10+ Years of HADS Photometry

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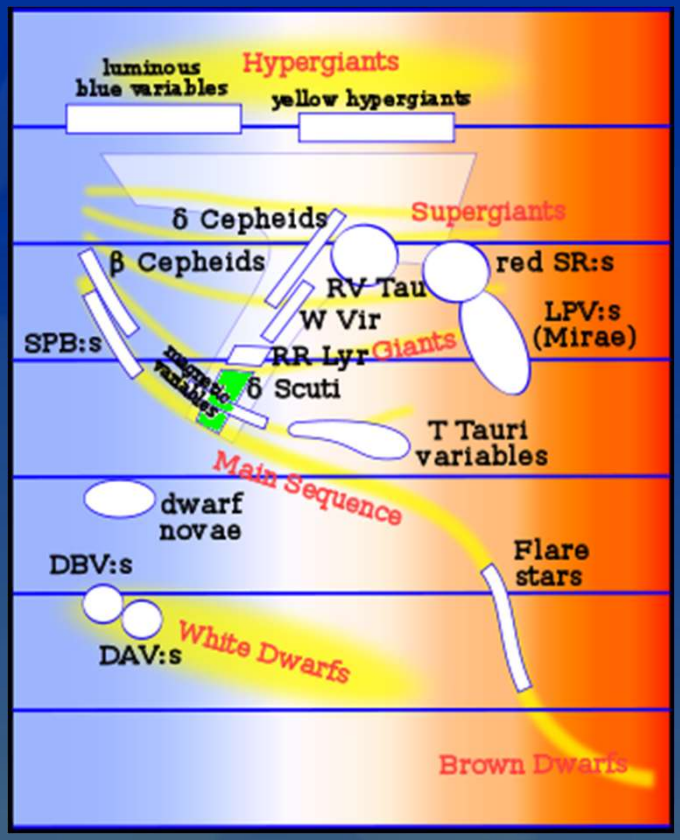
Dwarf Cepheids / RRs

- Delta Scuti stars
  - On or near the main sequence
    - Pre- (T Tau) + post-MS
    - Spectral type A-F
  - Cepheid instability strip
  - Generally: small amplitude
    - < 0.1 mag
  - Multiperiodicity:
    - periods 1 - 5 hours
  - Non-radial pulsations

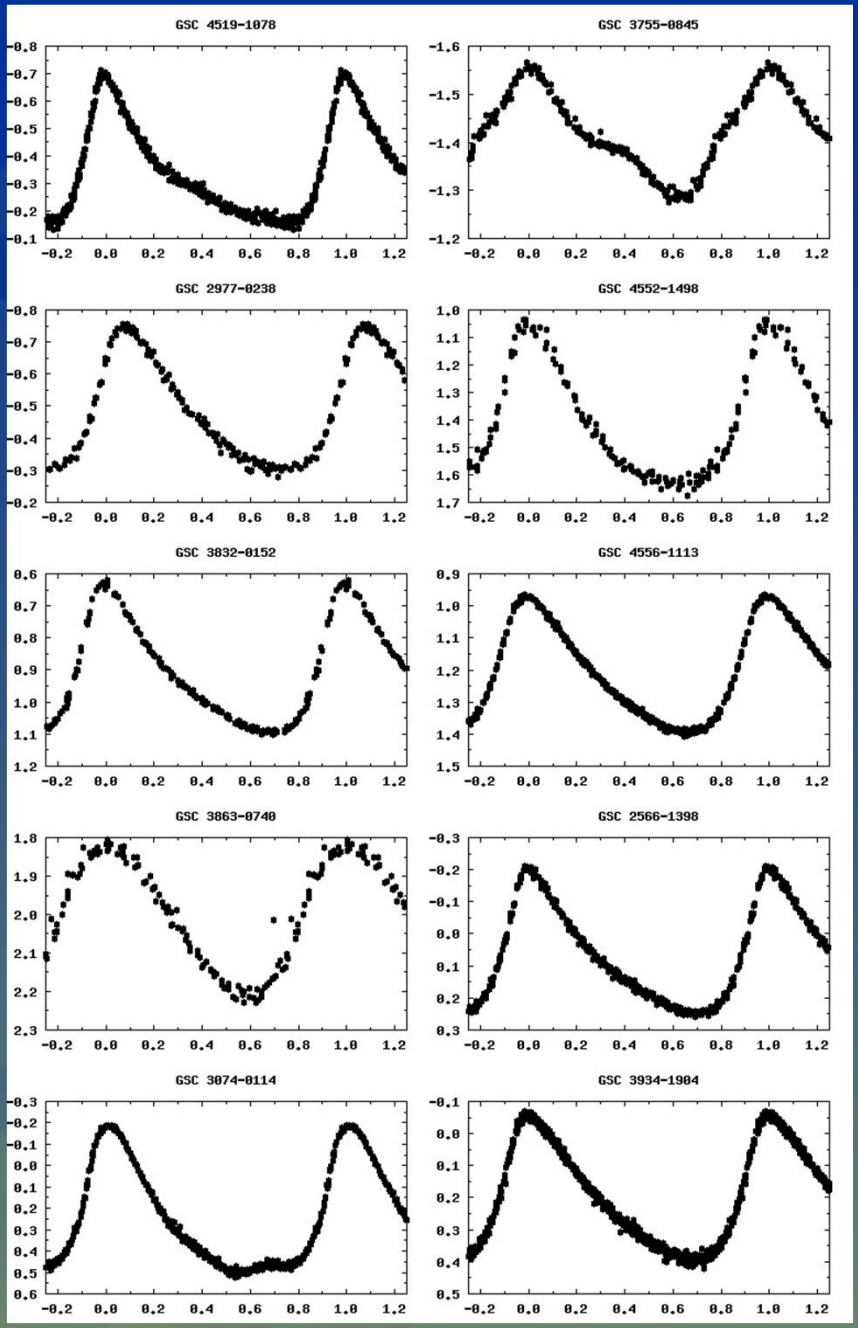
- High Amplitude Delta Scuti stars
  - Amplitude > 0.2-0.3 mag
  - Radial pulsations
  - Slowly rotating



- SX Phe-stars
  - Population II (Halo)
  - Low metallicity
  - Low mass
  - 2 old stars merged?

HADS Light Curves

- Asymmetric
  - Fast brightening / slow fading
  - Sharp maximum / broad minimum
- Many different shapes
  - Humps / bumps
- Shape is not related to period
  - ≠ Hertzsprung sequence in Cepheids
  - Metallicity?

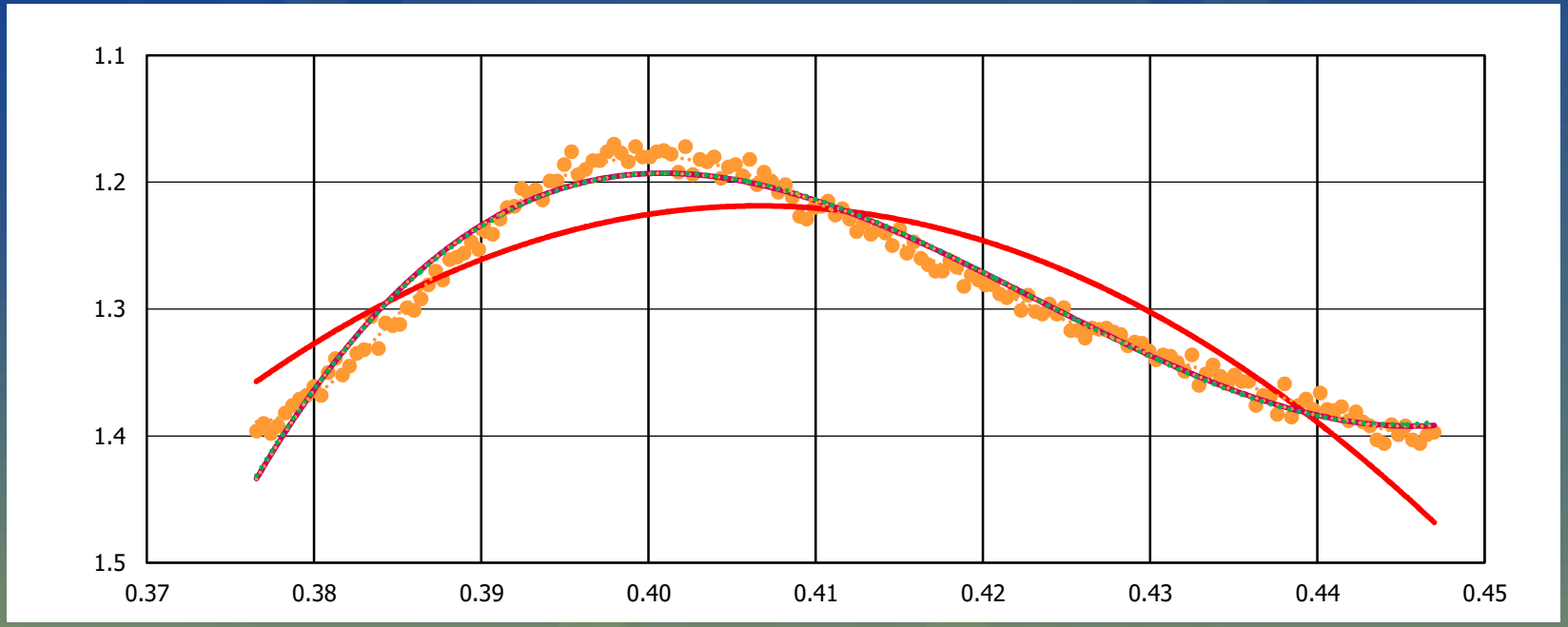


The HADS Project

- Originally started in 2005
  - Small number of observers from Belgium, Spain, Greece and USA
- "Official" start in 2008 as a VVS-WGVS project
  - Introduction to CCD photometry
- Advantages
  - Full light curve after a few hours
  - No predictions needed
- Purpose: detect period variations
  - Try observing a number of HADS once/month

Determining Time of Maximum

- Traditionally: Polynomial fit
- Disadvantages
  - Degree of fit "arbitrary"
    - Many free parameters
    - "Bends" to the data (e.g. differential extinction trend)



Determining Time of Maximum

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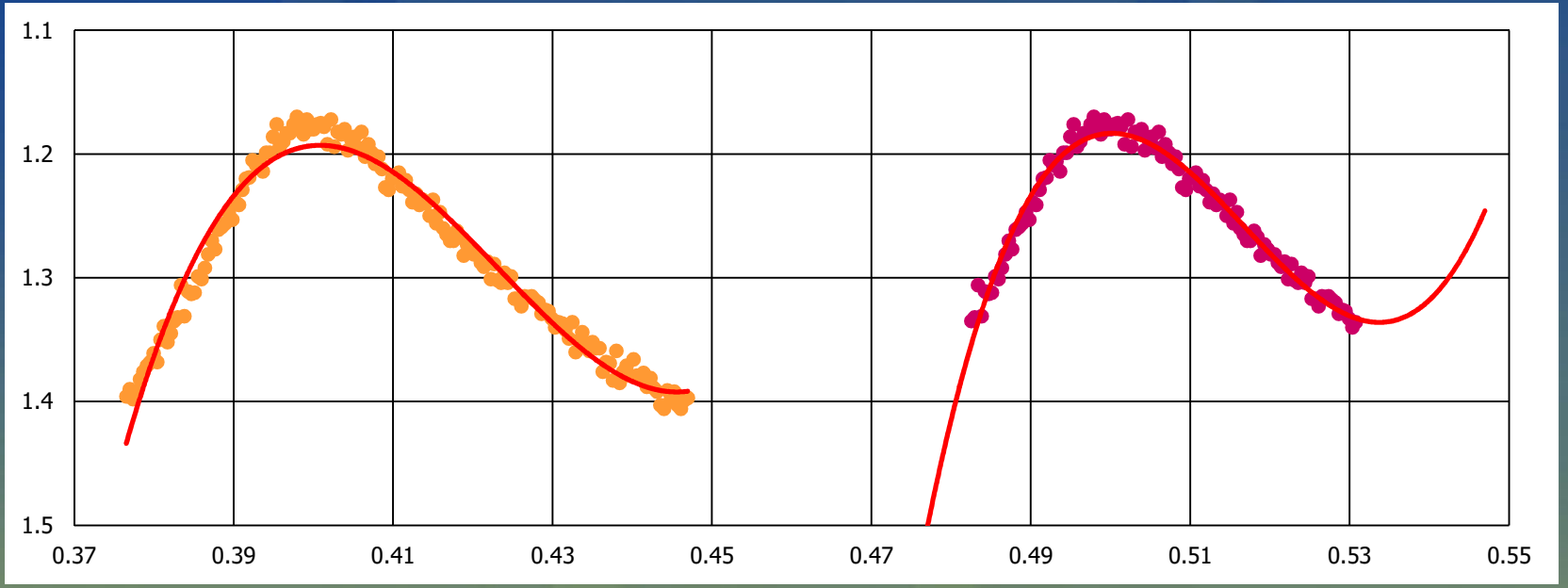
    - Choose which data points to use
    - Generally does not use data when the star varies fastest



