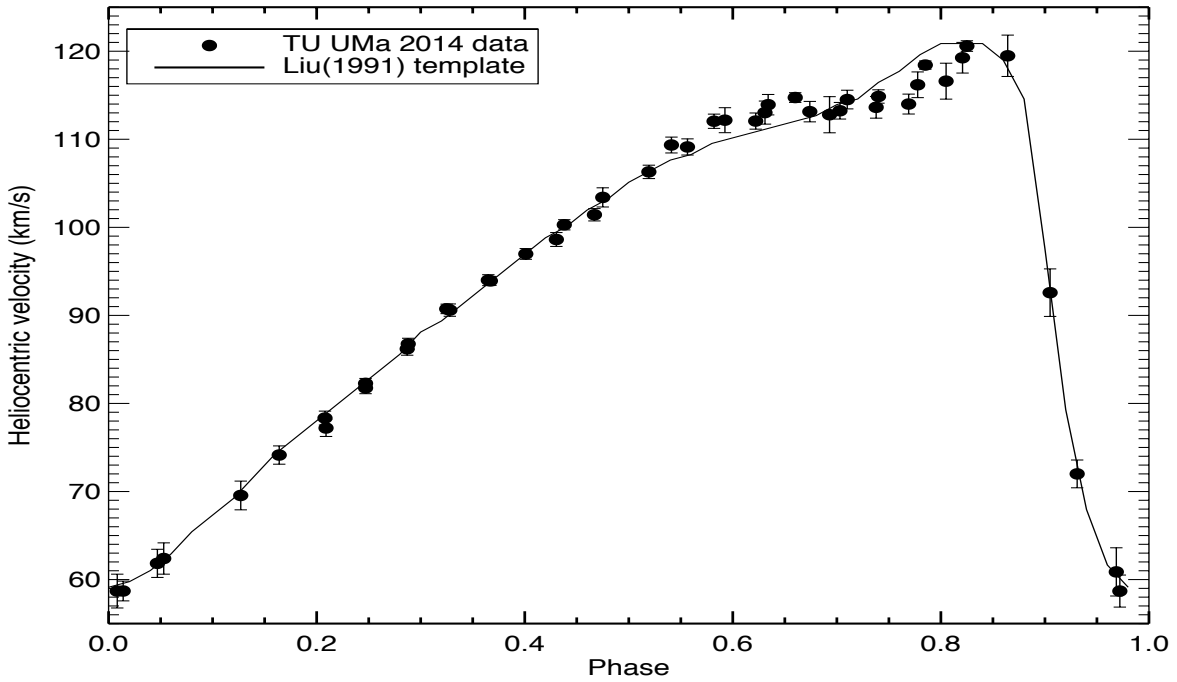



O-C values vs. elapsed cycles (E/10000)

Light-time effect (O-C diagrams)

