

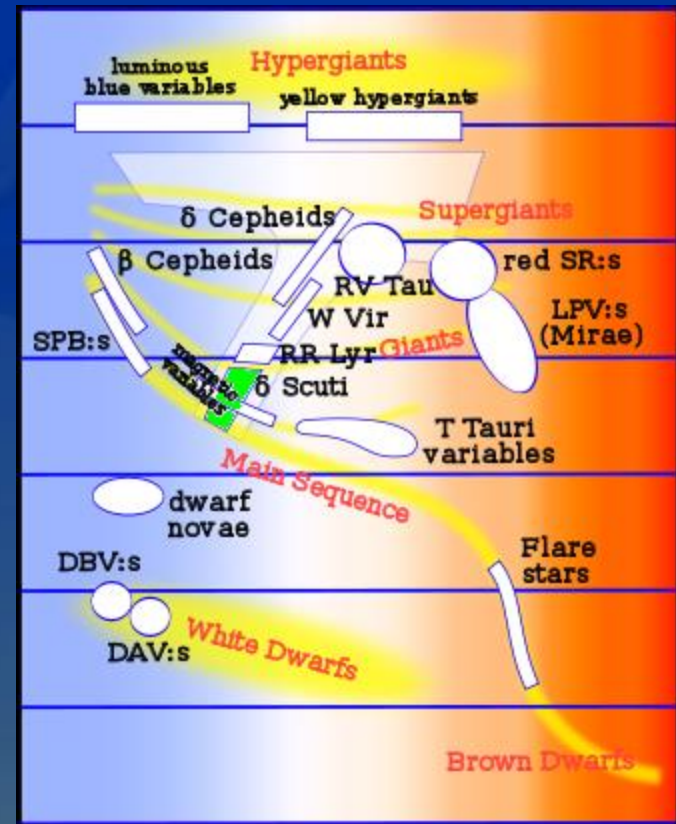
# Long-Term Photometry of HADS

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# Dwarf Cepheids / RRs

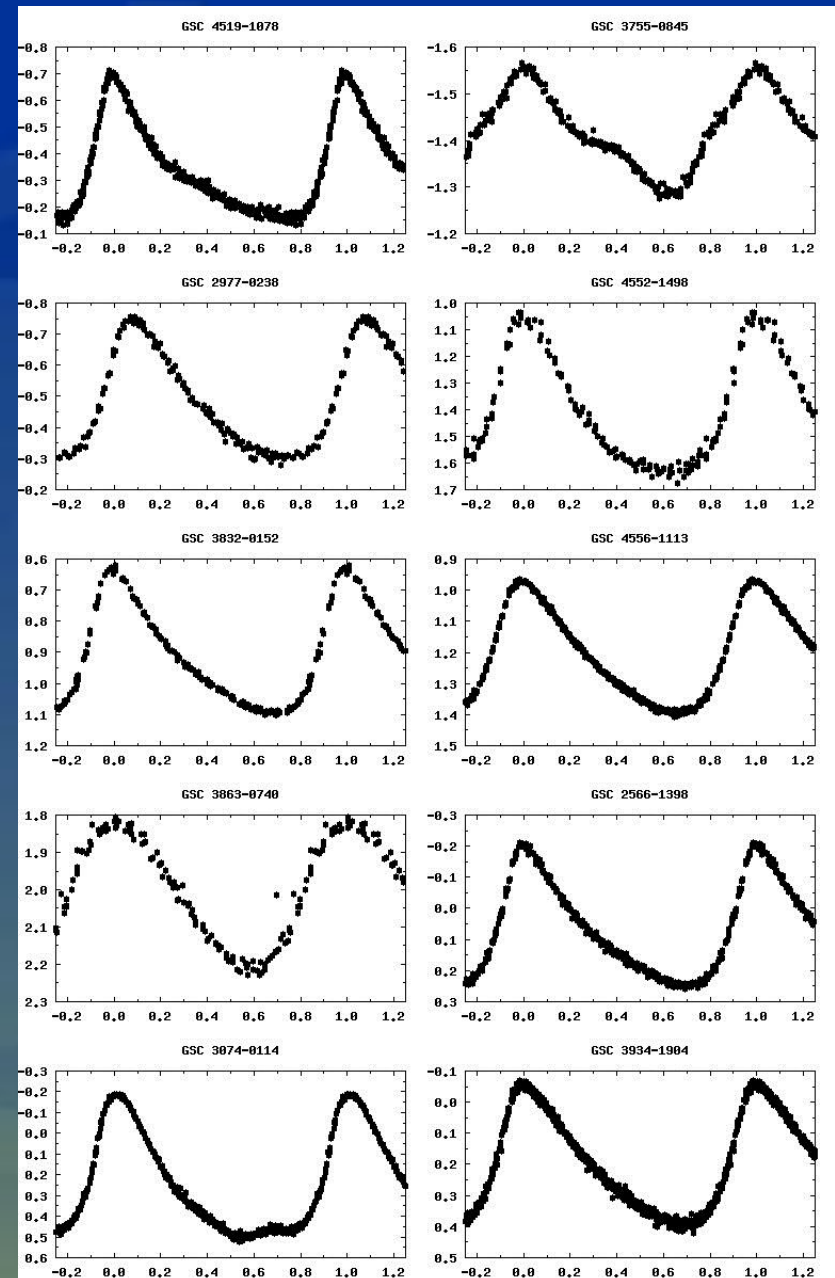
- Delta Scuti stars
  - On or near the main sequence
    - Pre- (T Tau) + post-MS
    - Spectral type A-F
  - Cepheid instability strip
  - Generally: small amplitude
    - < 0.1 mag
  - Multiperiodicity:
    - periods 1 - 5 hours
  - Non-radial pulsations
  
- High Amplitude Delta Scuti stars
  - Amplitude > 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
  - $\neq$  Hertzsprung sequence in Cepheids
  - Metallicity?



# The HADS Project

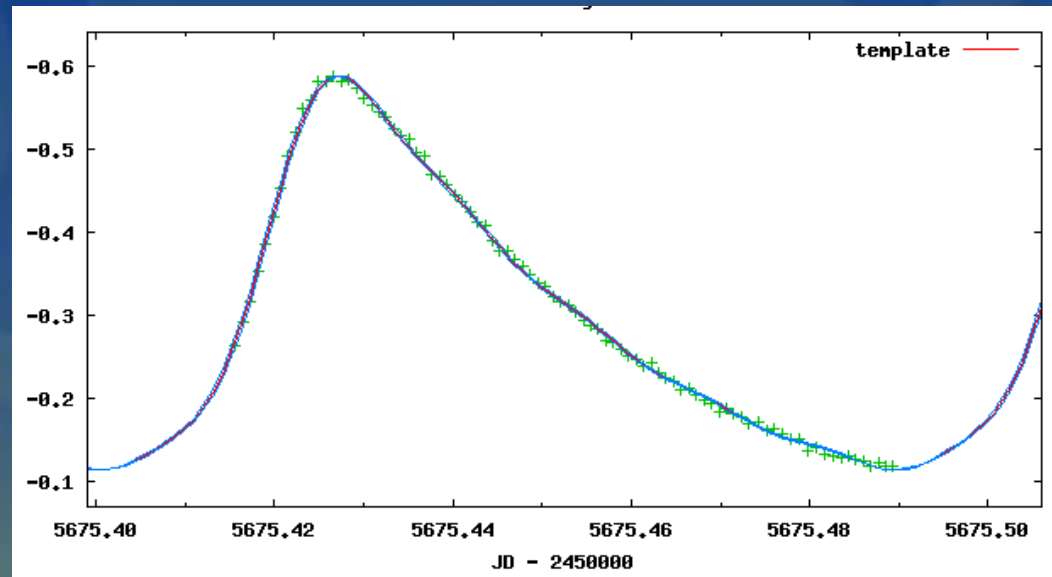
- Started in 2005
  - Small number of observers from Belgium, Spain, Greece and USA
- Advantages
  - Light curve after a few hours
  - No predictions needed
- Purpose: detect period variations
  - Try observing a number of HADS once/month

# Determining time of maximum

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

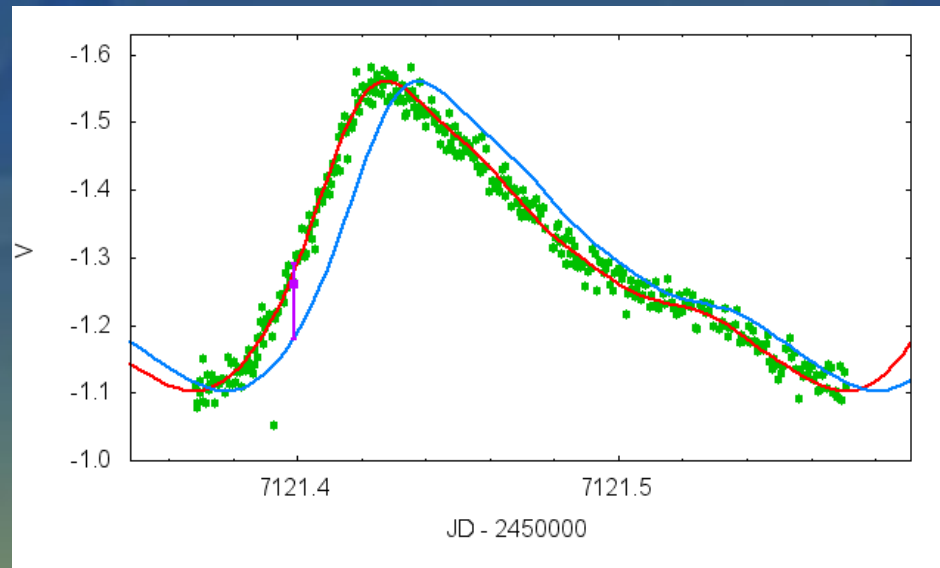
# Determining time of maximum: model curve