Determining Time of Maximum

- Traditionally: Polynomial fit
- Disadvantages
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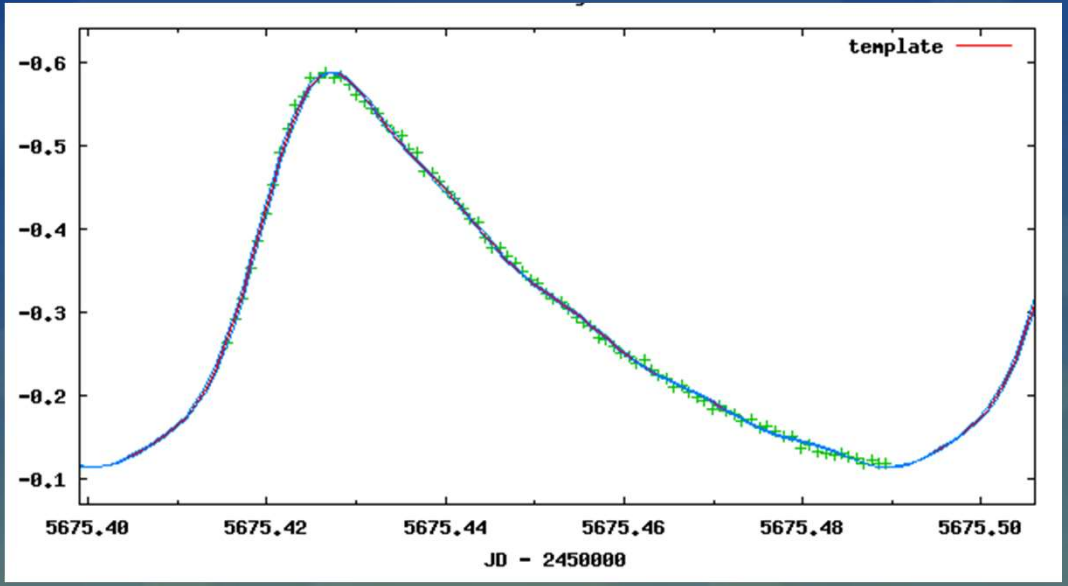
  - Does not use all data (only around maximum)
    - Choose which data points to use
    - Generally does not use data when the star varies fastest
  - -> Calculated time depends on who does the calculation

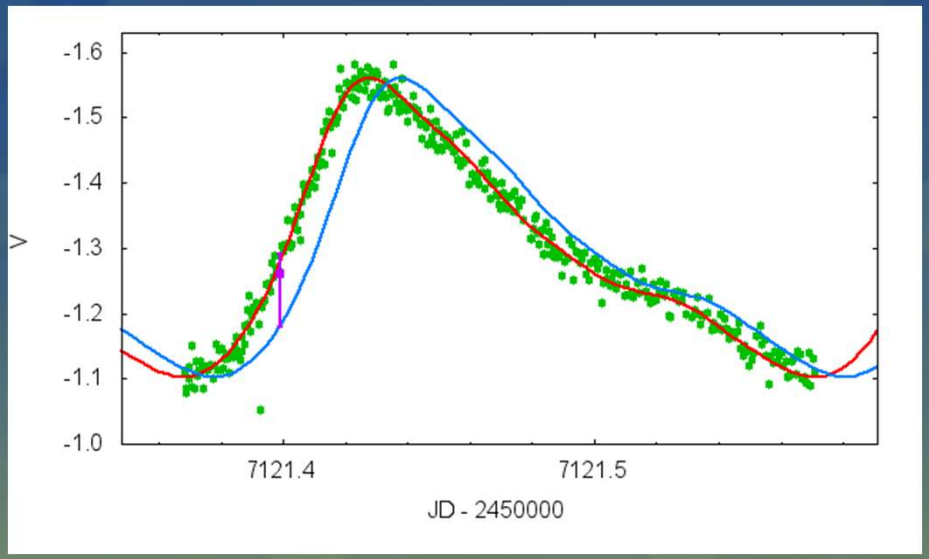
Determining Time of Maximum: Model Curve

- Fourier series
  - Mean light curve based on several cycles
  - Depends on filter used



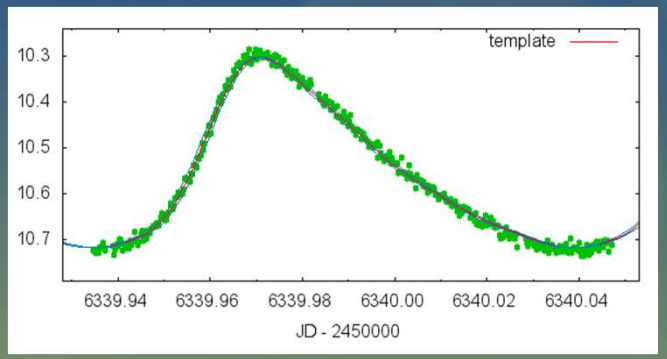
Determining Time of Maximum

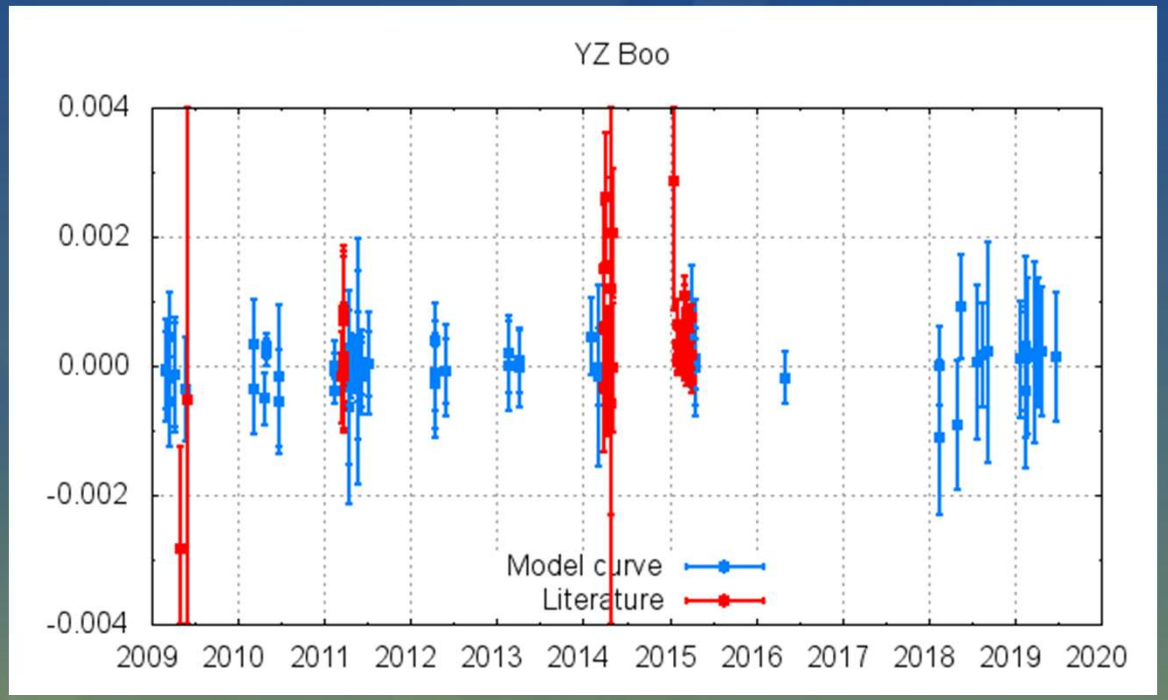
- Fit observations to model curve
  - Only 2 free parameters
    - Mean magnitude (vertical shift)
    - Time (horizontal shift)
  - Shift light curve so that difference in magnitude (vertical distance) is minimal (least squares)



Model Curve: Advantages

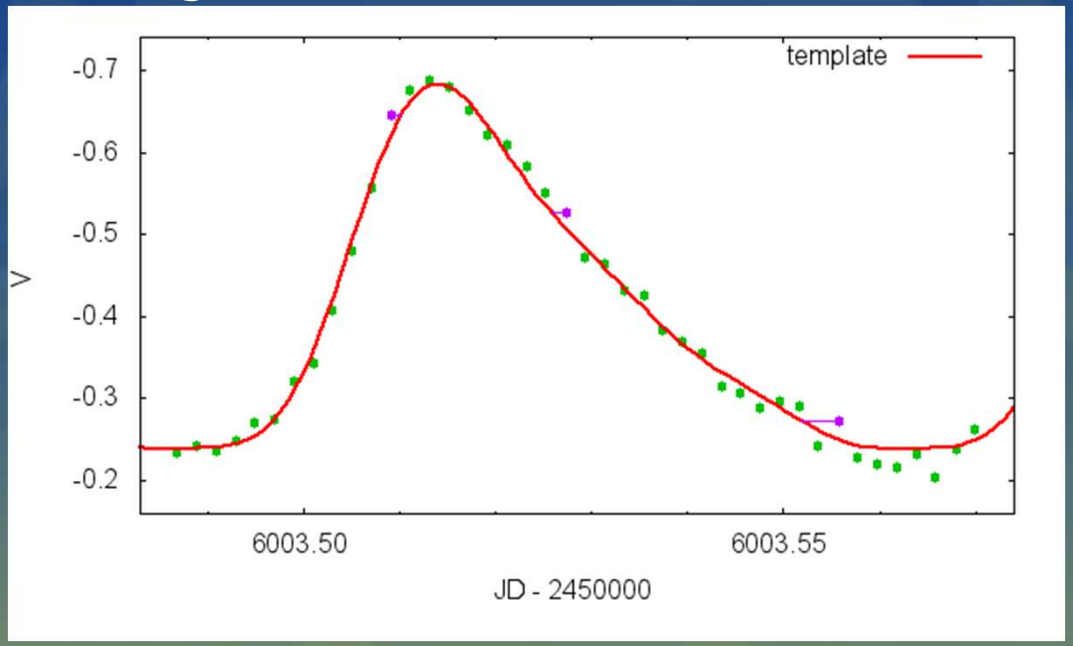
- All data are used
- Fastest variation weighs more in the end result
- Any phase can be chosen, not only maximum
- Maximum does not have to be observed
- Consistent times





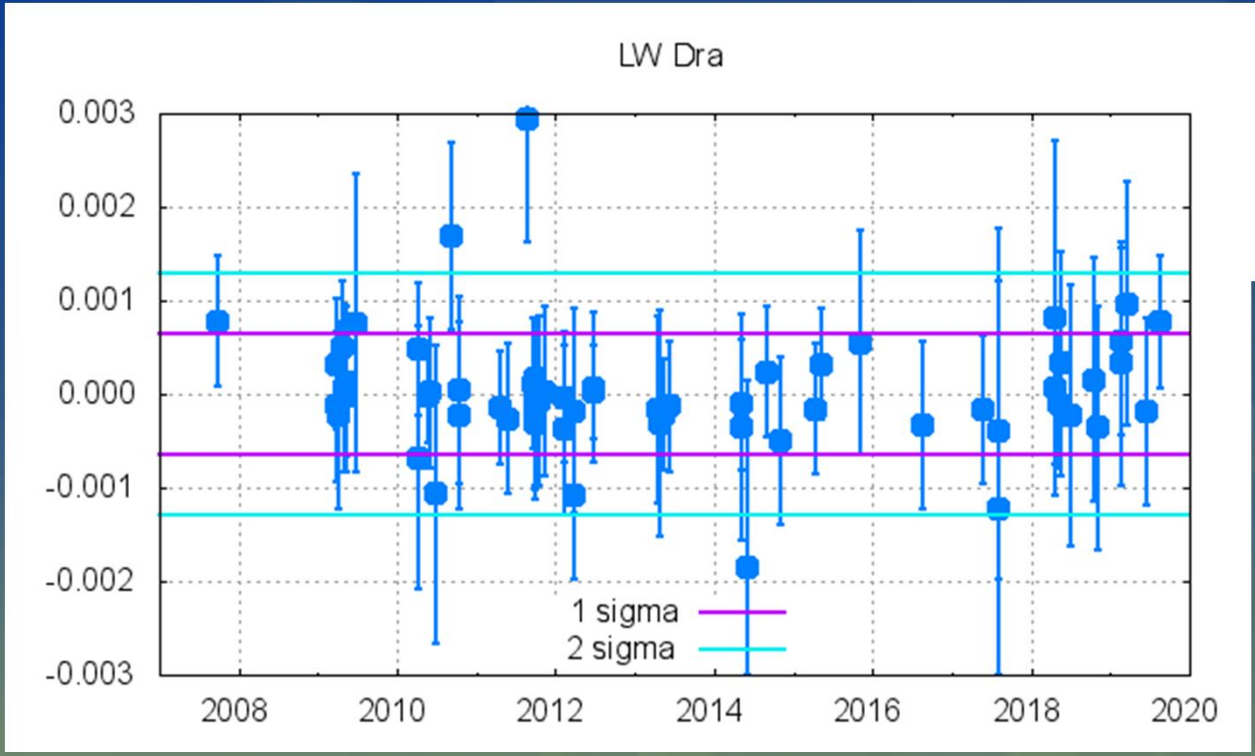
Uncertainty on Time of Maximum

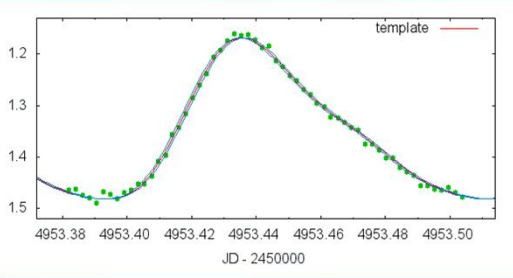
- Mean squared difference in time (horizontal distance) between observations and model curve
  - Weighted by slope of light curve
    - More weight when star varies fastest
    - Less weight near maximum and minimum