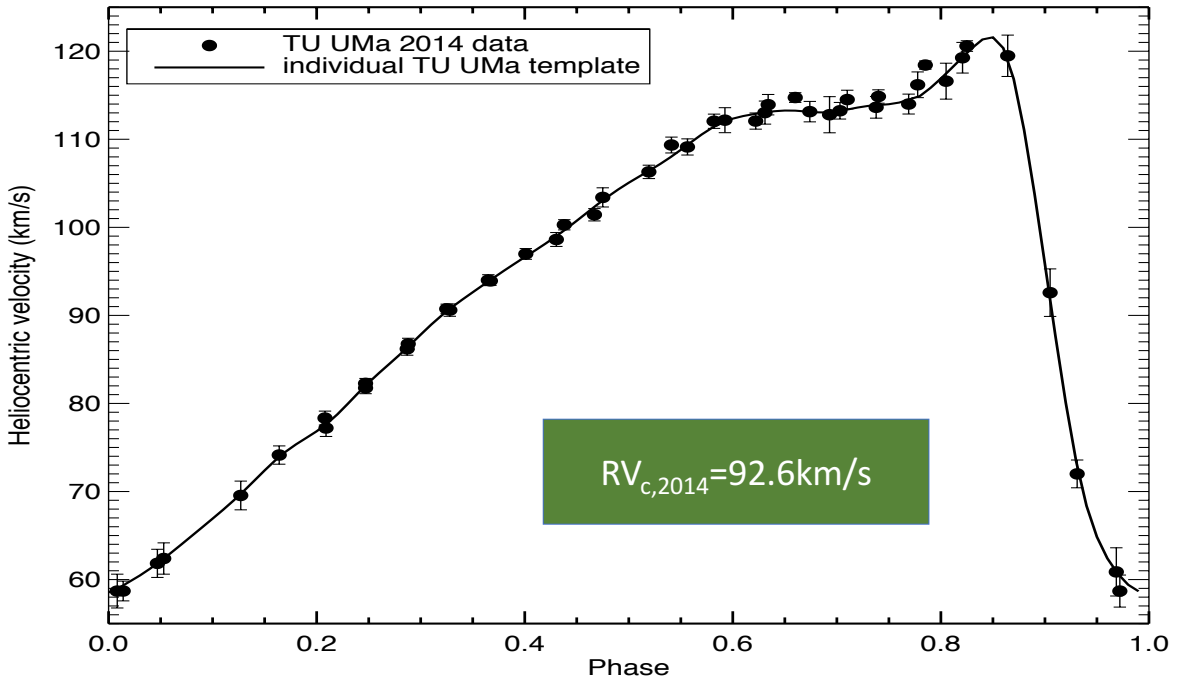
# Binarity

# Finding the center of mass velocity

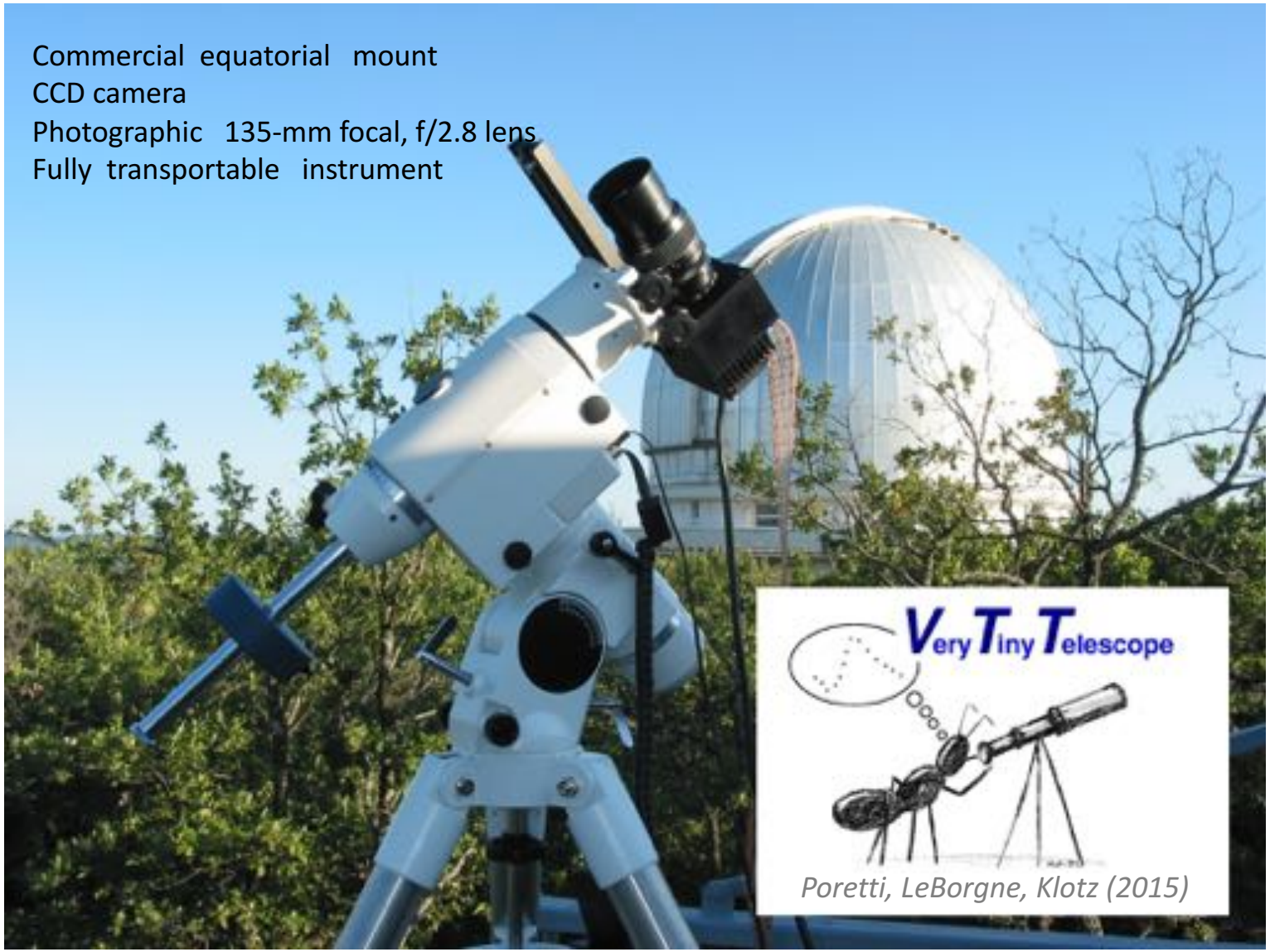



Guggenberger, Barnes, Kolenberg

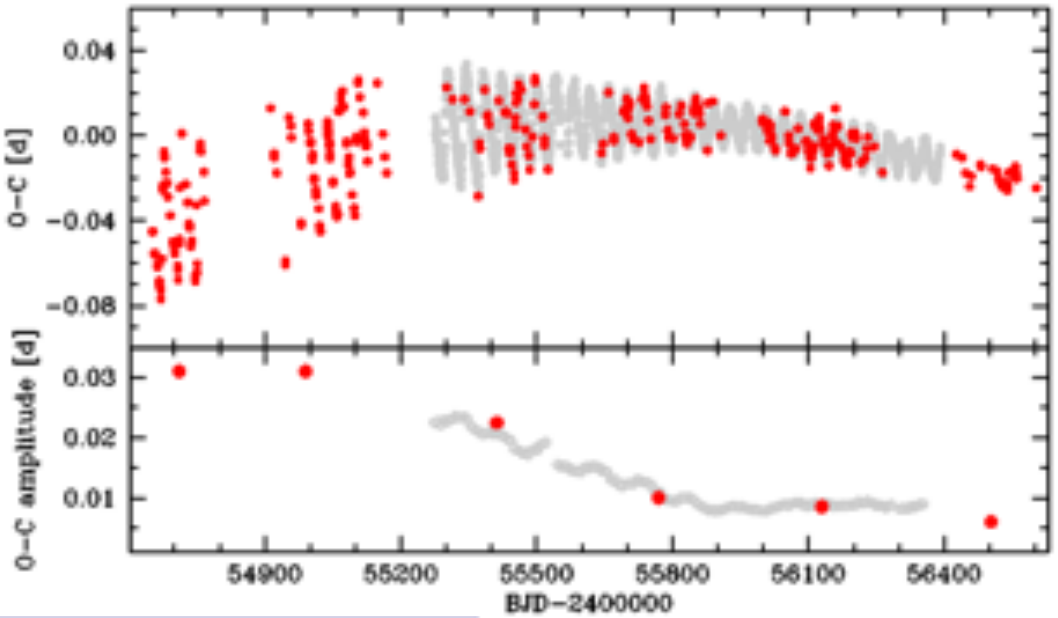
# Individual template




Elisabeth Guggenberger - RR Lyrae 2015


Commercial equatorial mount
CCD camera
Photographic 135-mm focal, f/2.8 lens
Fully transportable instrument
Very Tiny Telescope
Poretti, LeBorgne, Klotz (2015)

## *Kepler* and VTT monitoring




Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 448, 1435–1443 (2014)
doi:10.1093/mnras/stu671

