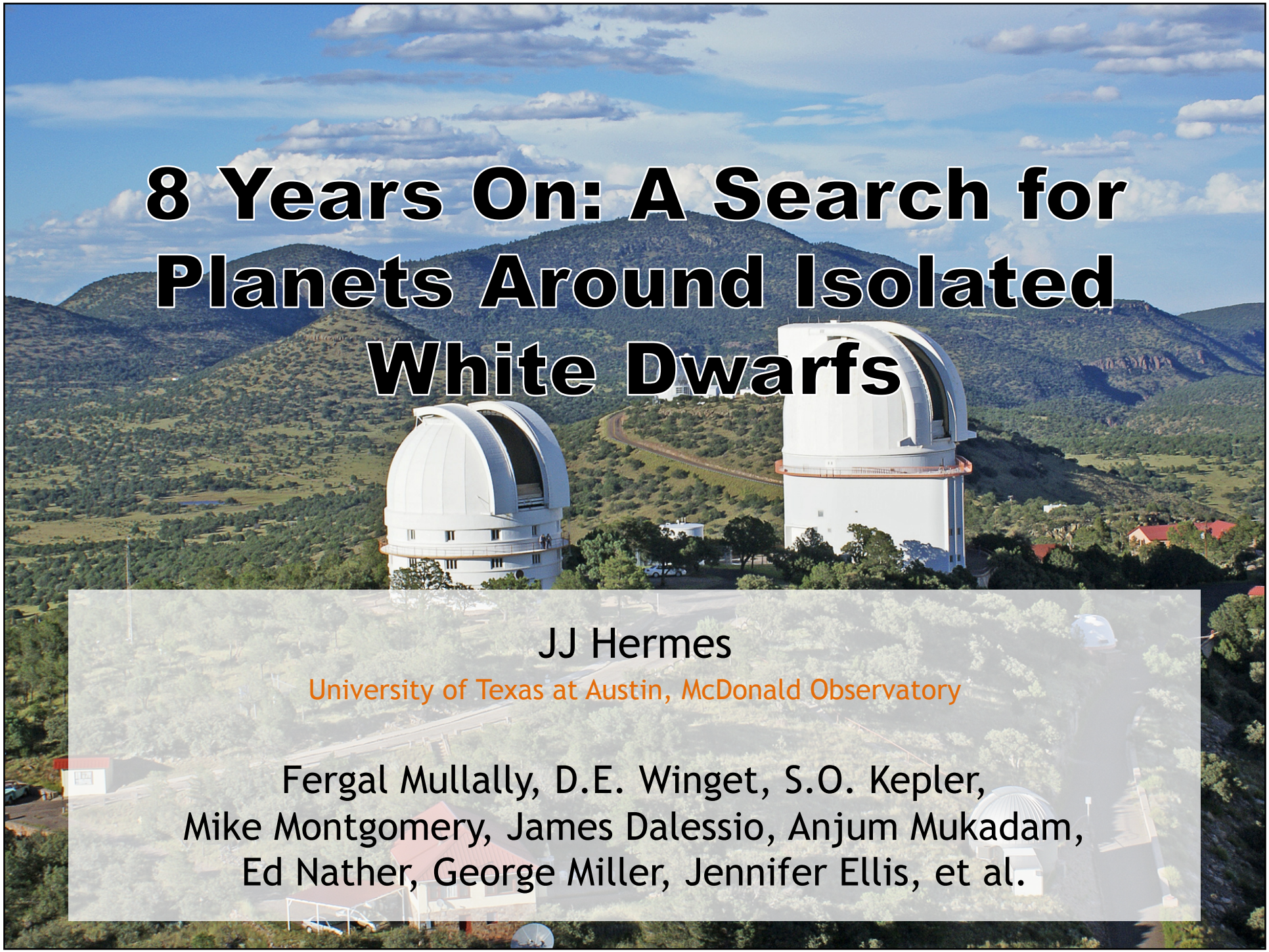


8 Years On: A Search for Planets Around Isolated White Dwarfs

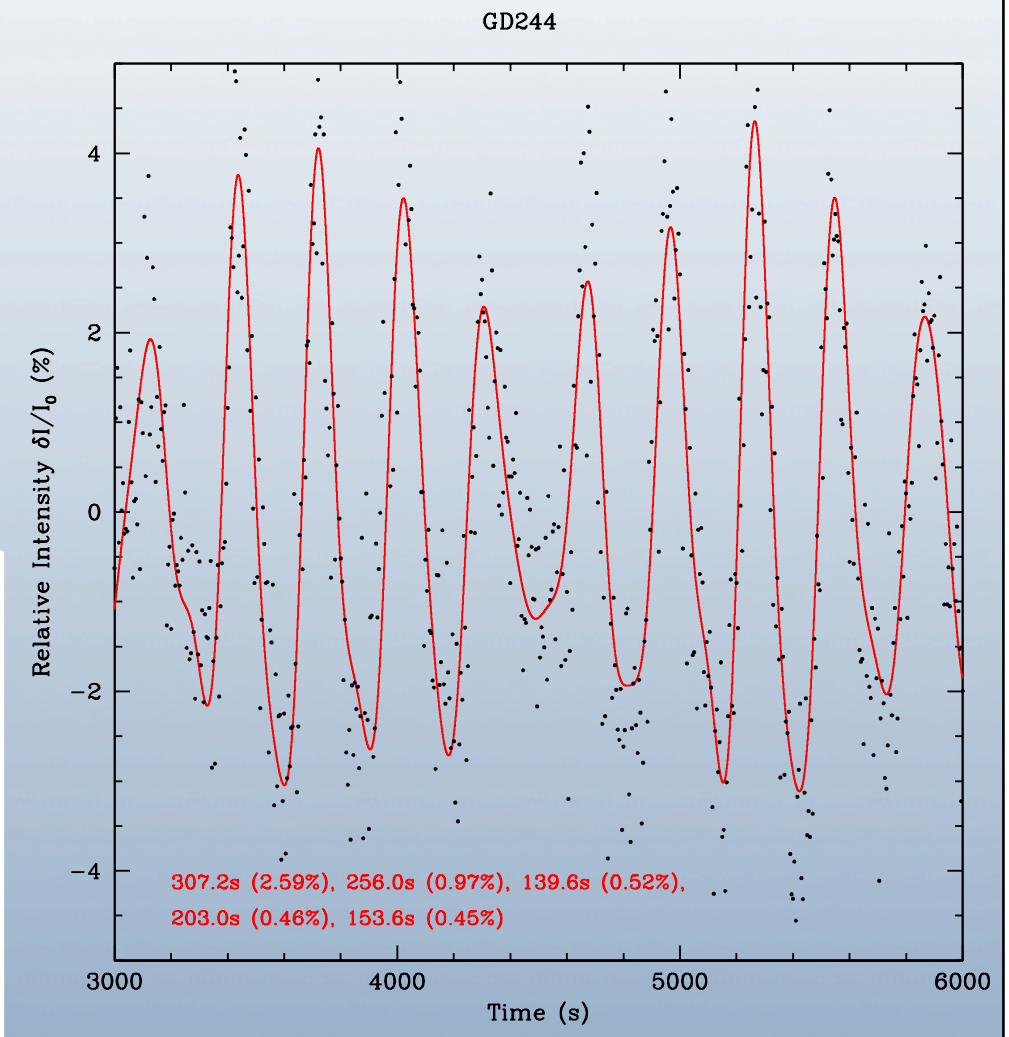
JJ Hermes

University of Texas at Austin, McDonald Observatory

Fergal Mullally, D.E. Winget, S.O. Kepler,
Mike Montgomery, James Dalessio, Anjum Mukadam,