Uncertainty on Time of Maximum

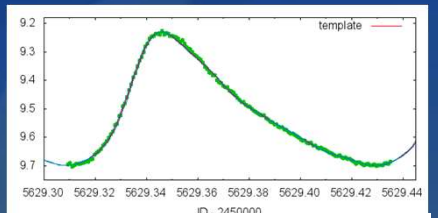
- Between 1 and 2 standard deviations of calculated times
- Realistic estimate

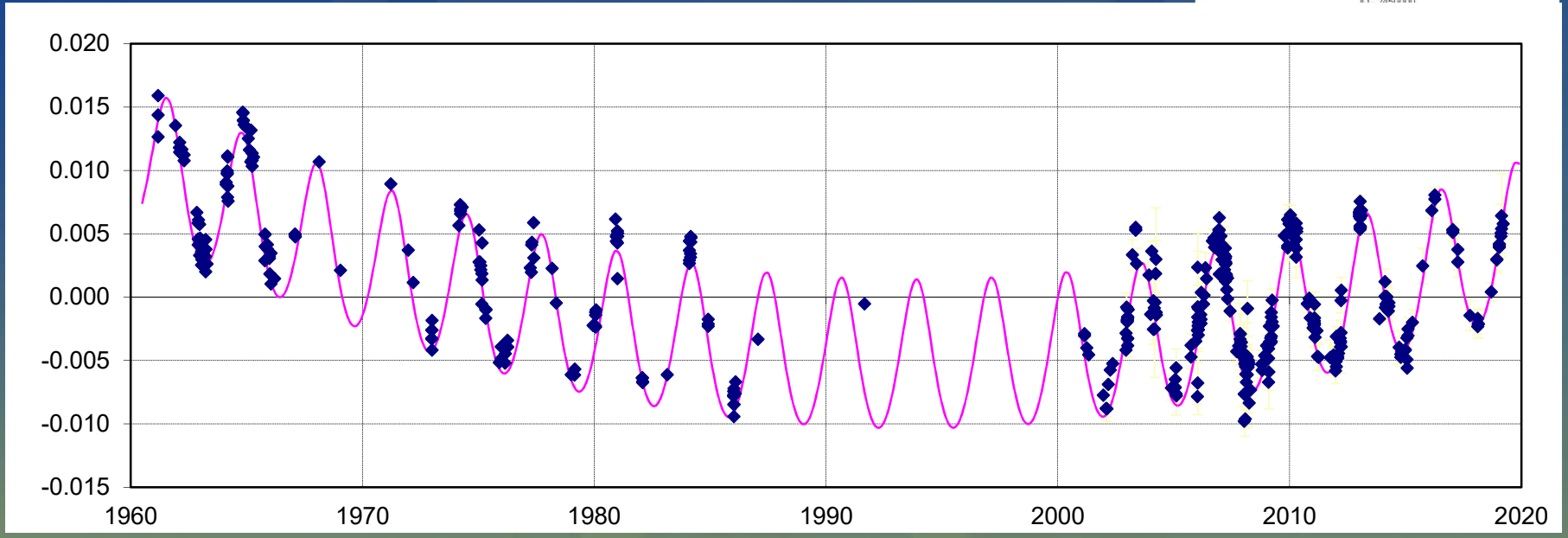




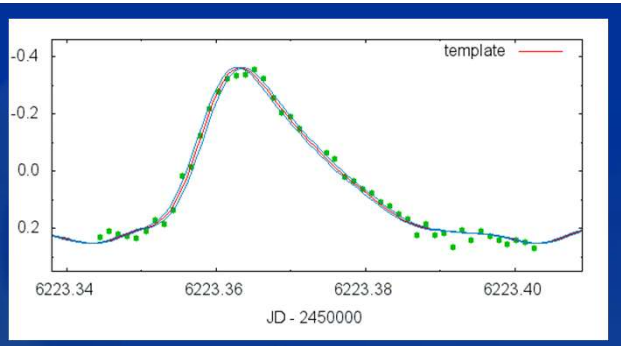
Causes for Period Changes: Binarity

- SZ Lyn: binary system (light time effect, cfr. Doppler)
  - Confirmed by radial velocity; Moffett et al. 1988
  - Binary period: 1190d, amplitude O-C ~ 20 minutes
  - Pulsation period slowy increases also
  - 1988 ephemeris still extremely accurate

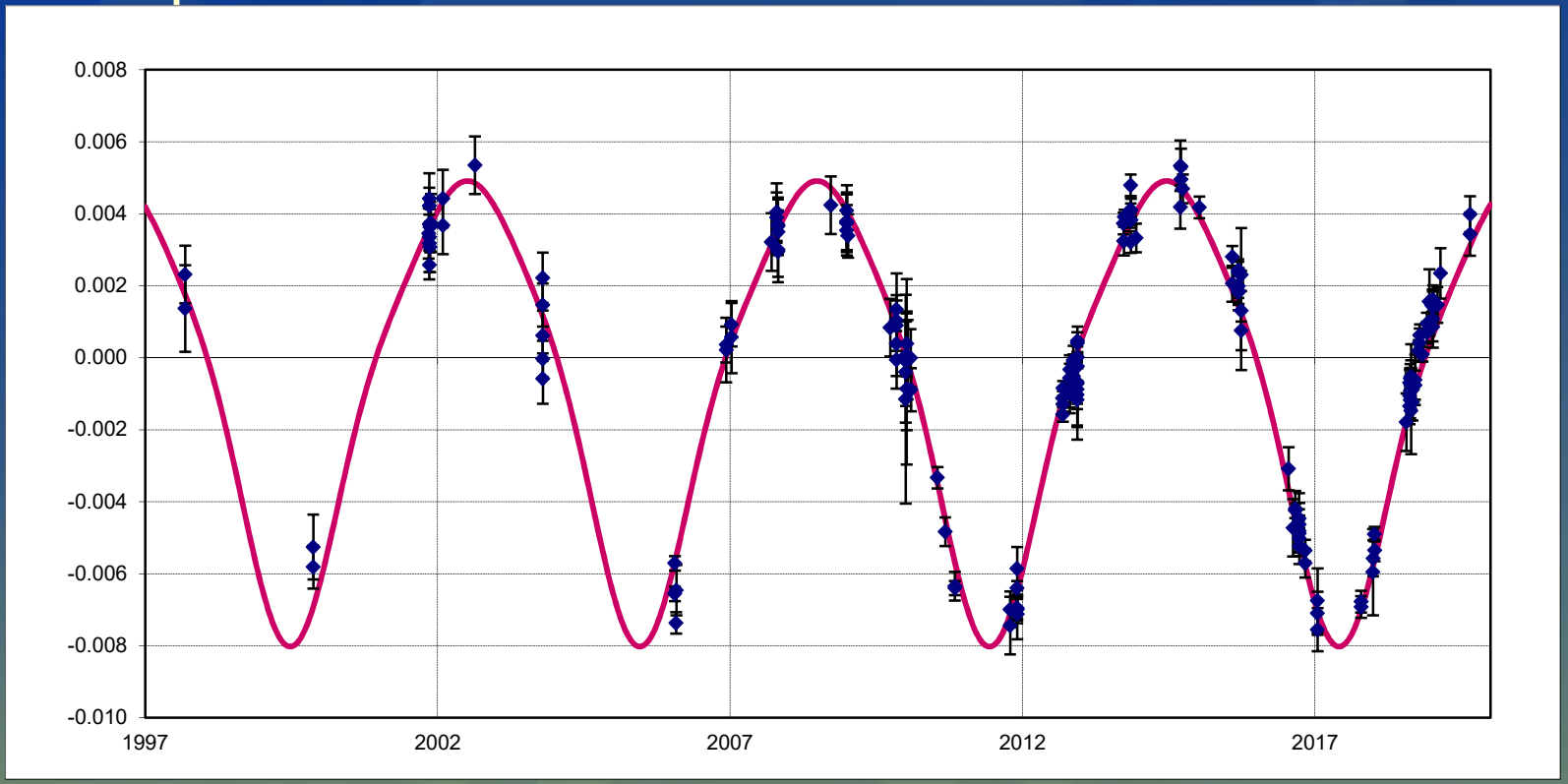




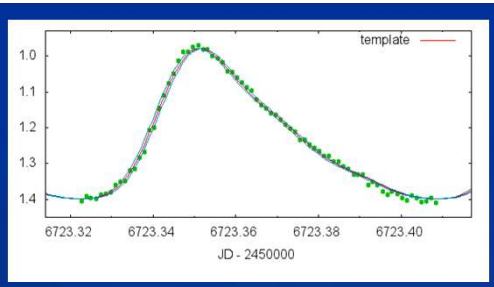
DW Psc: Binary!



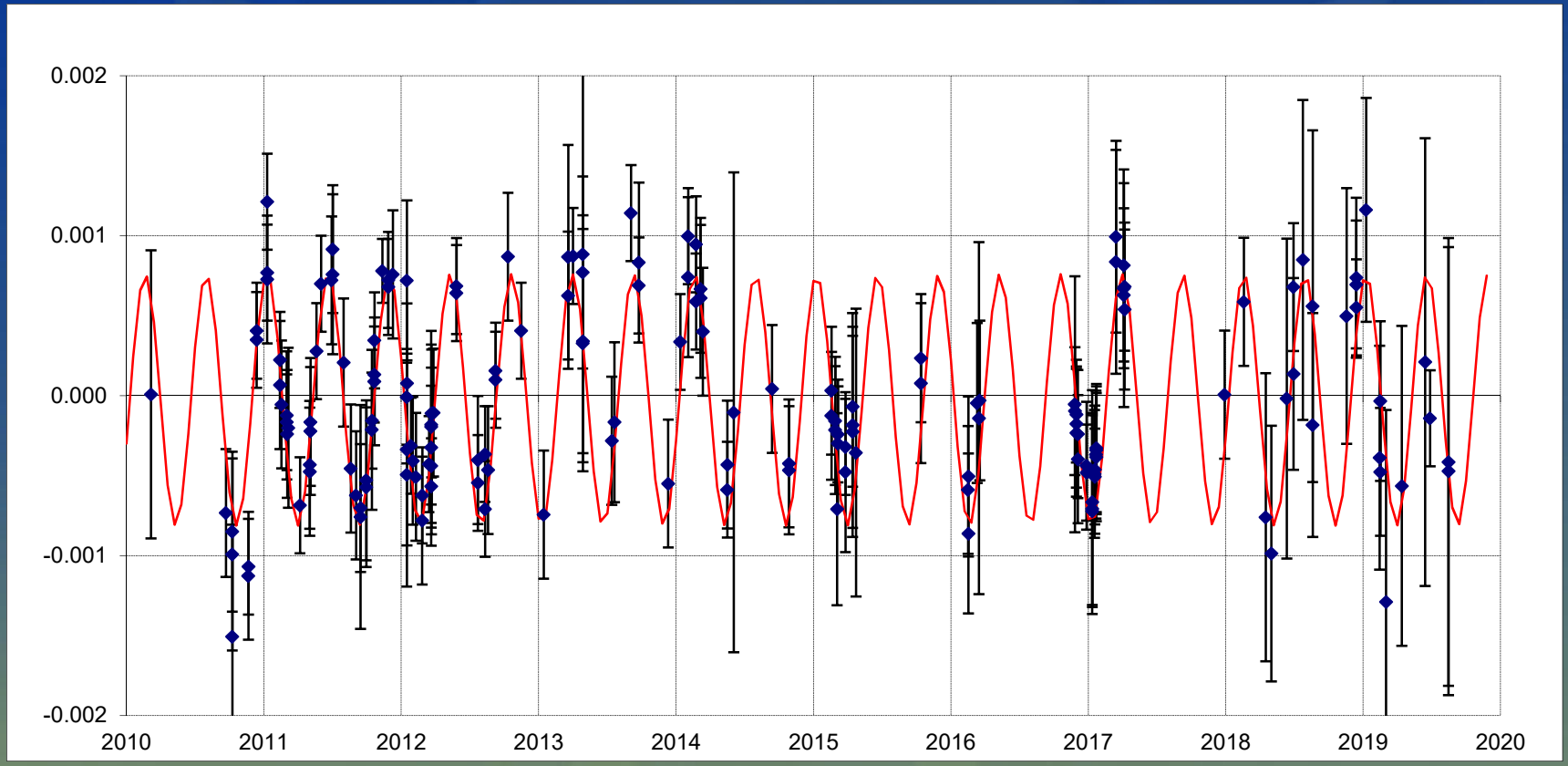
- Period 6.0 years
- Amplitude 2 * 8.7 minutes (= 1.04 AU)
- Companion > 0.6 M⊙ if HADS = 2 M⊙



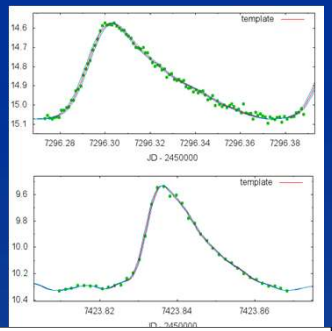
V572 Cam: Another Binary!