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



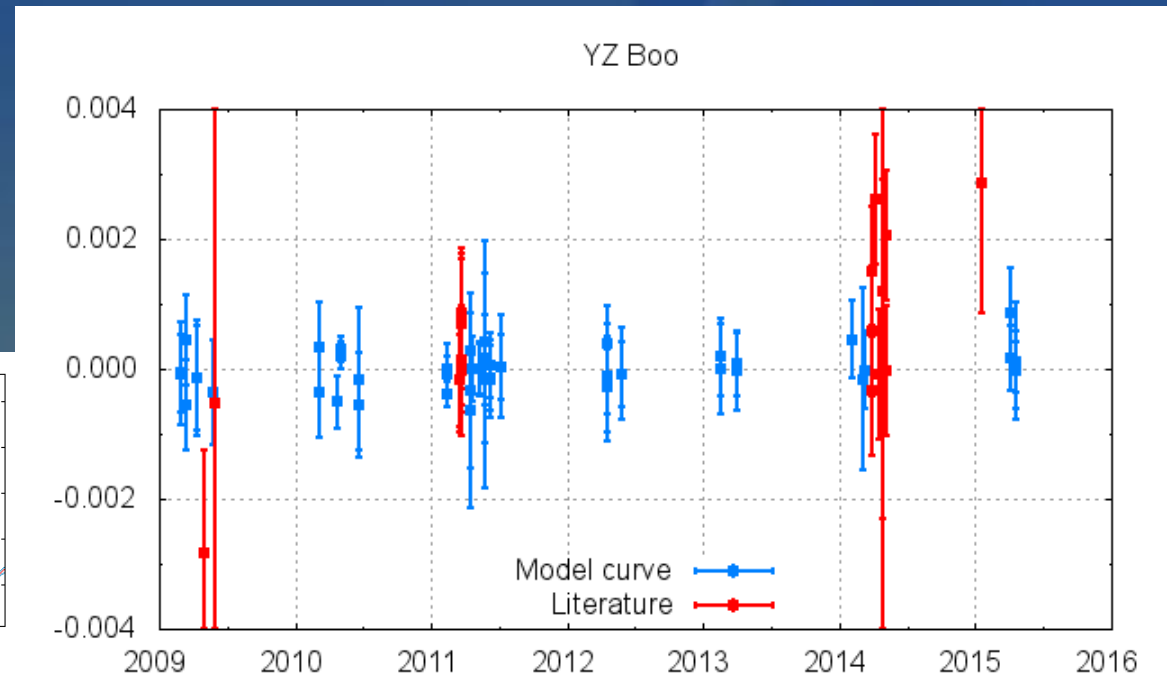
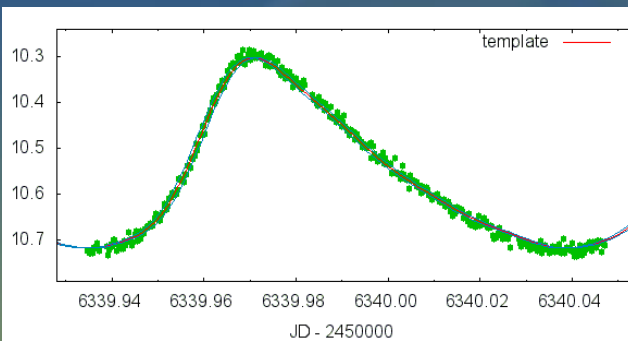
# Determining time of maximum

- 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

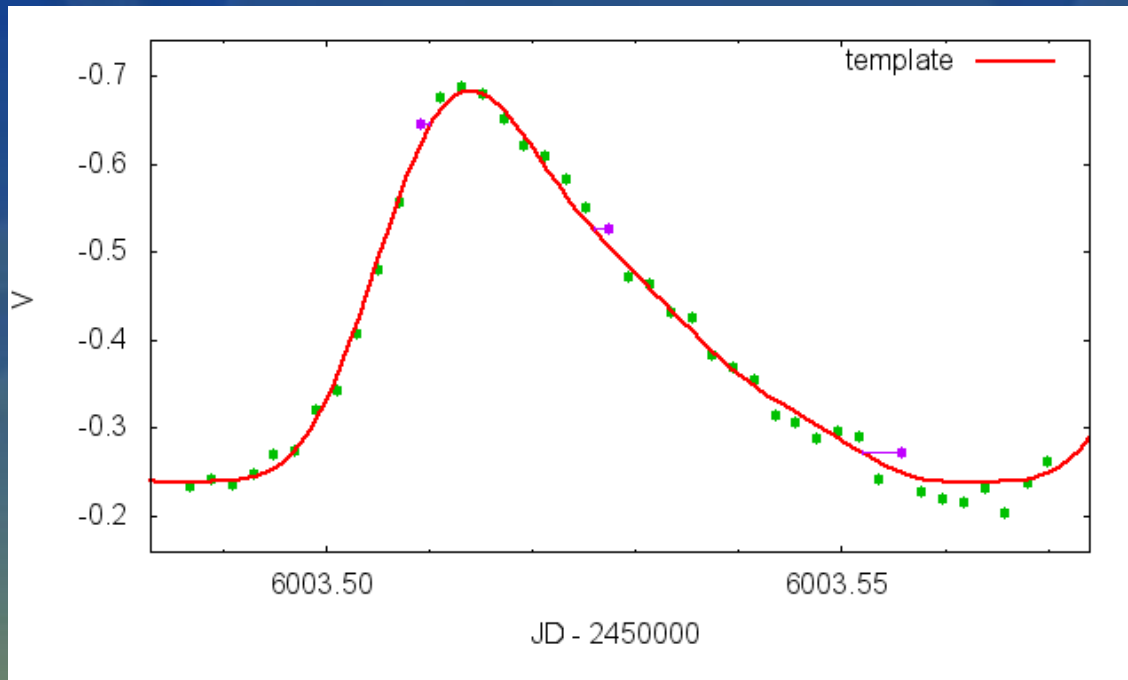
- All data are used
- Fastest variation weighs more in the end result
- Any phase can be chosen, not only maximum
- Maximum does not have to be observed
- Consistent times





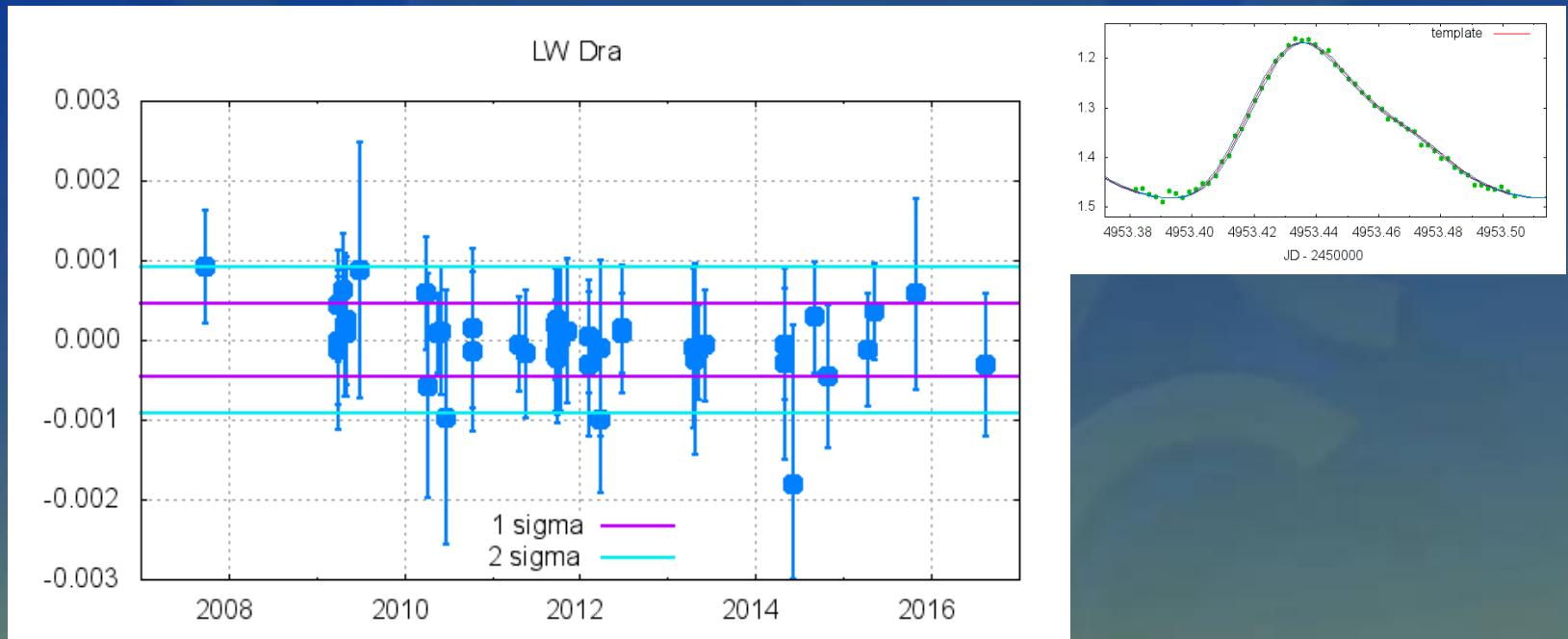
# Uncertainty on time of maximum

- Mean squared difference in time (horizontal distance) between observations and model curve
  - Weighted by slope (more weight when star varies fastest)



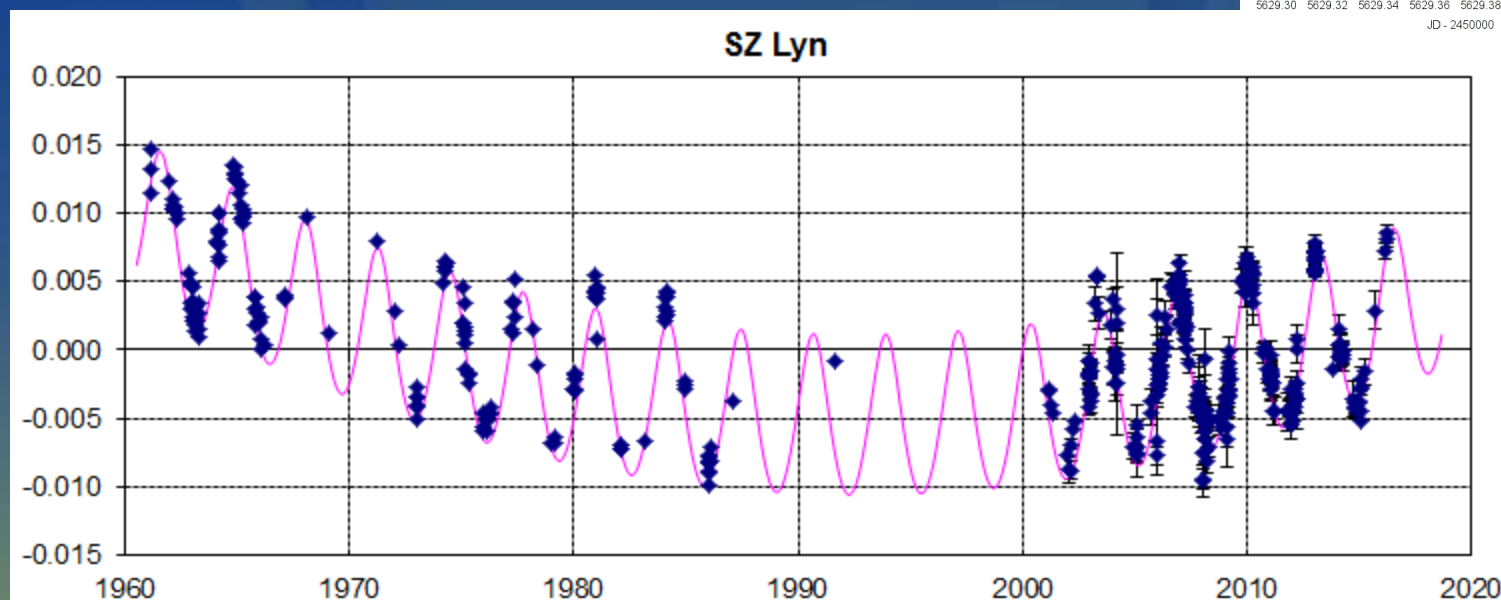
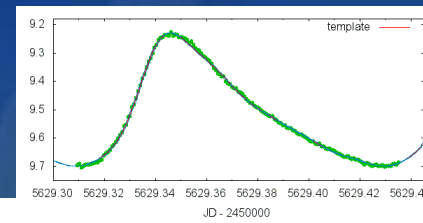
# Uncertainty on time of maximum