**Historical vanishing of the Blazhko effect of RR Lyr from the GEOS and *Kepler* surveys**

J. F. Le Borgne,[1,2,3*] E. Poretti,[1,2,3,4] A. Klotz,[1,2,3] E. Denoux,[3] H. A. Smith,[5] K. Kolenberg,[6,7] R. Szabó,[8] S. Bryson,[9] M. Audejean,[10] C. Buil,[11] J. Caron,[12] E. Conseil,[13] L. Corp,[3,14] C. Drillaud,[13] T. de France,[14] K. Graham,[14] K. Hirosawa,[15] A. N. Klotz,[3] F. Kugel,[12] D. Loughney,[16] K. Menzies,[14] M. Rodríguez[17] and P. M. Ruscitti[18]

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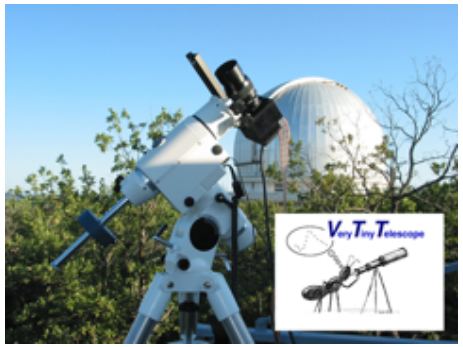
[2] *CNRS, IRAP, 14, avenue Edouard Belin, F-31400 Toulouse, France*
[3] *Groupe Européen d'Observations Stellaires (GEOS), 23 Parc de Levesville, F-28300 Bailleau l'Evêque, France*
[4] *INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807, Merate (LC), Italy*

**The amplitude of the Blazhko effect is decreasing since 2008**

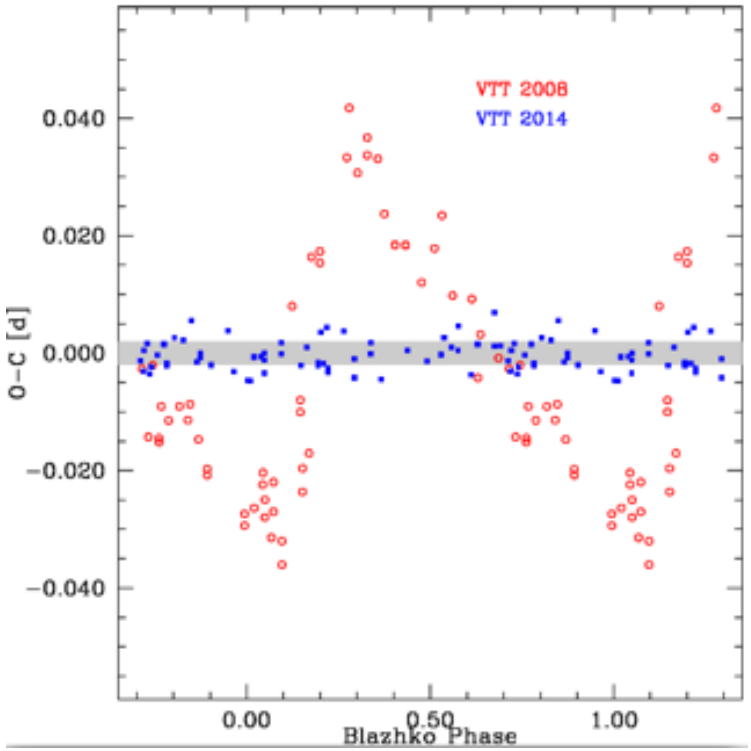
| | | |
|---|---|---|
| 2008 | 55 | 0.062 d |
| 2009 | 78 | 0.062 d |
| 2010 | 42 | 0.045 d |
| 2011 | 56 | 0.020 d |
| 2012 | 75 | 0.017 d |
| 2013 | 27 | 0.012 d |