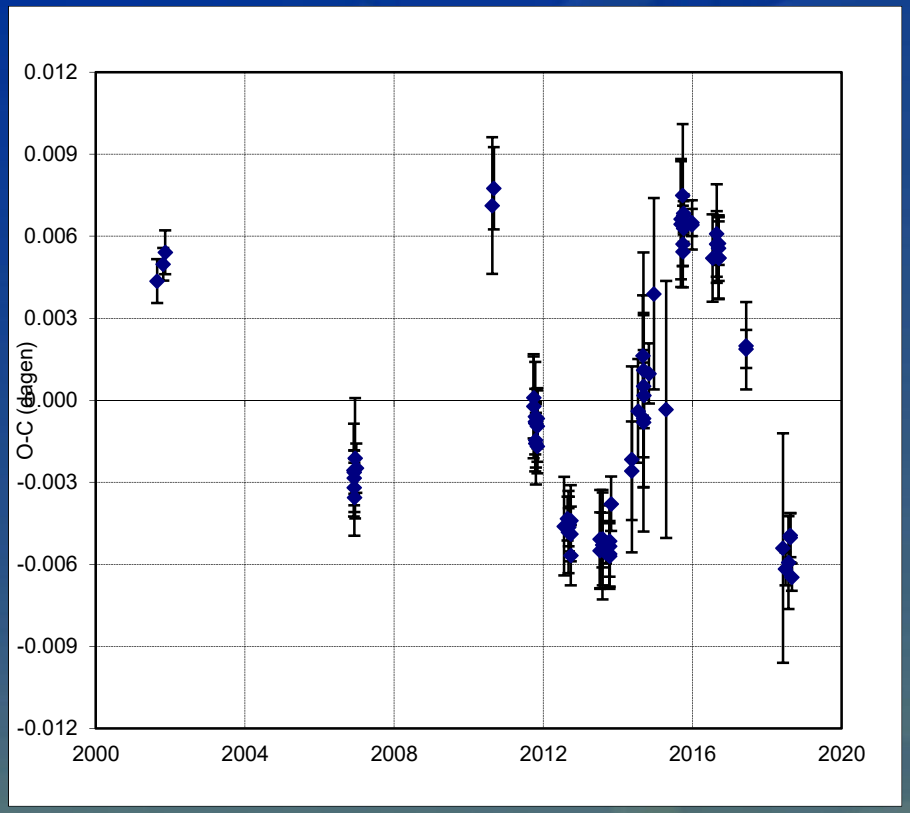
- Orbital period: 167 days
- O-C amplitude: 2 * 68 seconds (1/3 orbit Mercury)
- If HADS = 2 M⊙ and i = 90°: companion = 0.41 M⊙

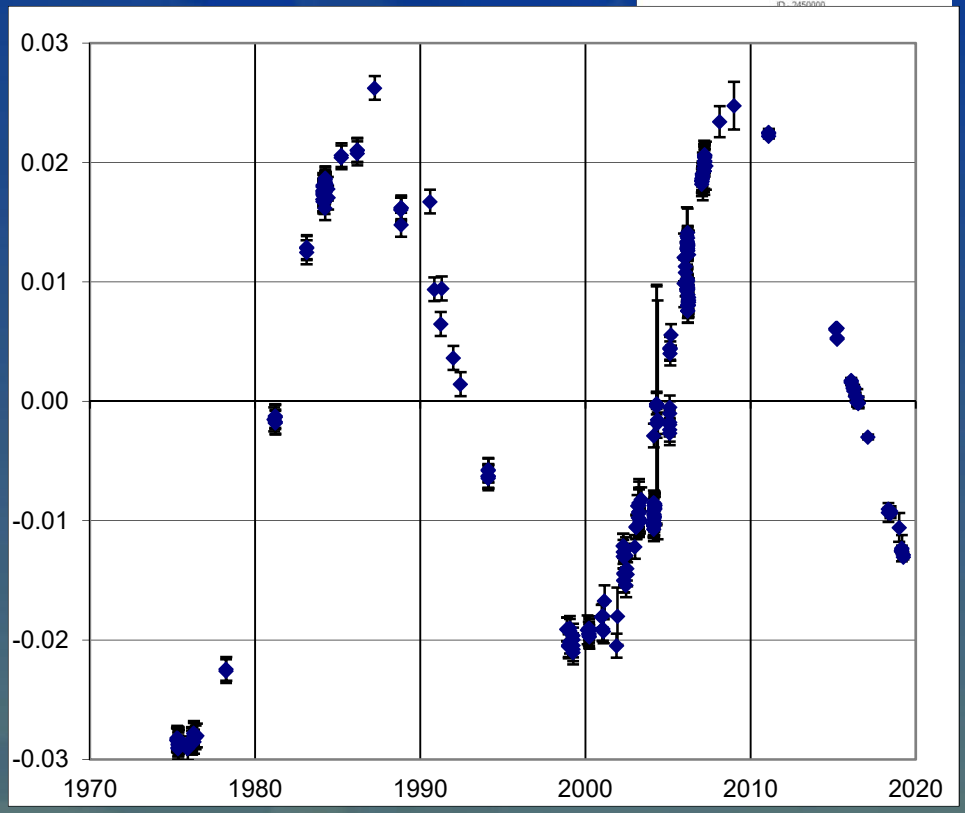


More Binaries? KZ Lac and KZ Hya



- P ~ 5 and 25 years?

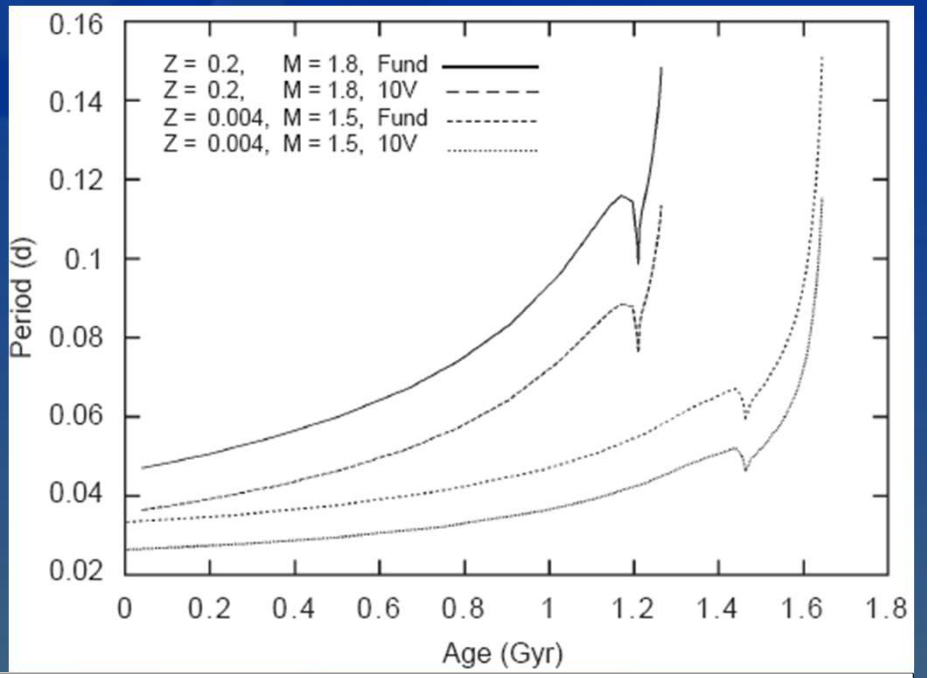


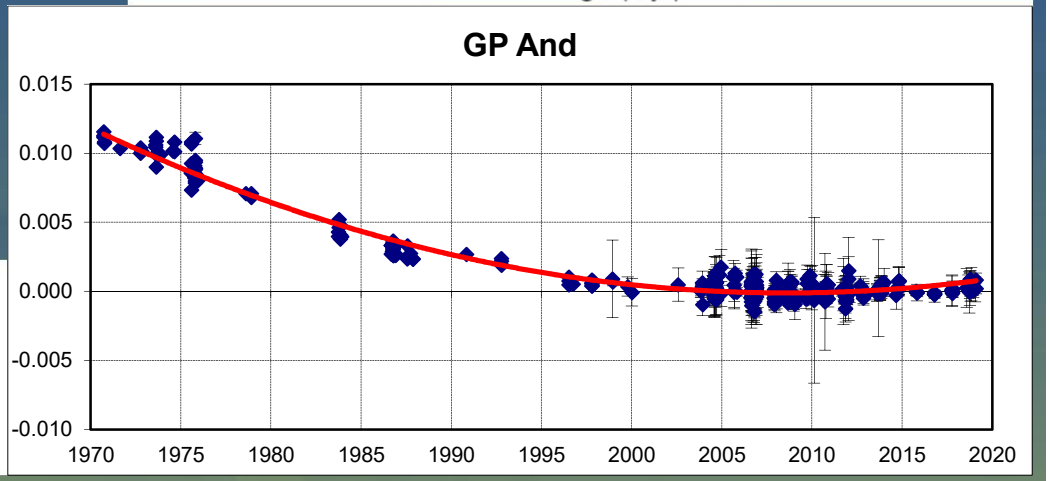


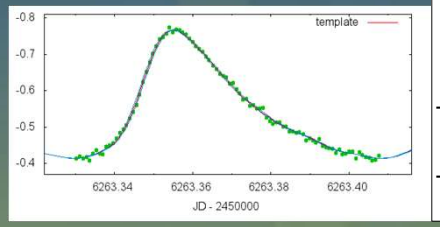
- ~10 other HADS: less than 2 "cycles" of several months/years

Causes for Period Changes: Evolution

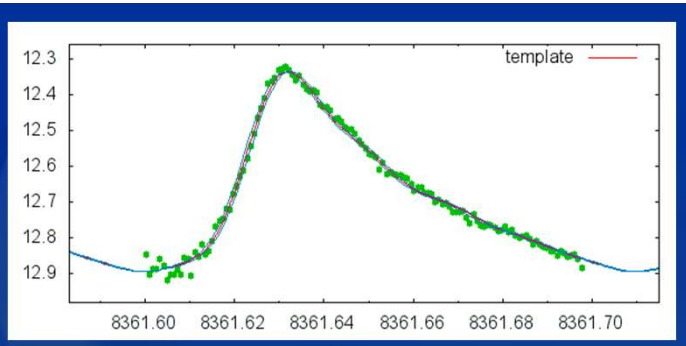
- Pulsation constant
  - $Q = P \sqrt{\rho}$
- Fusion H -> He
  - Main sequence
  - Star expands
  - Density decreases
  - Period increases
- Very slowly: < 10^{-7}/year
  or: 10 ms/century
  O-C ~ ½ min/10 years
- Parabola in O-C-diagram