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



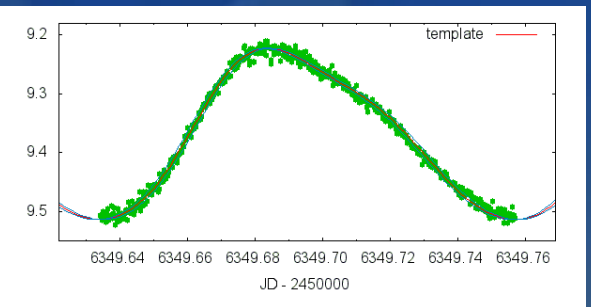
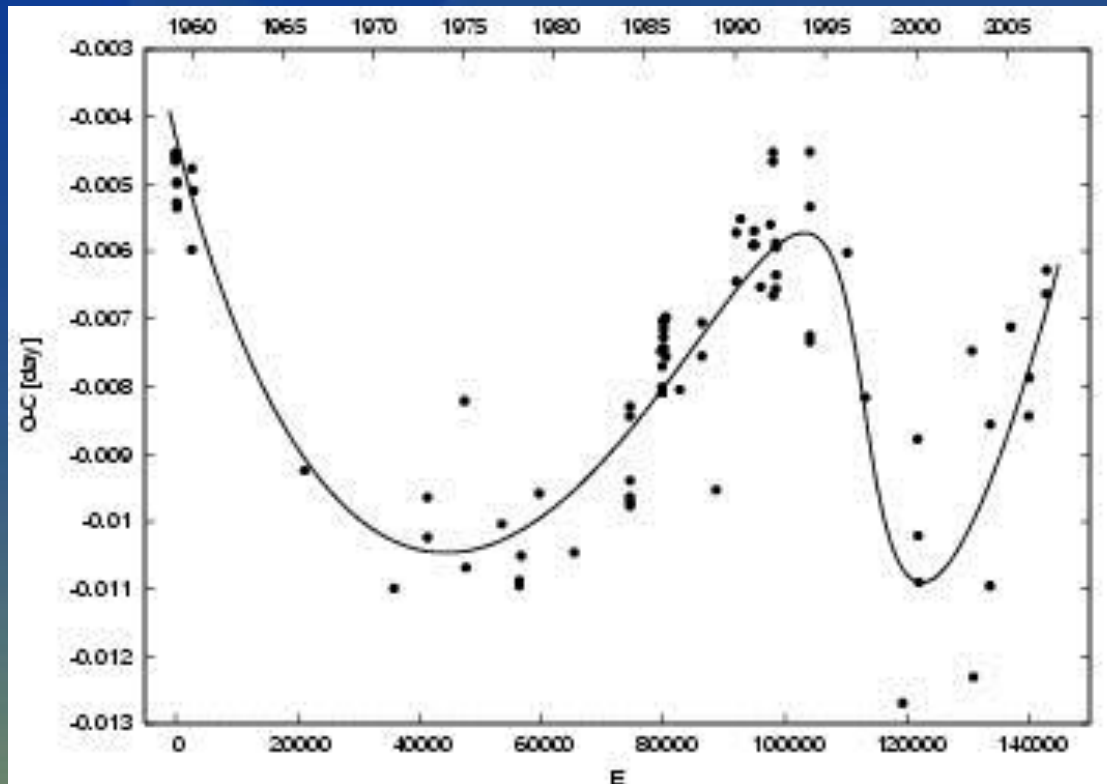
# Causes for period changes: 1. Binary

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



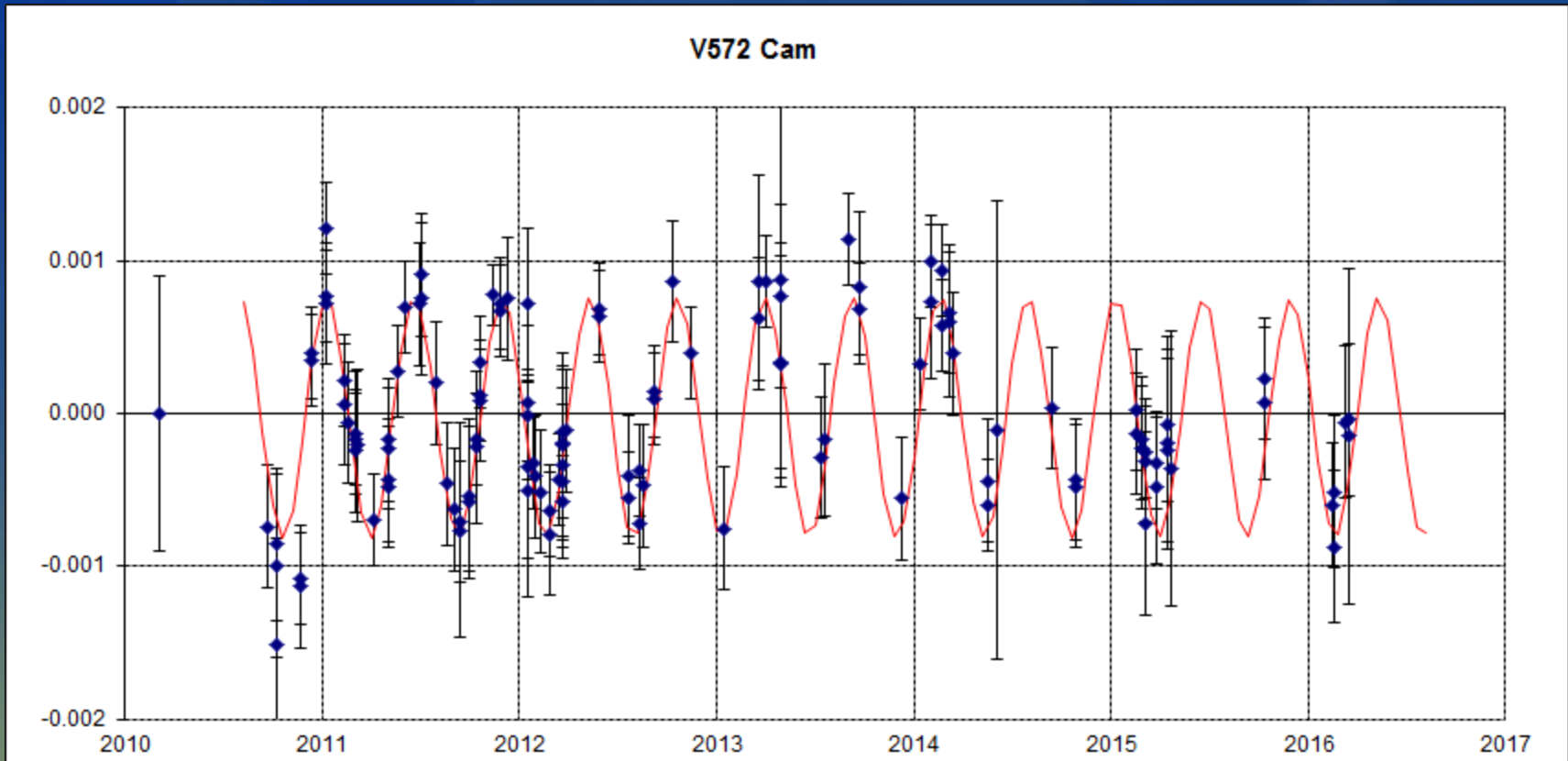
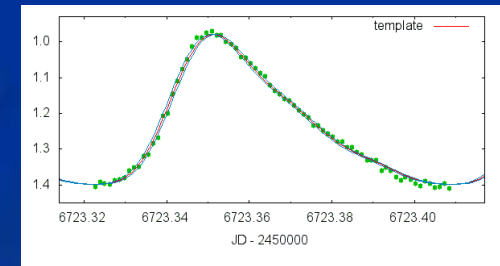
# Not all changes caused by binaries!