*Joint CoRoT-Kepler Meeting, Toulouse, July 2014*

# IN 2014 RR Lyr WAS NOT A BLAZHKO STAR

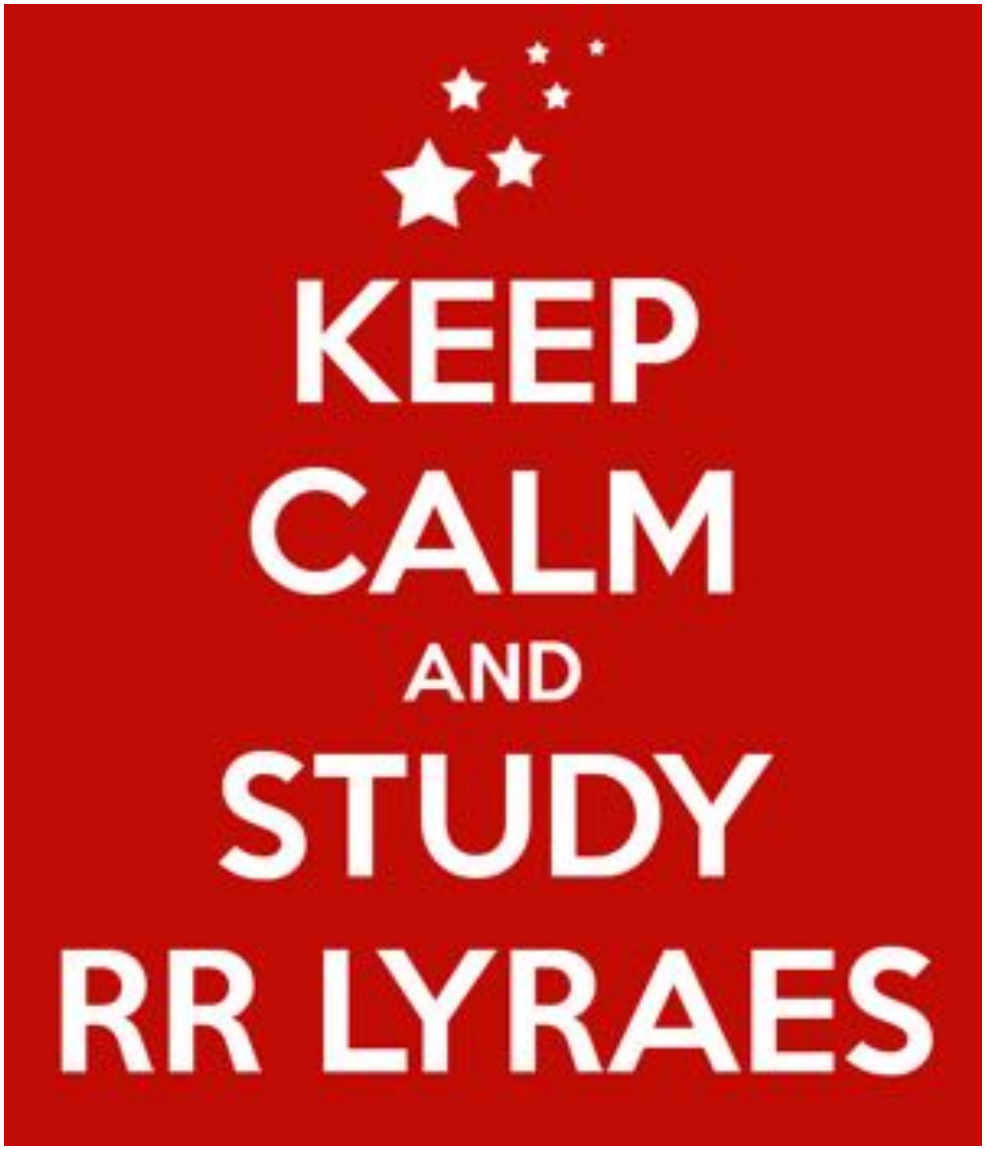
At least not in phase modulation




±1σ

*© Poretti, LeBorgne, Klotz*
*presented at joint CoRoT-Kepler Meeting, Toulouse, July 2014*

**But what about amplitude modulation?**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AND
STUDY
RR LYRAES

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