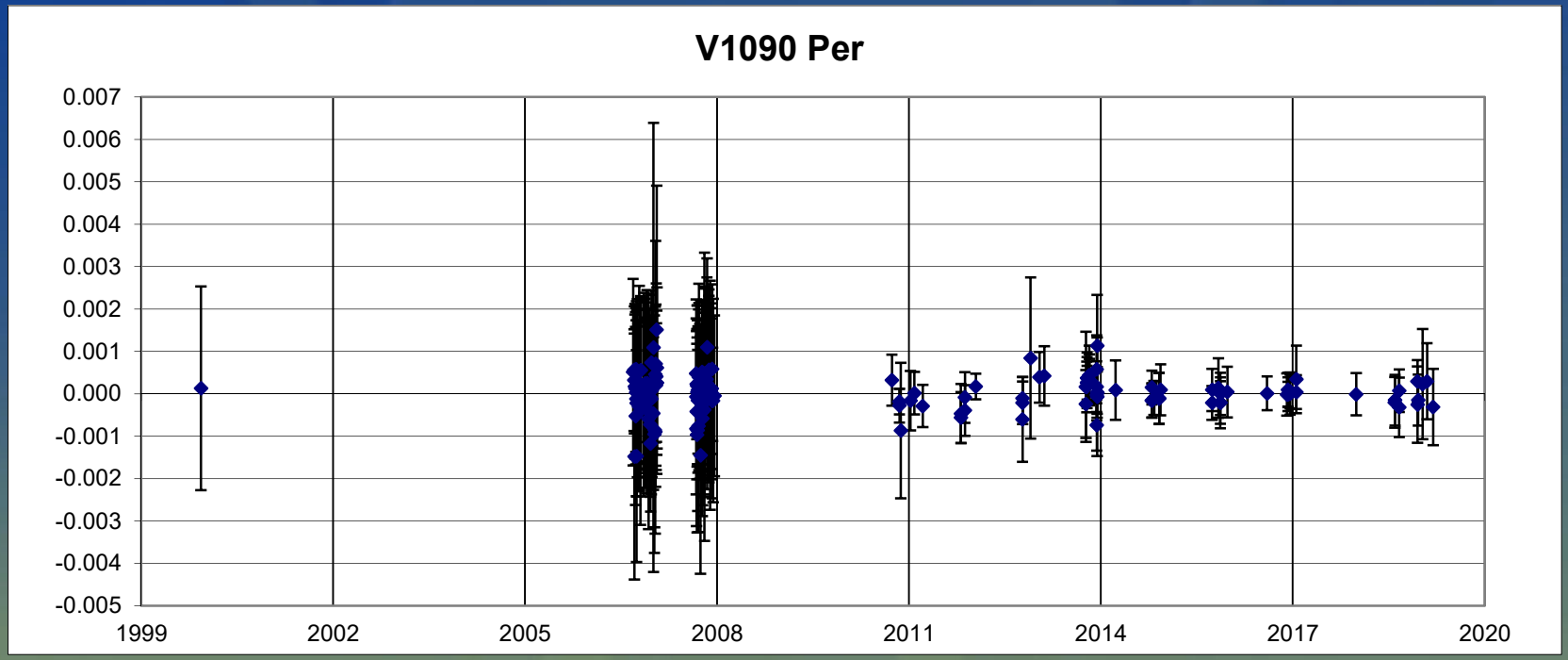




Observed Period Changes

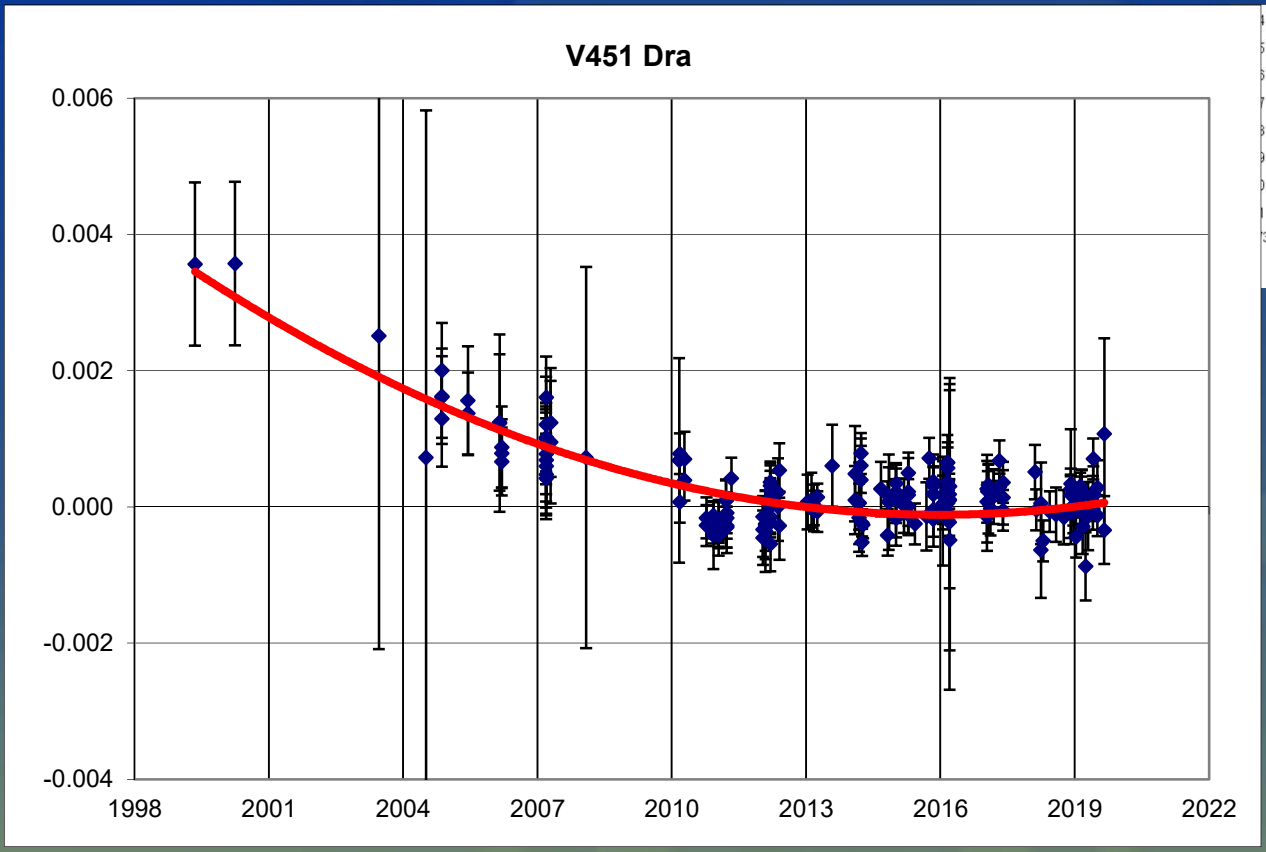


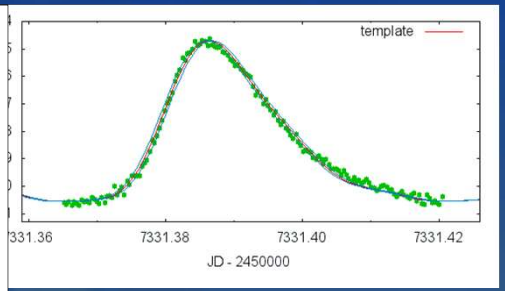
- Many HADS: constant period
  - Accuracy of timings ~ 10 sec or more
- But many observed less than 10 years!
  - Survey data (ASAS, NSVS, …): further back, less accurate



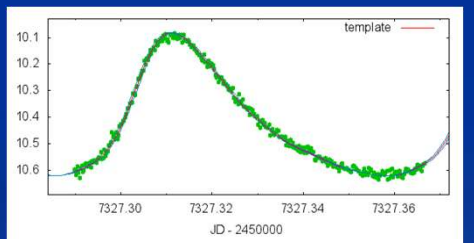
Observed Period Changes

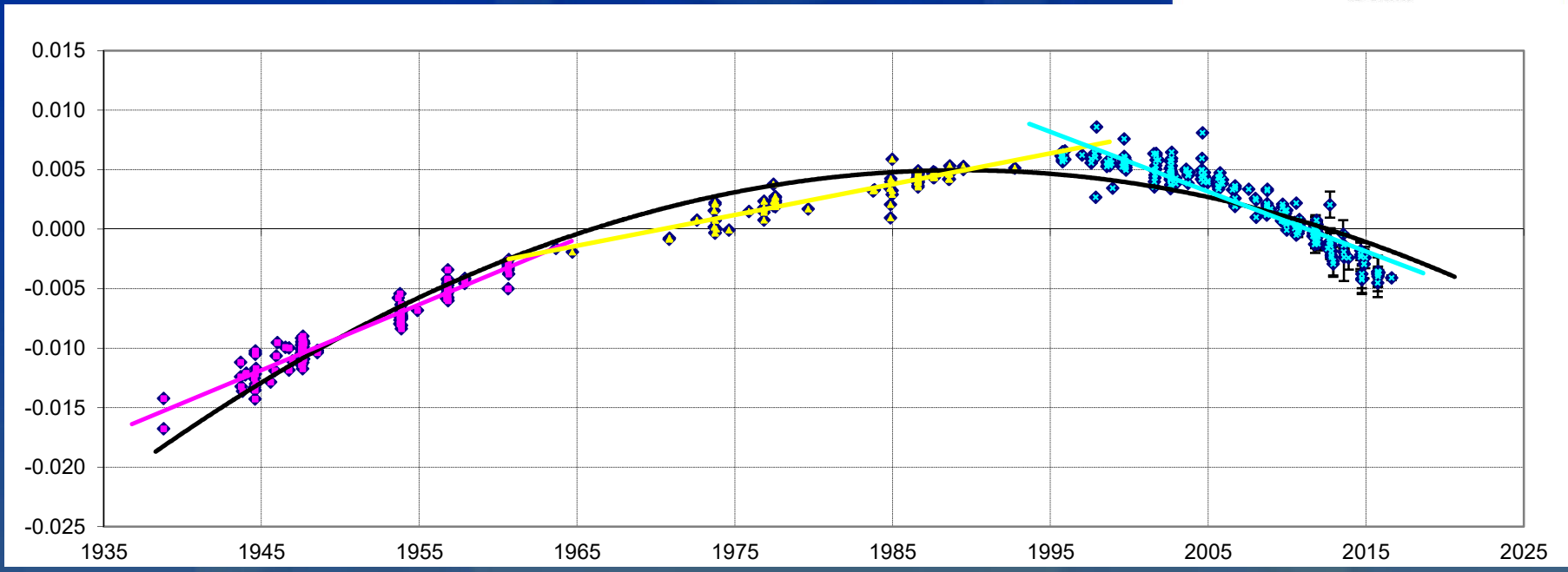
- Most observed linear period changes are too large
  - V451 Dra: ~2 min / 10 years





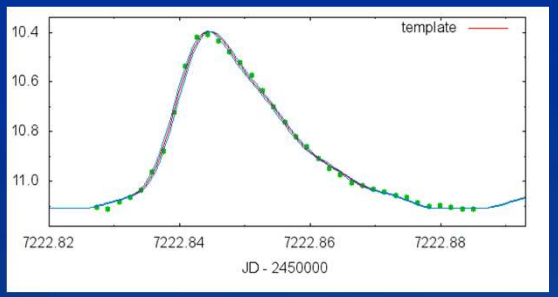
Evolution?



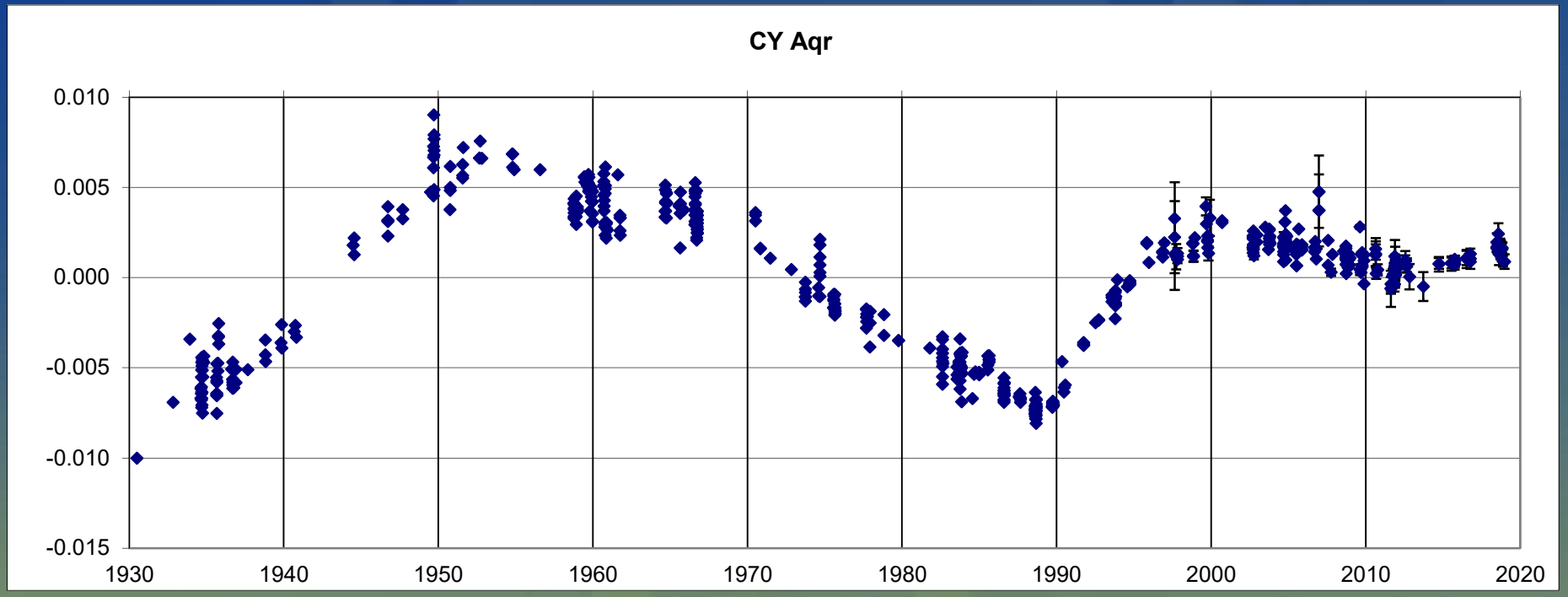


- About as many period decreases as increases
- Changes much larger than predicted
- Not always a linear change
  - Often sudden changes

Other Causes of Period Changes?