- Example: AD CMI
- After more than one "cycle", data no longer fit



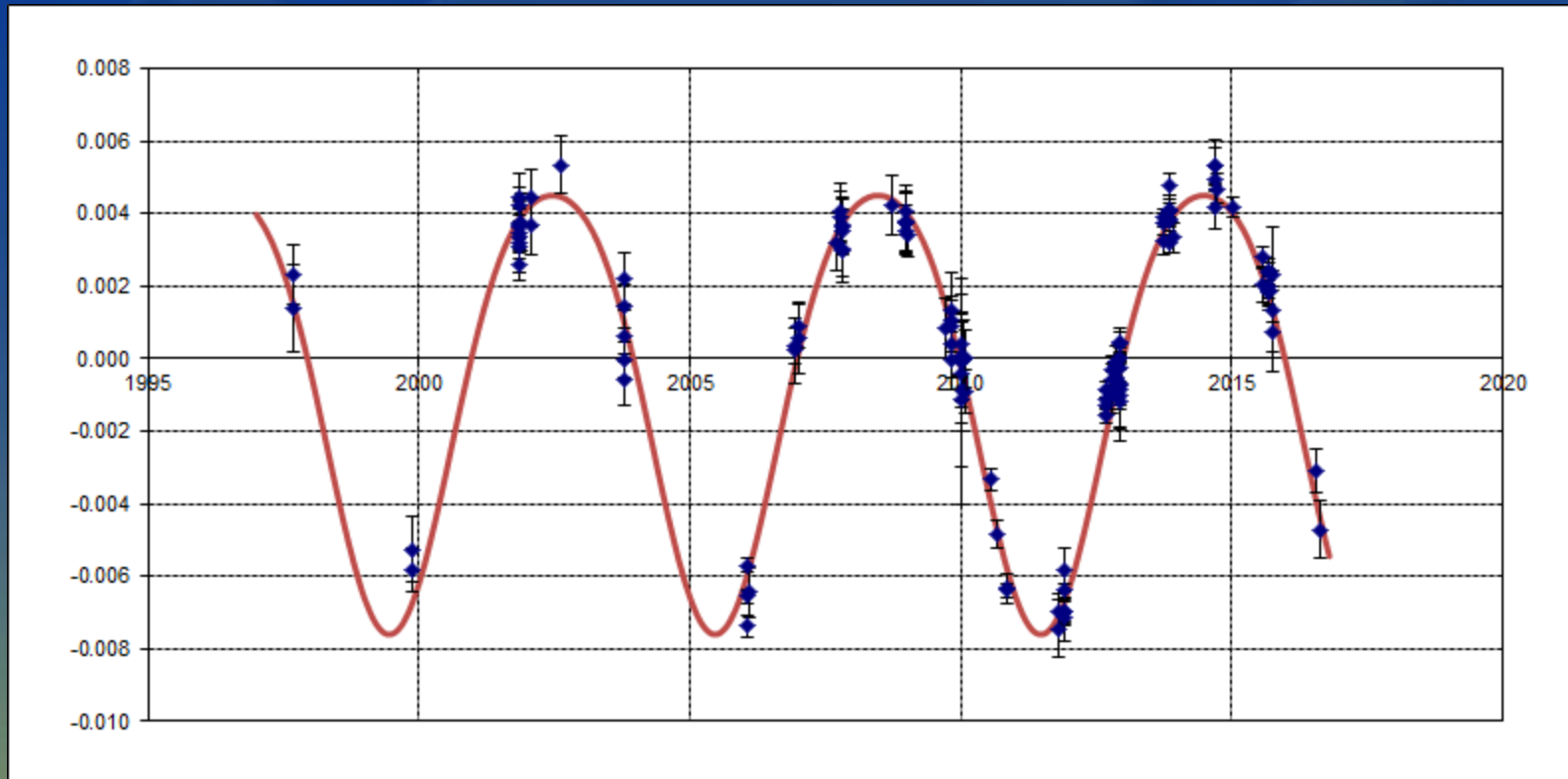
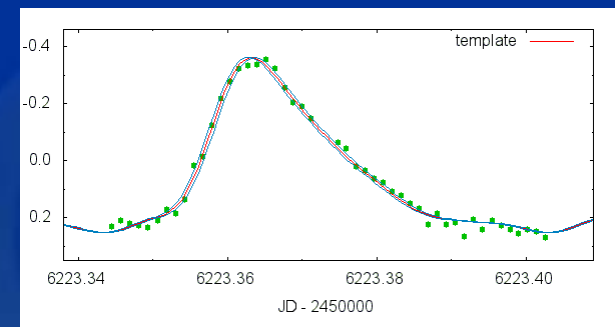
# V572 Cam: binary!

- Orbital period: 167 days
- O-C amplitude:  $2 * 68$  seconds
- If HADS =  $1 M_{\odot}$  and  $i = 90^{\circ}$ : companion =  $0.27 M_{\odot}$



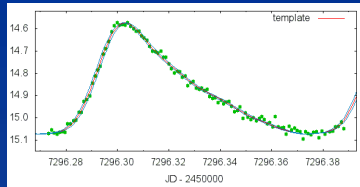
# DW Psc: Another binary!

- Period 6.0 years
- Amplitude  $2 * 8.7$  minutes (= 1.04 AU)
- Companion  $> 0.4 M_{\odot}$  if HADS =  $1 M_{\odot}$

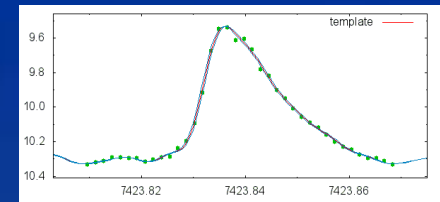
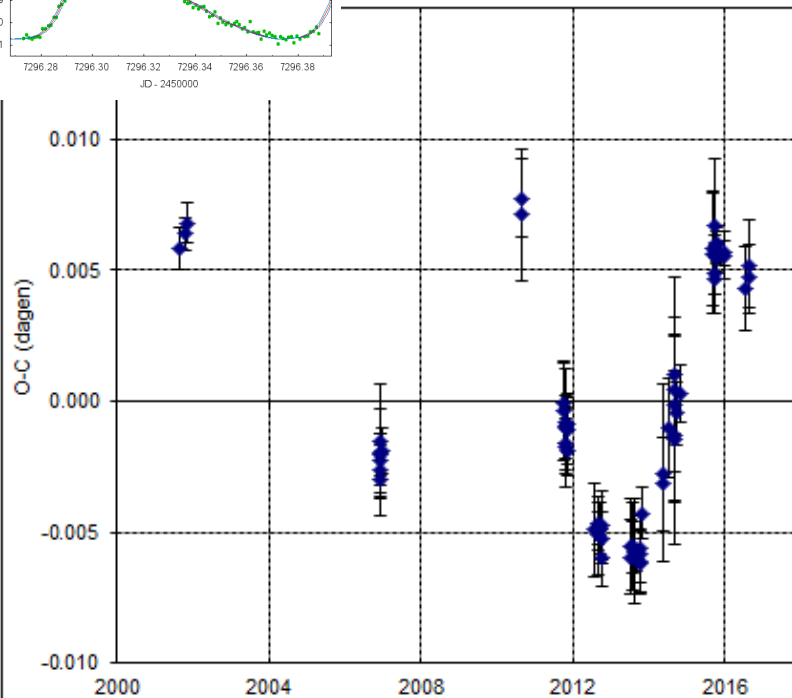


# More binaries? KZ Lac and KZ Hya

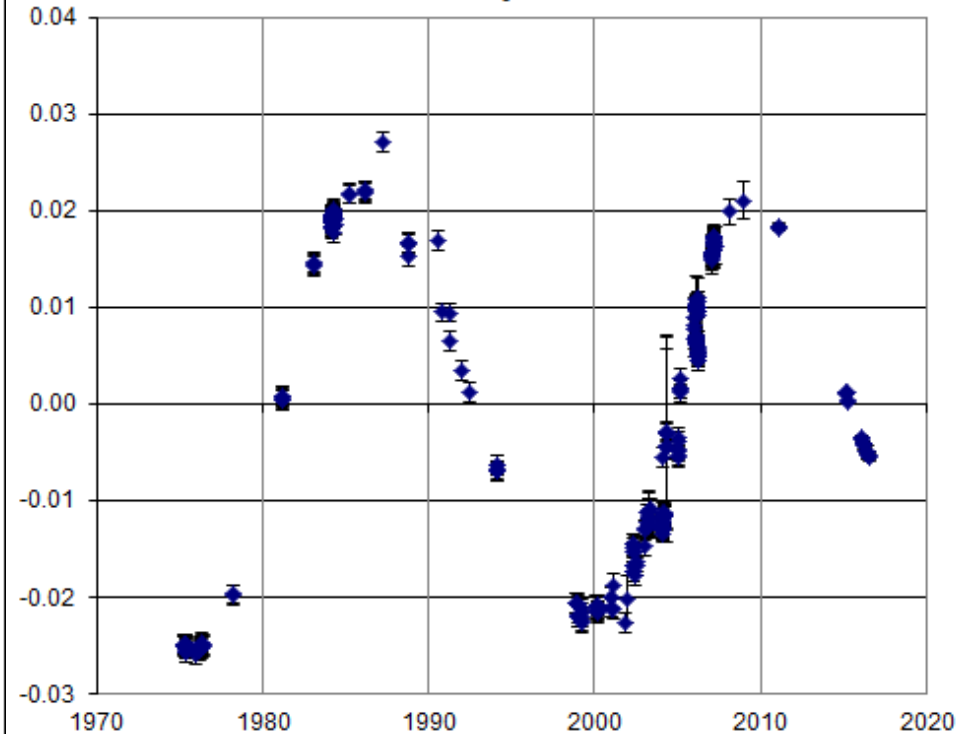
- $P \sim 5$  and 25 years?



KZ Lac



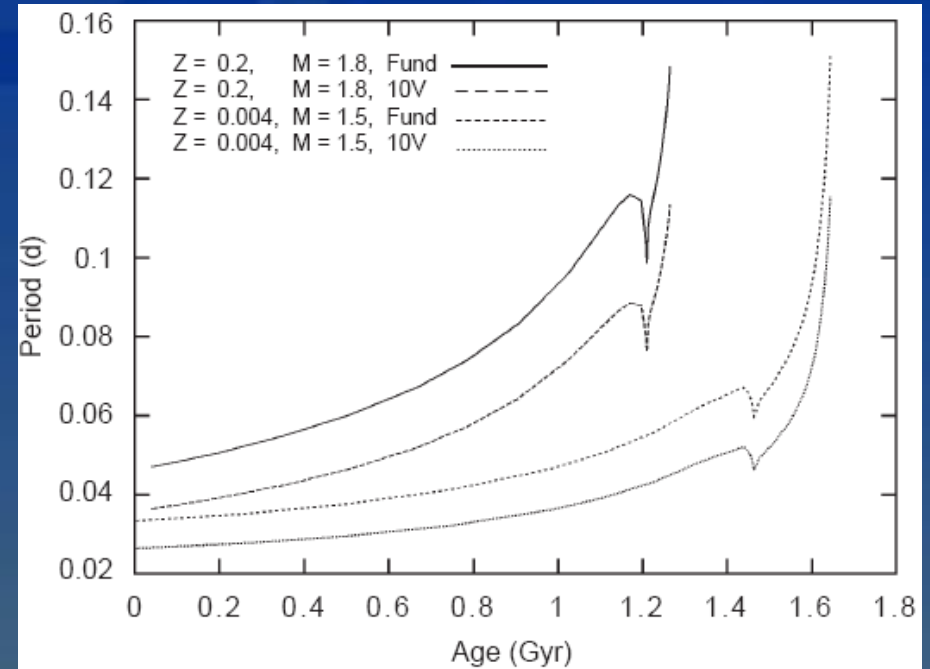
KZ Hya



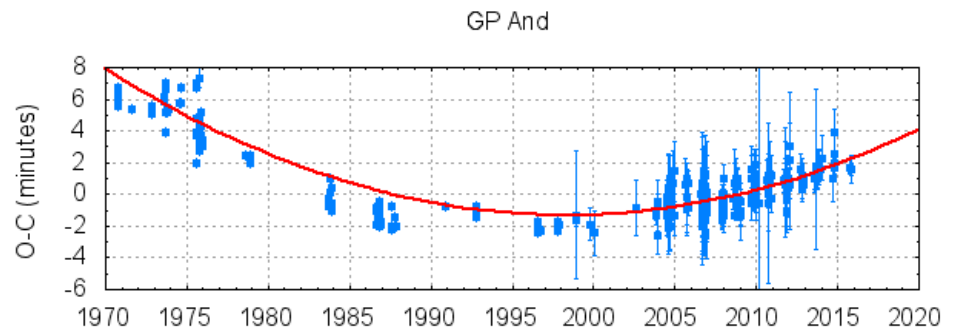
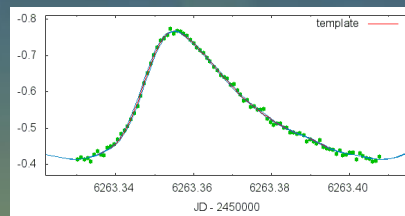
- 5 other HADS: less than 2 "cycles" of several years

# Causes for period changes: 2. Evolution

- Pulsation constant
  - $Q = P \sqrt{\rho}$
- Fusion H  $\rightarrow$  He
  - Main sequence
  - Star expands
  - Density decreases
  - Period increases
- Very slowly:  $< 10^{-7}$ /year  
or: 10 ms/century  
O-C  $\sim 1/2$  min/10 years
- Parabola in O-C-diagram



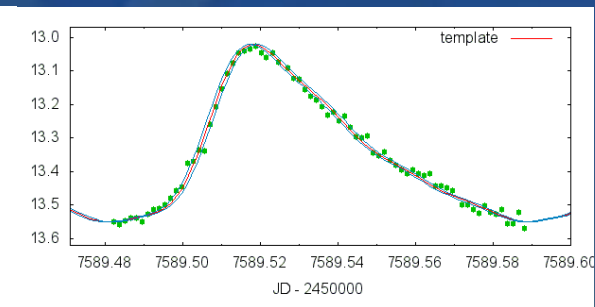
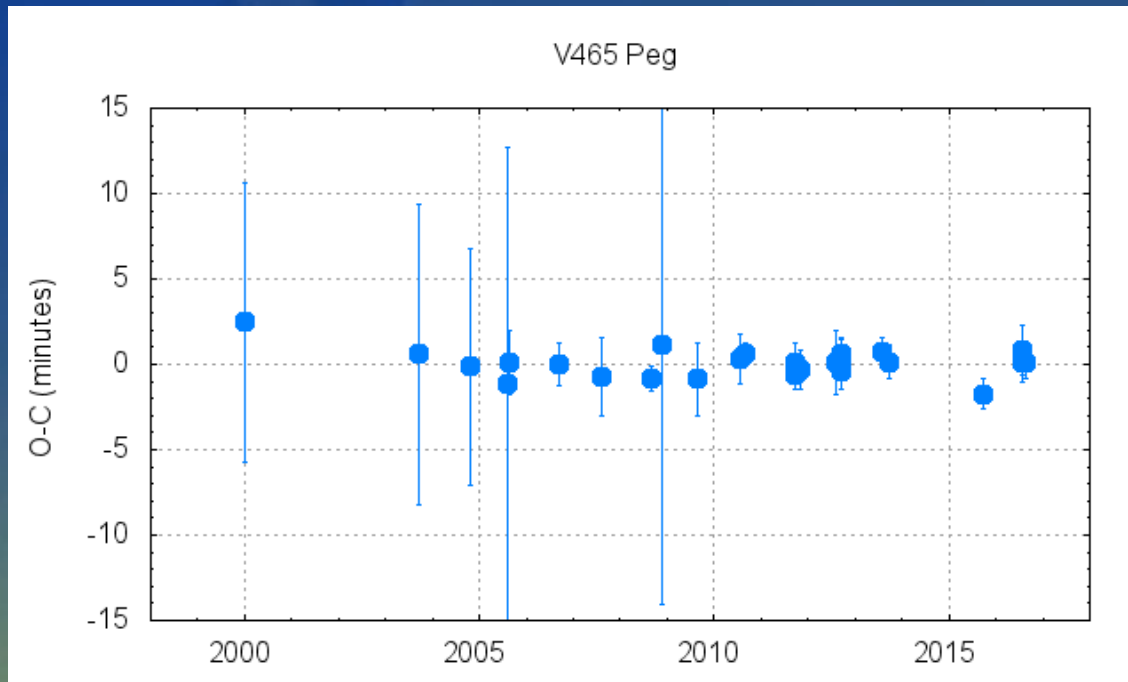
M. Templeton, 2005, JAAVSO