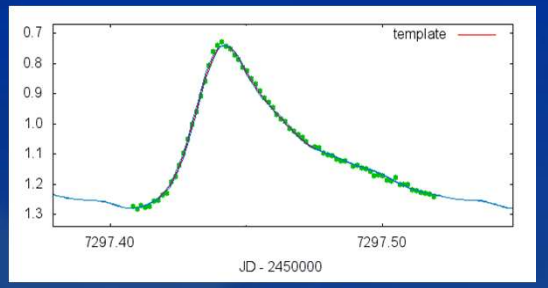


- CY Aqr
  - Since 1930: at least 5 period changes
  - ~ constant period in between changes
  - Very little theoretical work

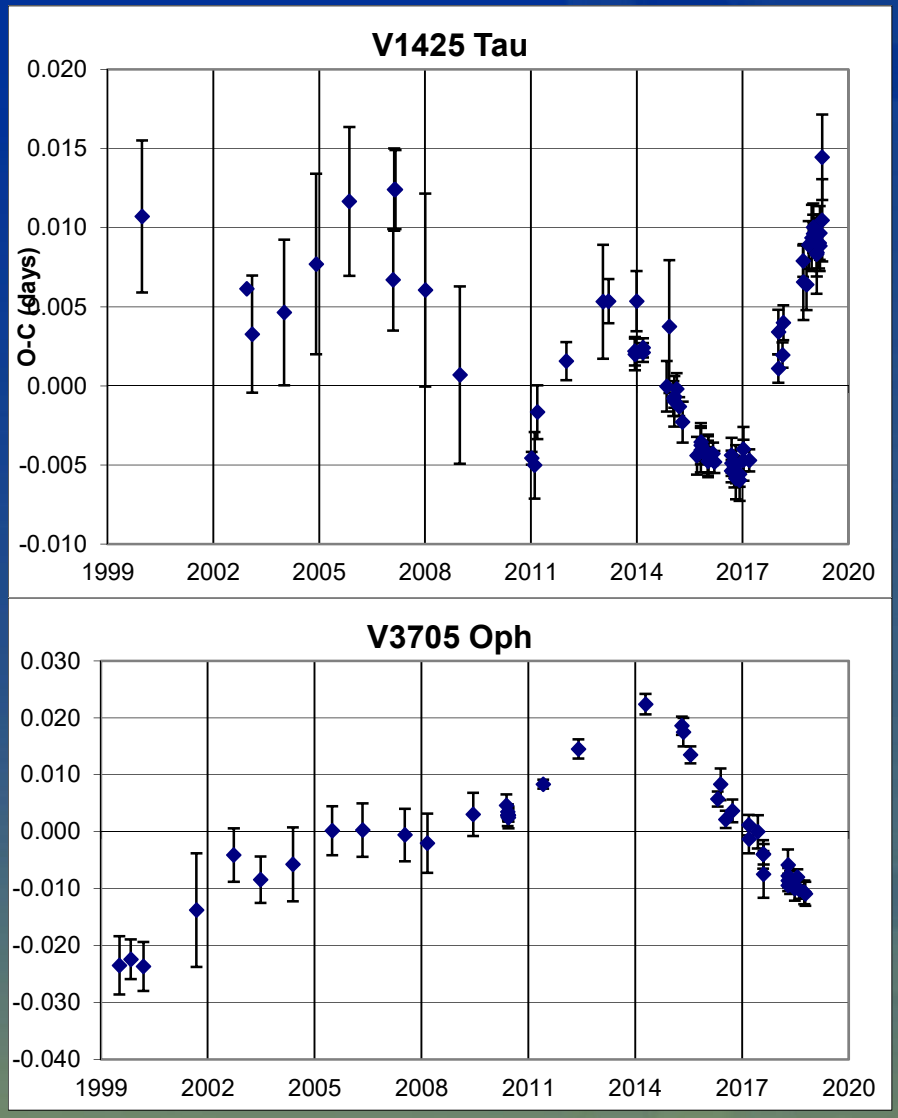


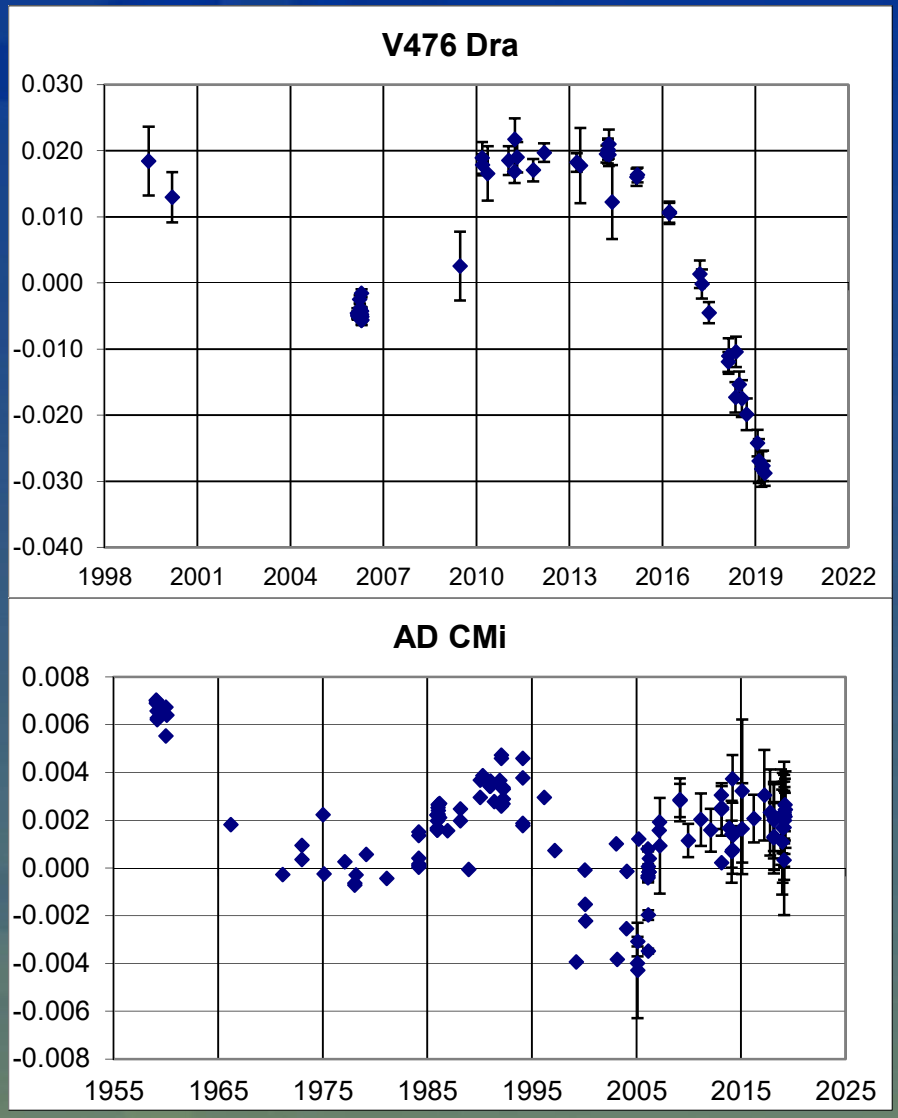
Sudden Period Changes?

- V376 Cam
- At least 3 changes in 5 years
- Or is it cyclical after all?



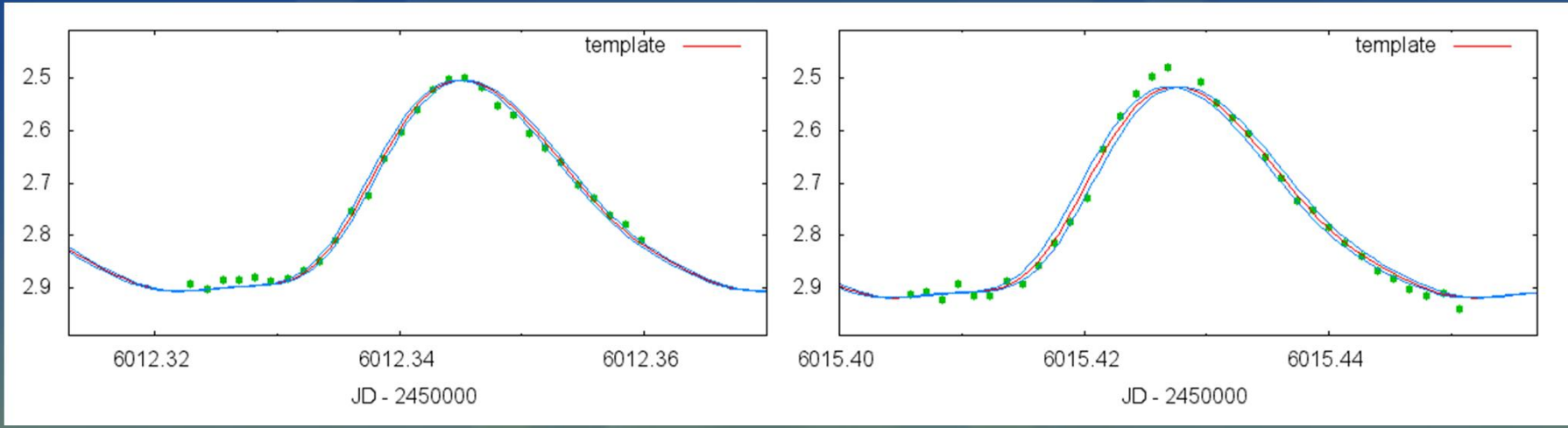
Other O-C Diagrams



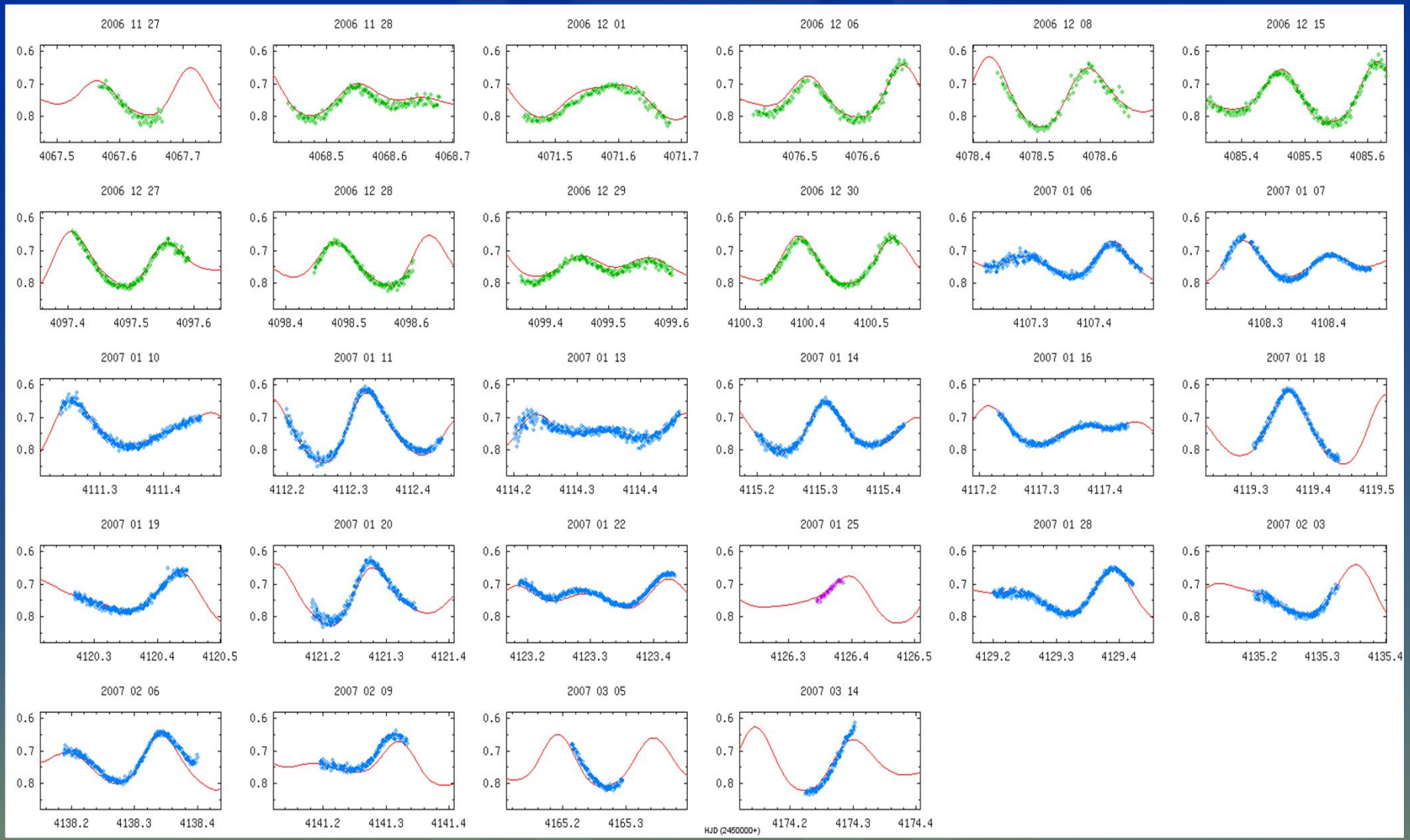


Deviations from Model Curve: Multiperiodicity

- Comparison of observations with model curve
  - Other frequencies?
  - 30 multiperiodic HADS found