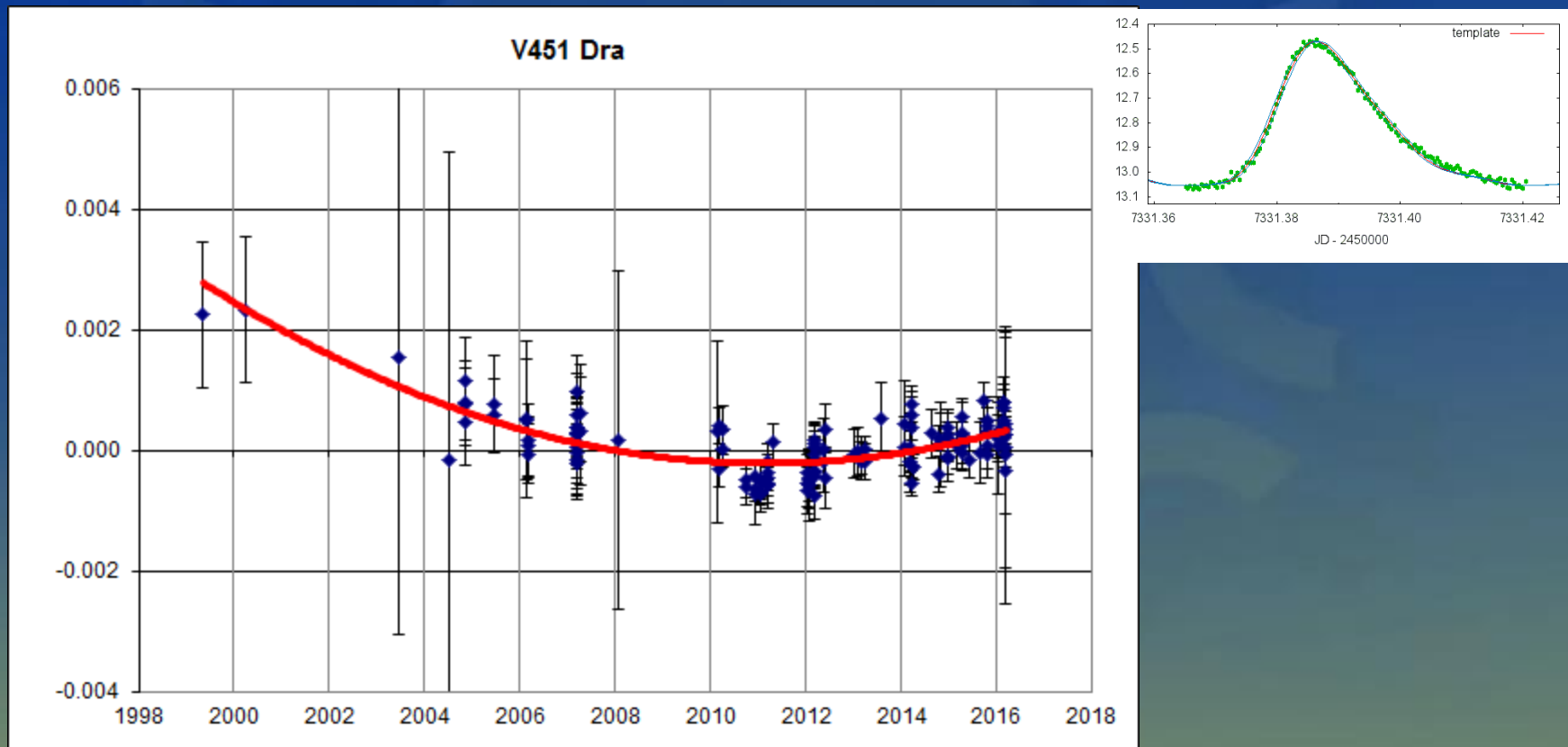
# Observed period changes

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

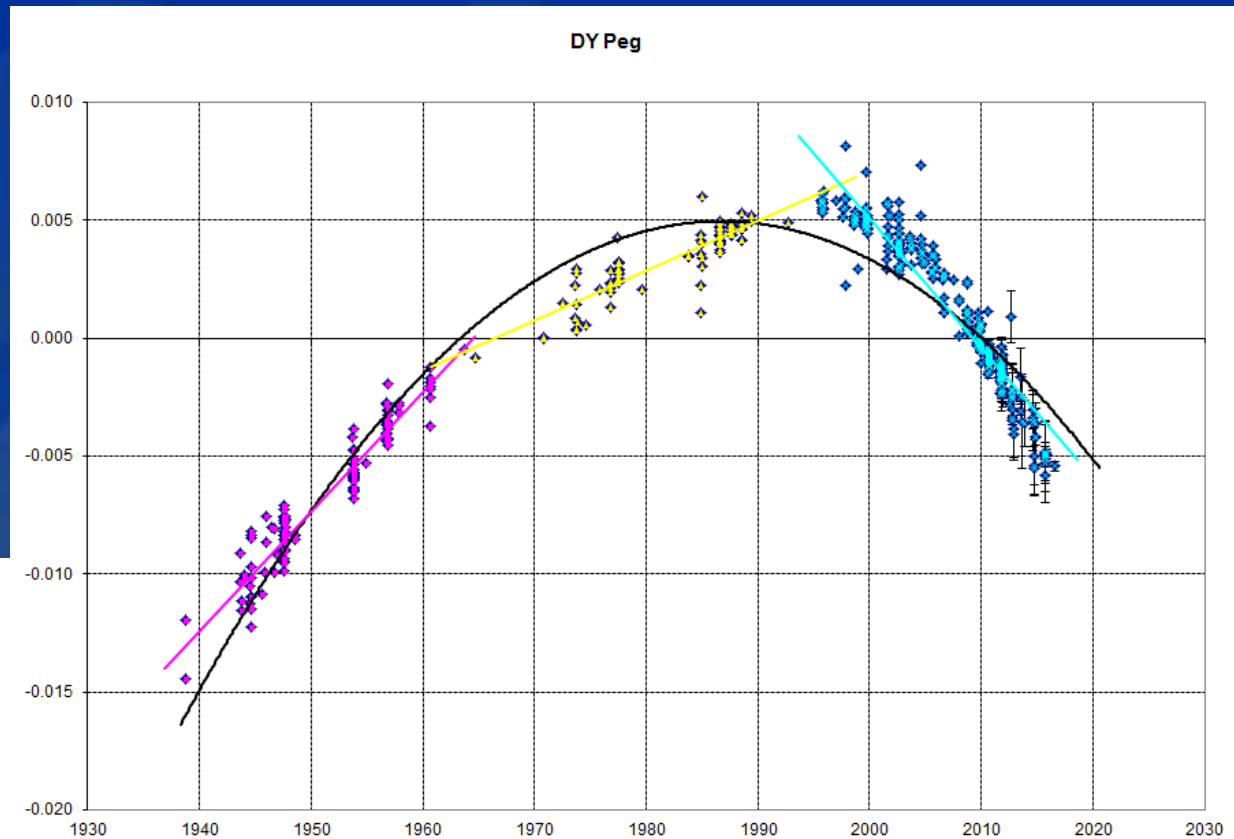
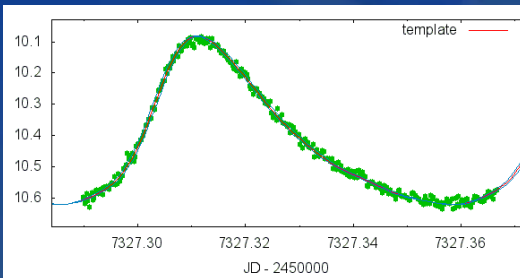


# Observed period changes

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



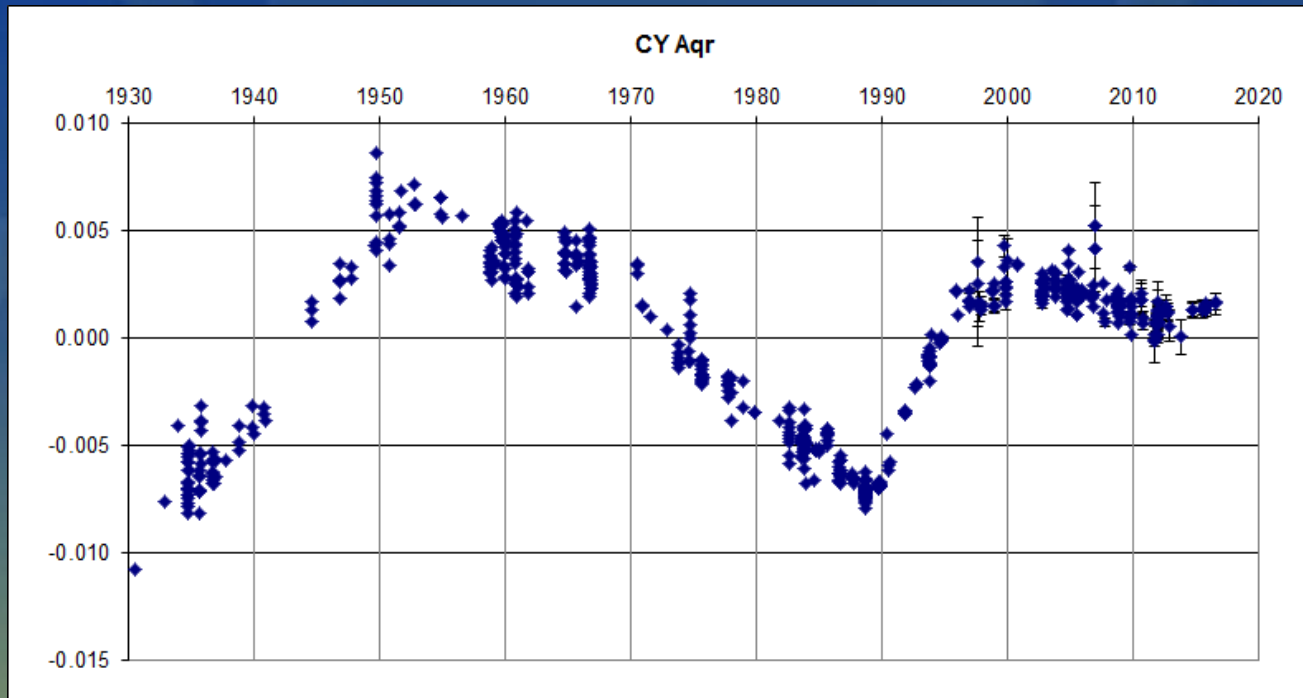
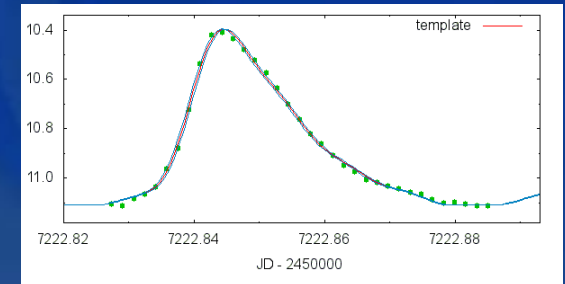
# Evolution?



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

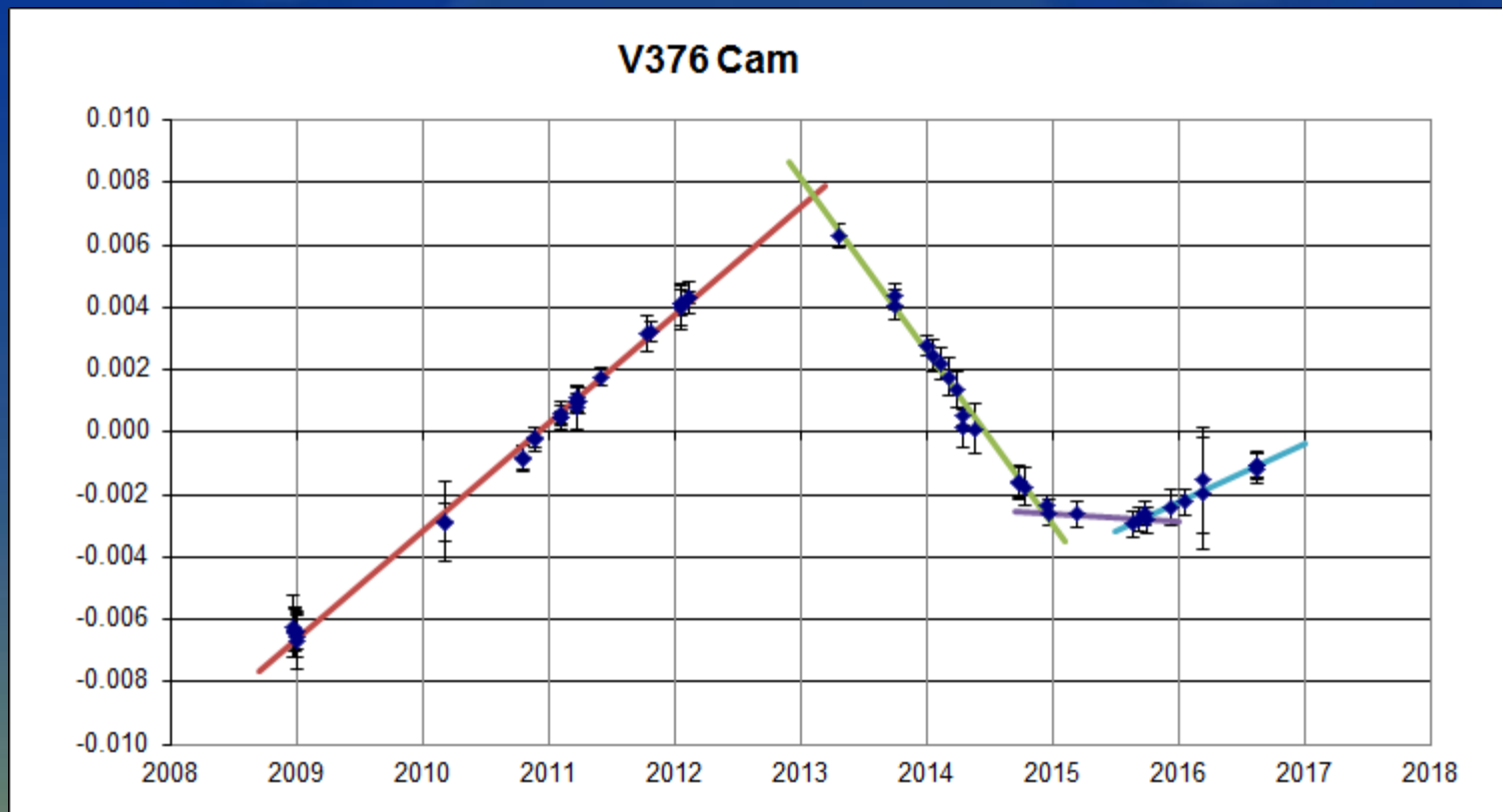
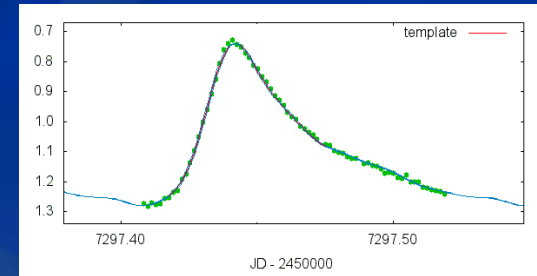
# Other causes of period changes: 3. ?

- CY Aqr
  - Since 1930
  - At least 5 period changes
  - $\sim$  constant period in between changes



# Sudden period changes

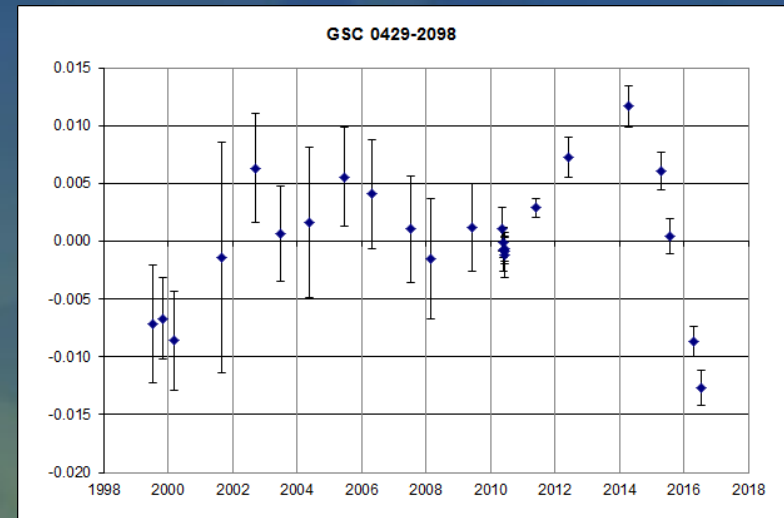
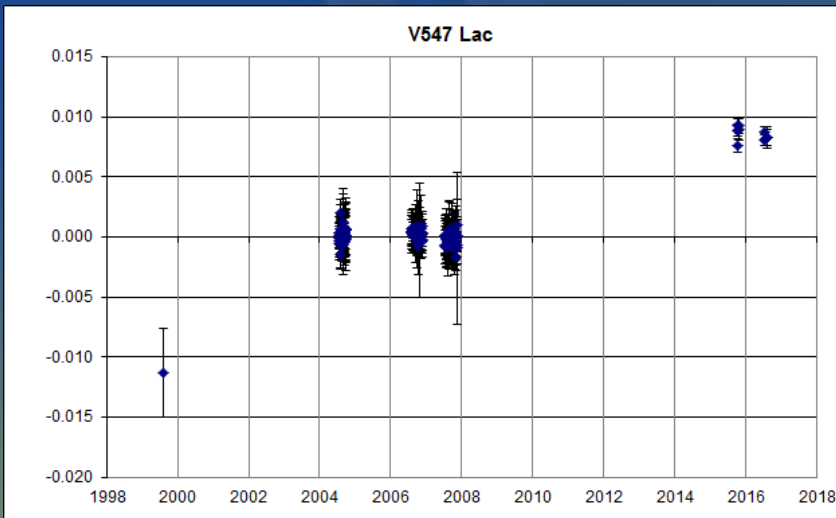
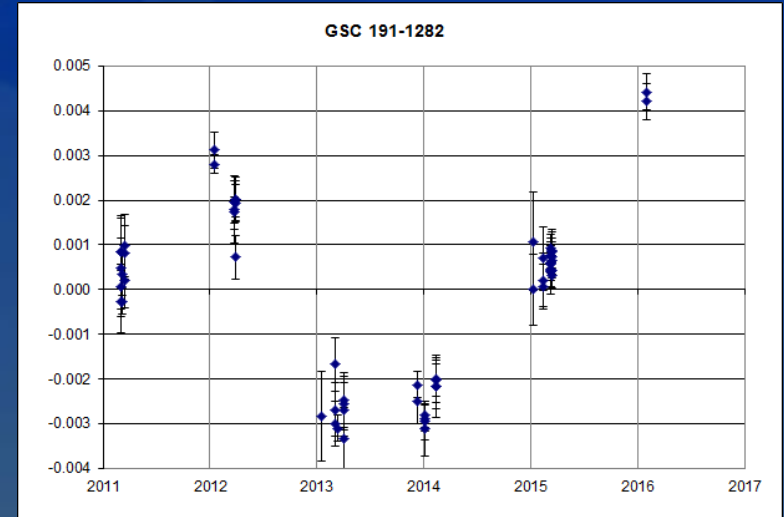
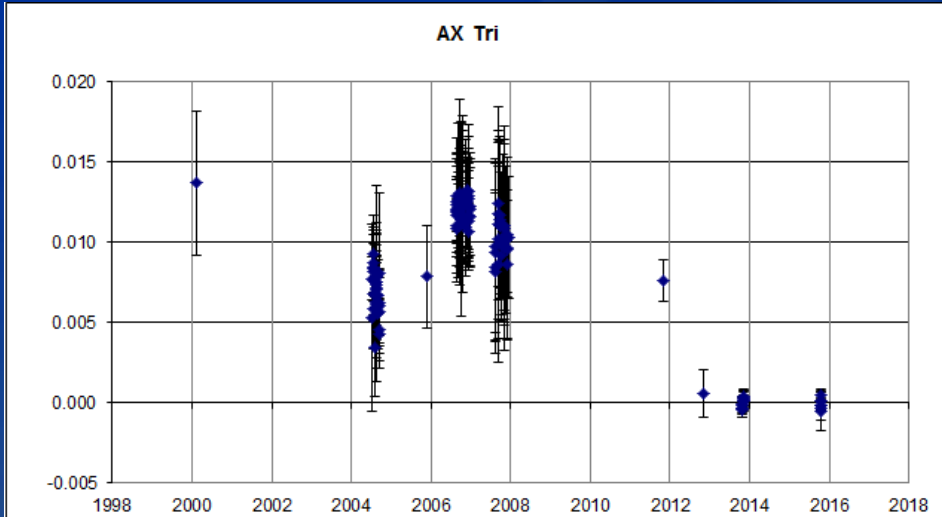
- V376 Cam
- 3 changes in 3 years



# Sudden period changes

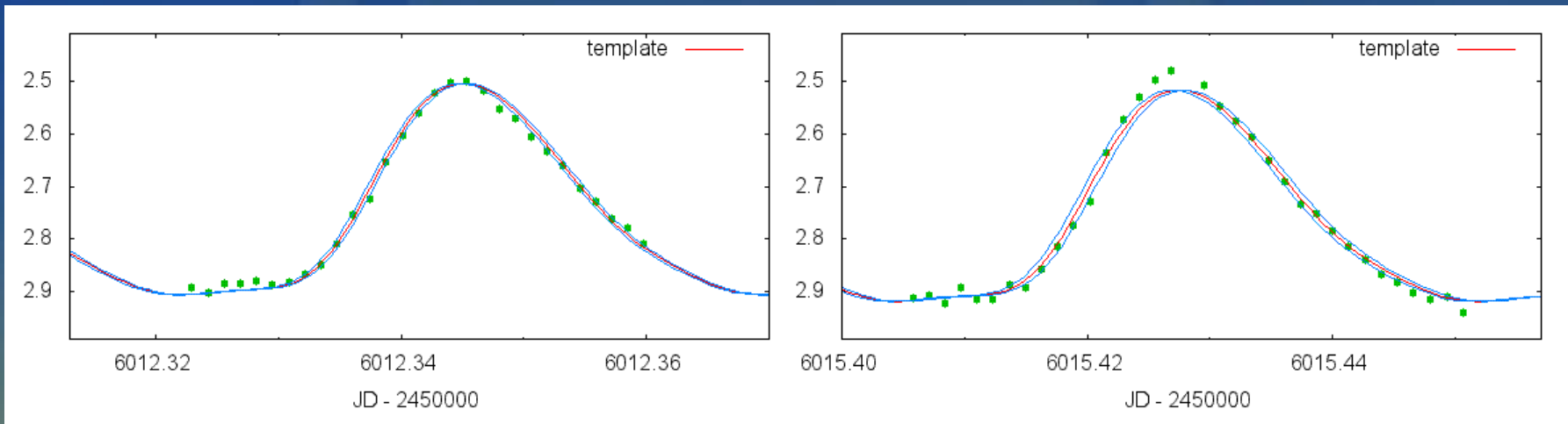
- Very little theoretical work
- Sweigart & Renzini 1979
  - Discrete mixing events in semiconvective zone (not in DSct)
- Cox 1998
  - Dredge-up of helium (giants)
- Non-linear mode interactions (non-radial)
  - Gradual changes only?
- Time scales for a change and between changes + direction of the change