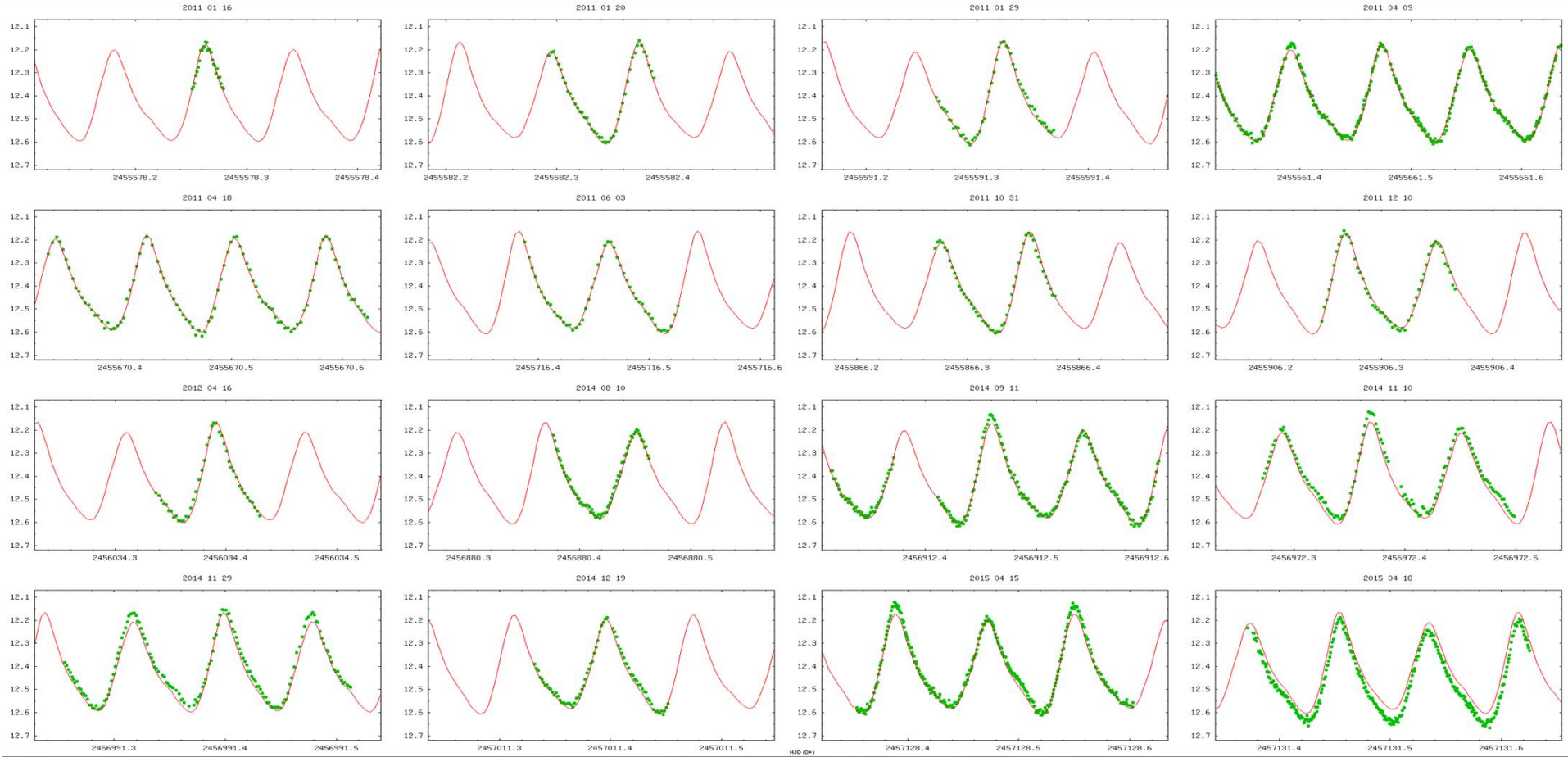


Multiperiodicity



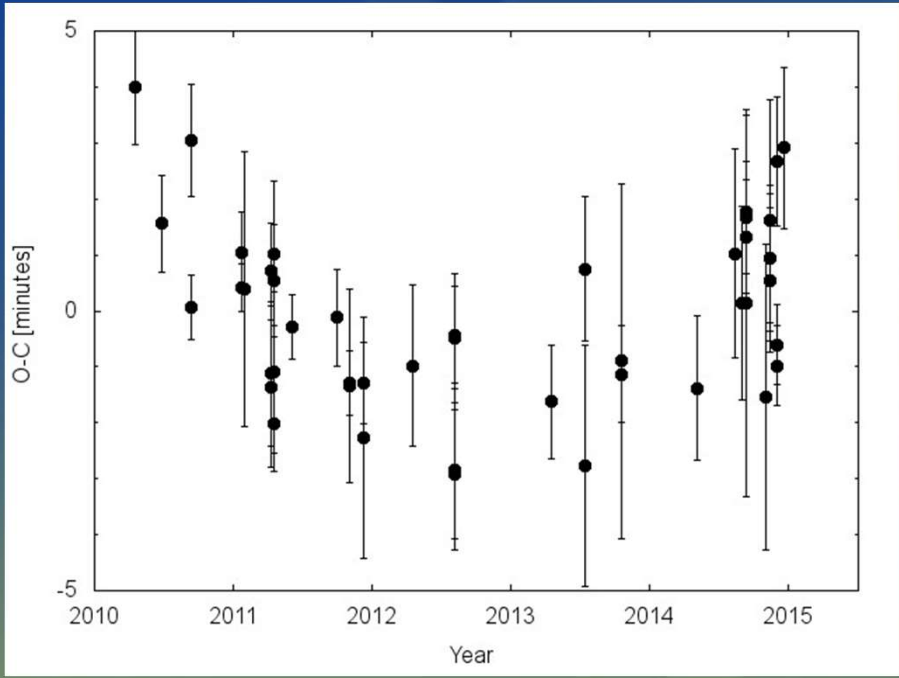
Multiperiodicity

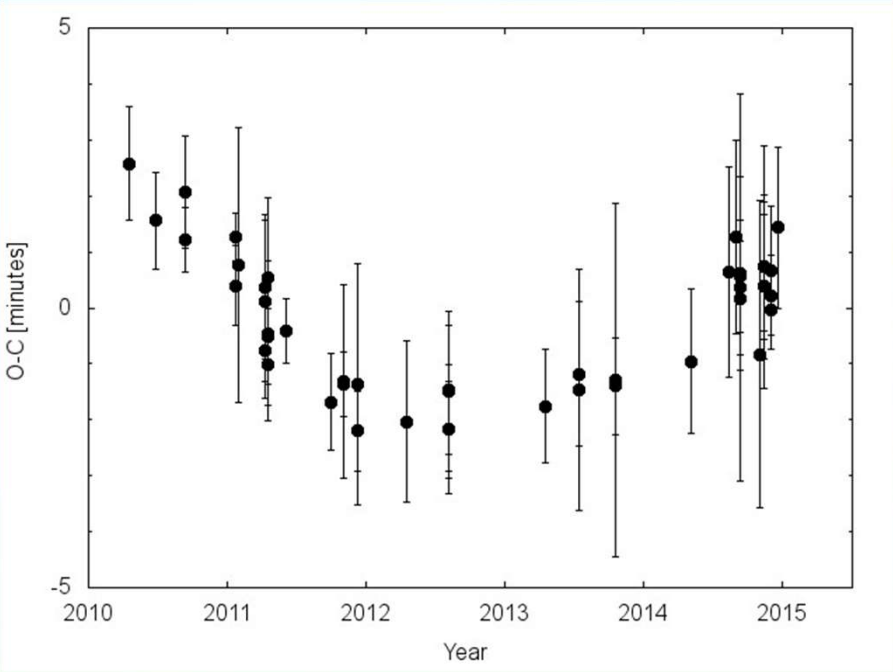
- Time of maximum depends on additional frequencies



Multiperiodicity: O-C

- O-C method less accurate
  - Accuracy decreases when secondary amplitude increases
- Phase corrections needed