# Other O-C diagrams



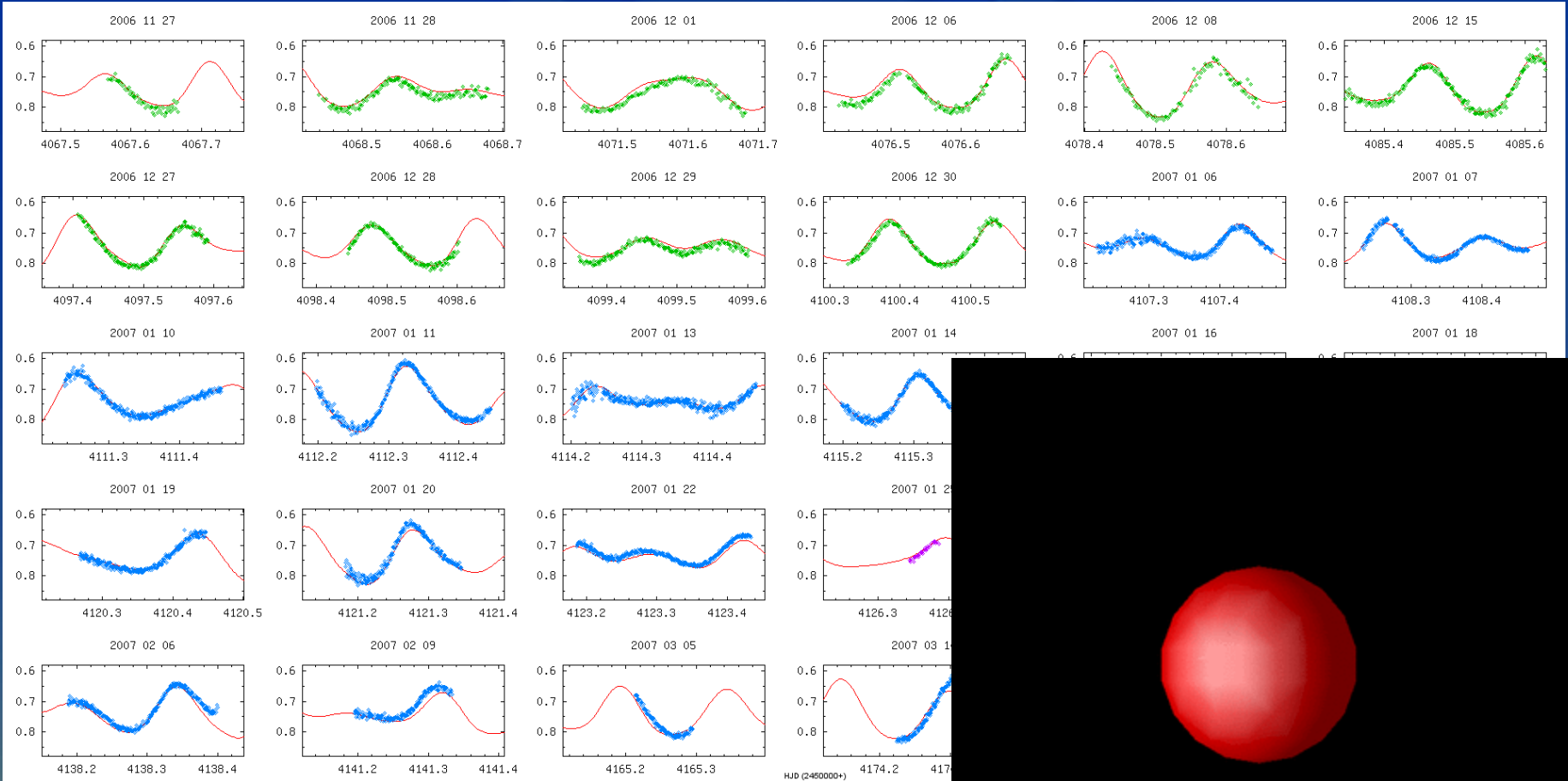
# Deviations from model curve

- Comparison of observations with model curve
  - Other frequencies?
  - More than 20 multiperiodic HADS found





# Multiperiodicity: 2 radial frequencies



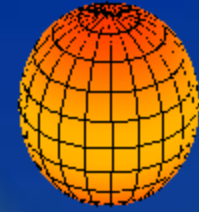
- Similar amplitudes

Animation: T. Bedding

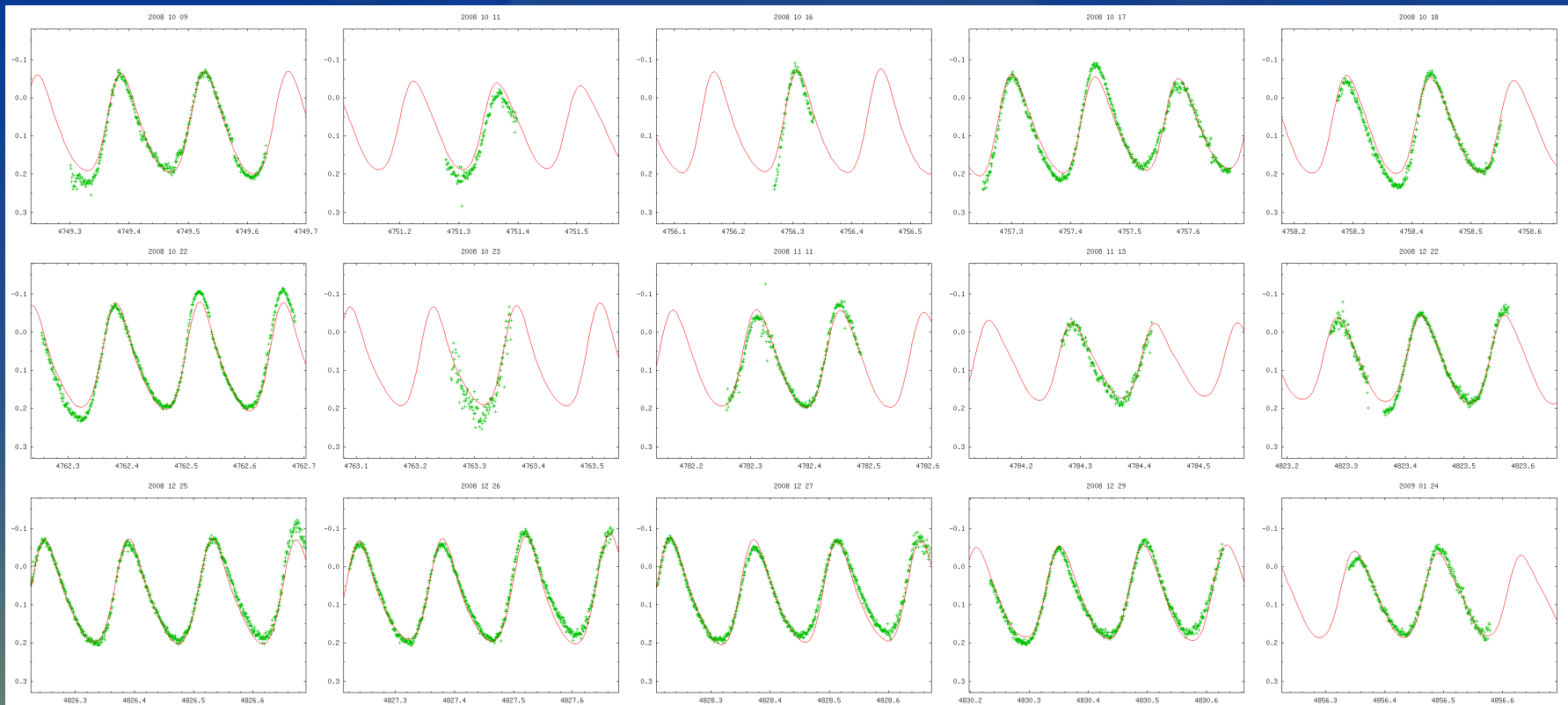


# Multiperiodicity: non-radial frequencies

- Small amplitudes compared to radial mode

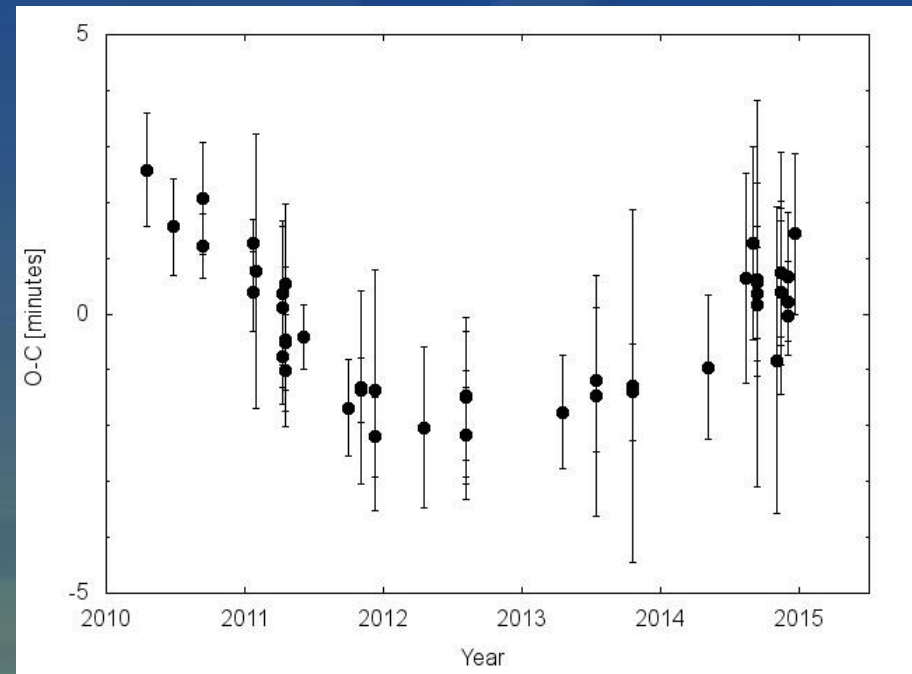
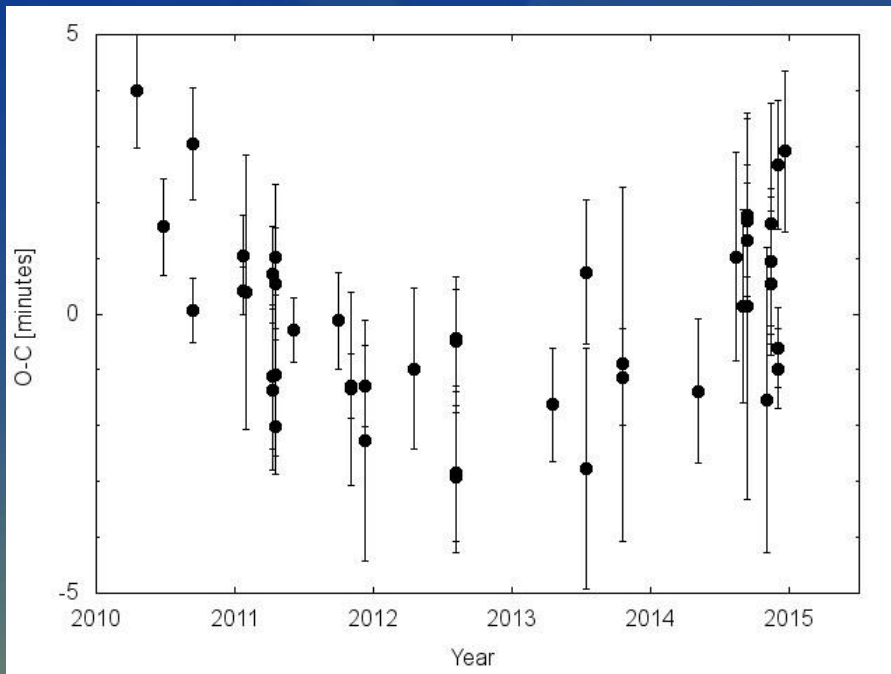


Animation: TOPS - Vienna



# Multiperiodicity: O-C

- Time of maximum depends on additional frequencies
- O-C method less accurate
- Phase corrections needed



## Conclusion

- Many HADS do not show period changes ( $\sim 10$  years)
  - No evidence for evolution yet
  - When changes are present, they are larger than expected
- A number of HADS show sudden period changes
  - More theoretical work needed
- At least 2 HADS reside in a binary (apart from SZ Lyn)
- $\sim 1$  in 4 HADS is multiperiodic
  - amplitude  $> 0.01$  mag
- $\sim 30$  observers from Argentina, Belgium, Finland, Germany, Greece, Spain, The Netherlands, UK, USA