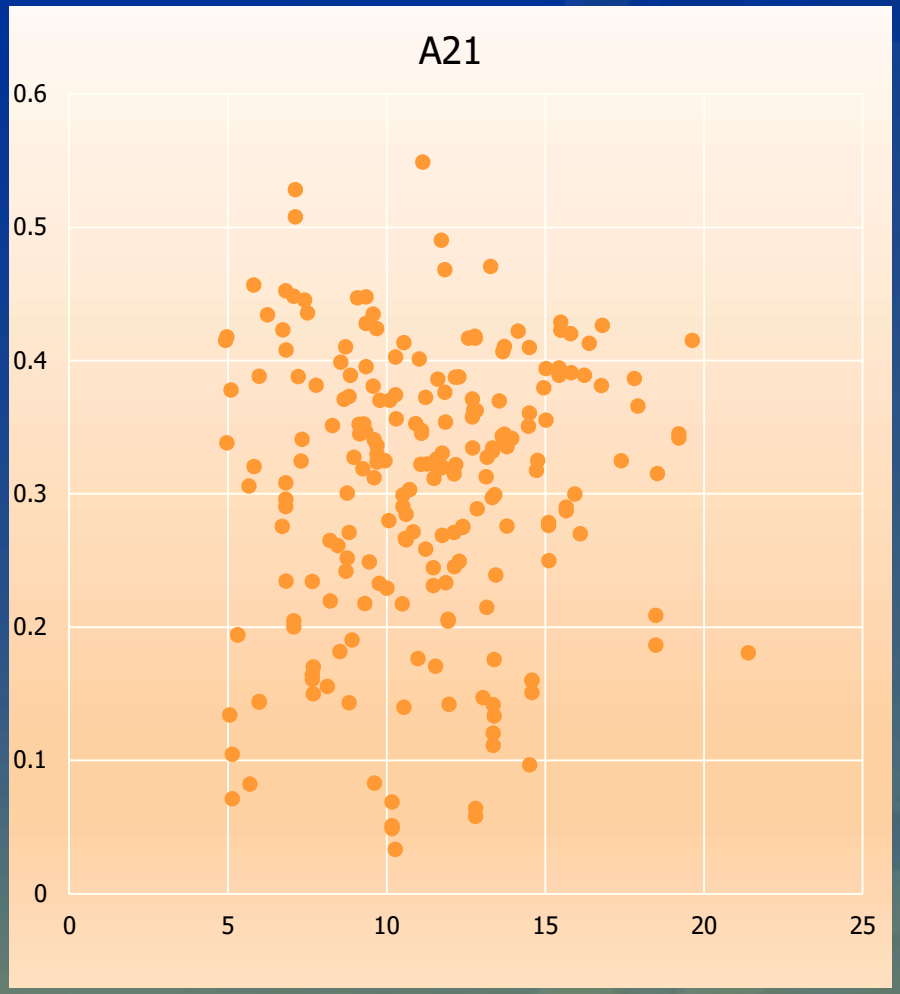


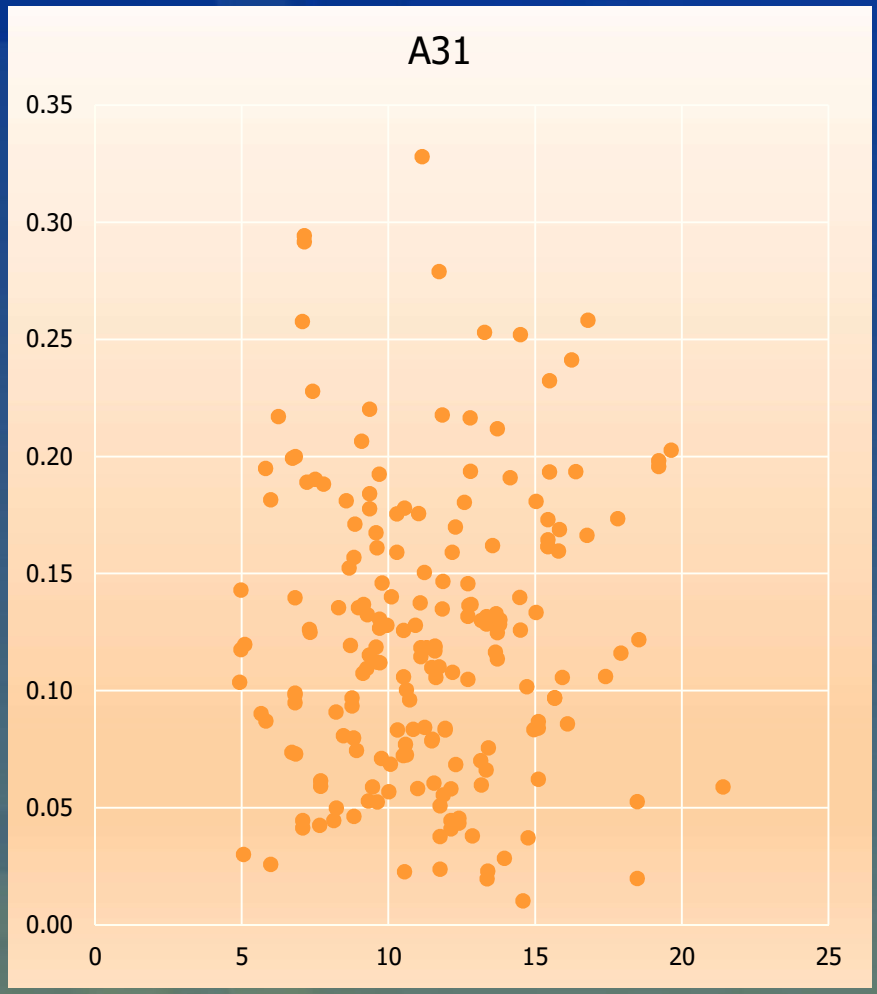


Period Change Statistics

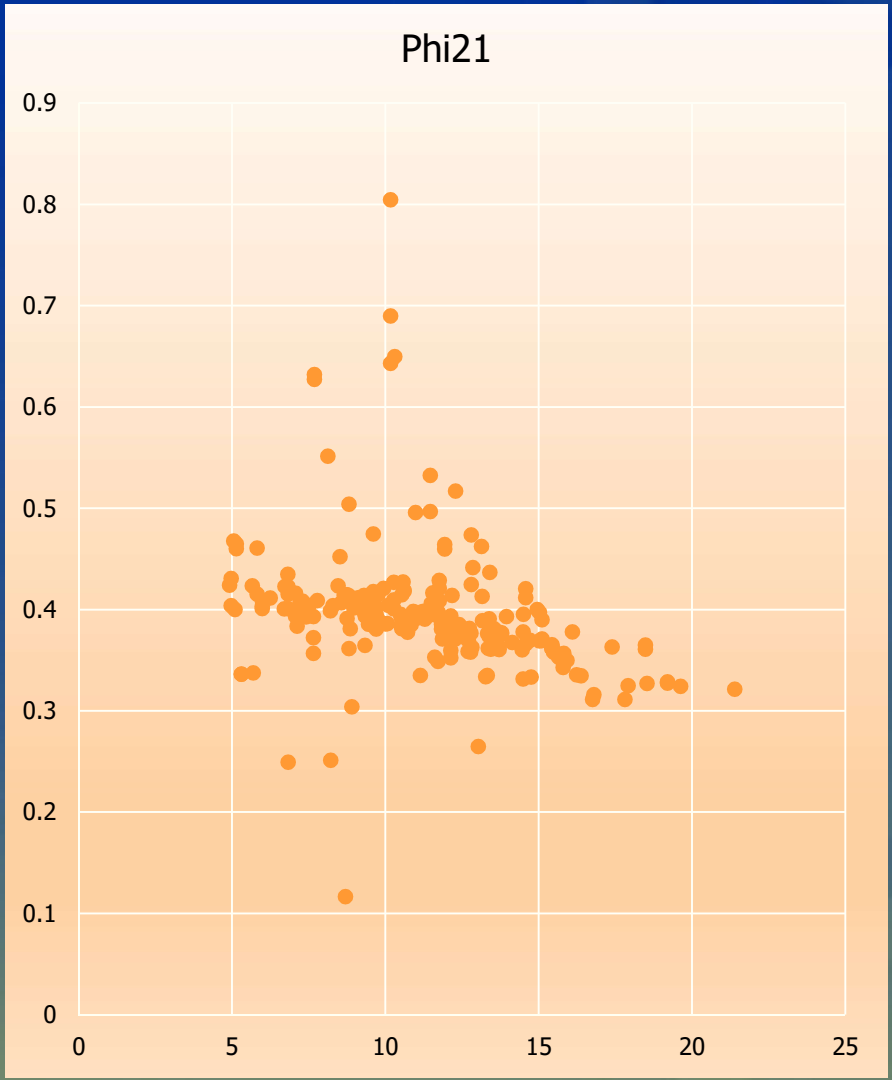
- 170 HADS observed
- Multiperiodicity: 30
- (Quasi) Linear period changes: 10
- Cyclical period changes: 15 (to be confirmed)
- Irregular period changes: 15

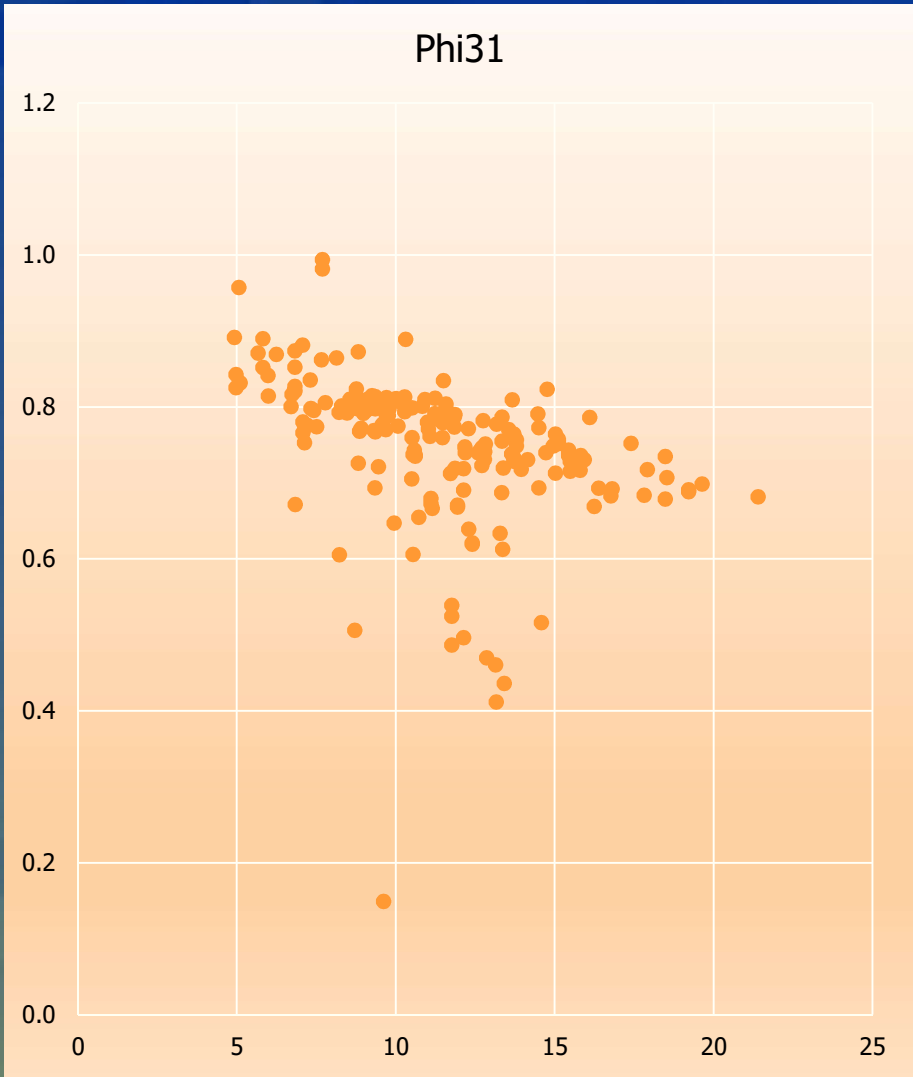
Model Curves: Harmonic Amplitude vs. Frequency



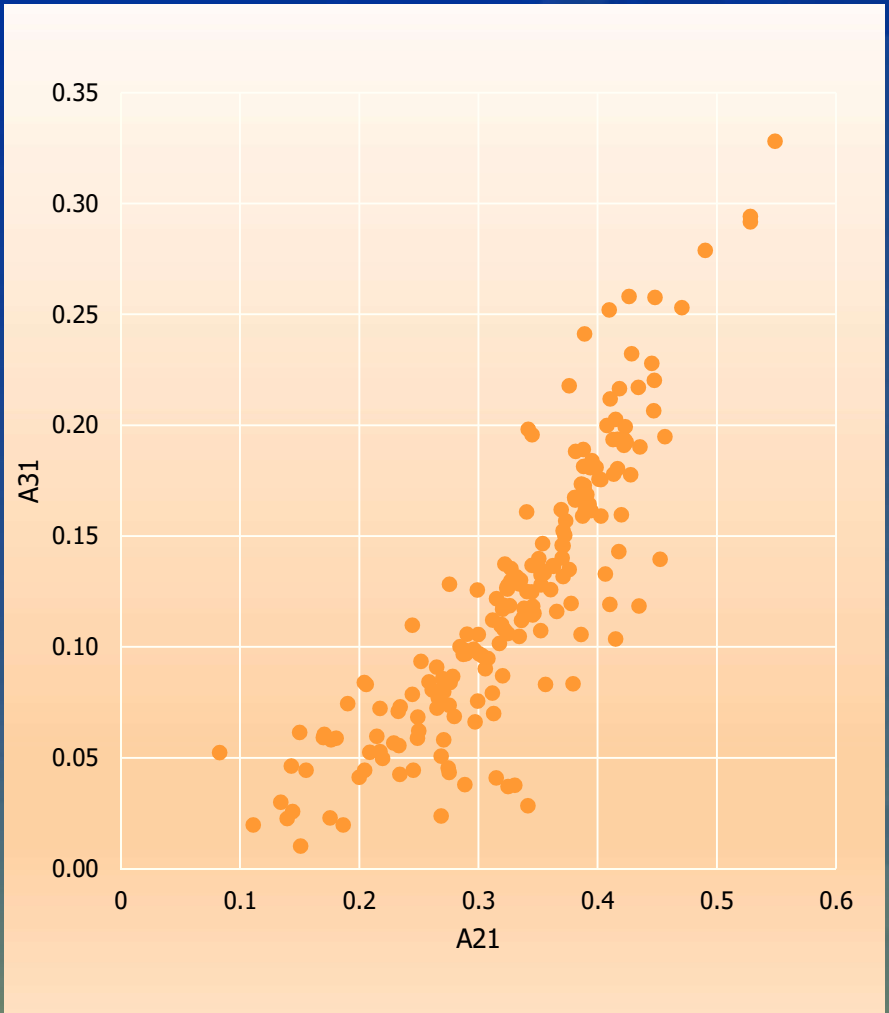


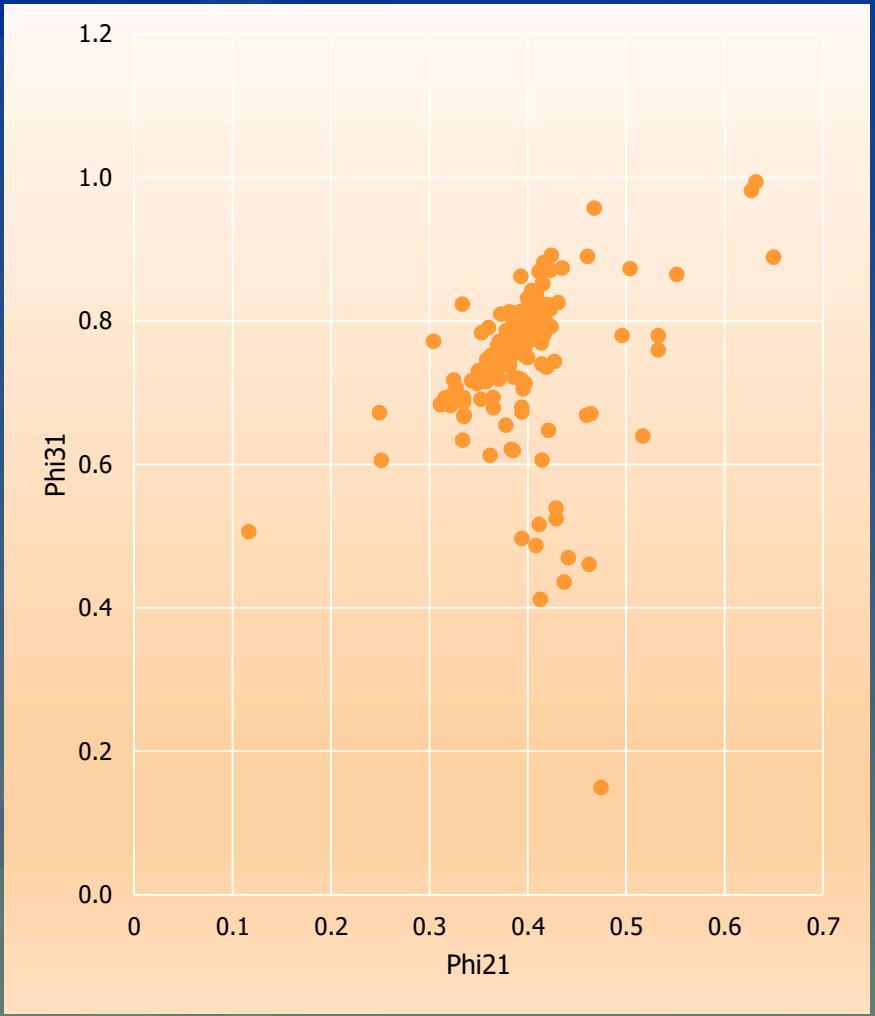
Model Curves: Harmonic Phase vs. Frequency





Model Curves: 2nd vs. 1st Harmonic





HADS and Large Surveys

- More HADS are discovered
- Data can be used to calculate 1-2 maxima per year
- Can survey data be used to discover binaries?
- Ex. V572 Cam:
  - 4 years of ASAS-SN, 120 data points
    - -> No secondary cycle
  - 1 observer, same period: 25 nights, 3600 data points
    - -> Secondary cycle is obvious
- Photometry is still useful

Conclusion

- Many HADS do not show period changes (~ 10 years)
  - No evidence for evolution yet
  - When changes are present, they are larger than expected
- A number of HADS show sudden/irregular period changes
  - Theoretical work needed
- At least 2 HADS reside in a binary (apart from SZ Lyn)
  - More data needed for ~10 others (< 3 cycles)
- ~1 in 5 HADS is multiperiodic
  - Secondary amplitude > 0.01 mag
- 45 observers
  - Argentina, Belgium, Finland, Germany, Greece, Slovakia, Spain, The Netherlands, UK, USA