Ed Nather, George Miller, Jennifer Ellis, et al.

The UT White Dwarf Pilot Planet Search

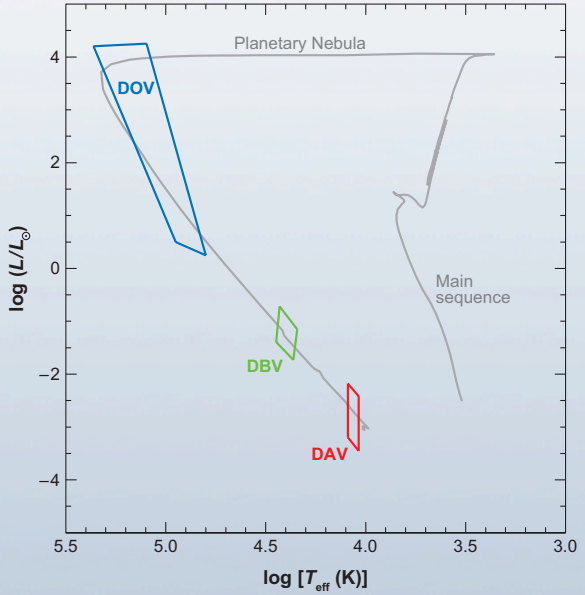
- Commissioned with the Argos instrument on the 2.1m Otto Struve Telescope in 2001
- Chose 15 pulsating white dwarf stars to monitor as stable clocks; watch pulse arrival times

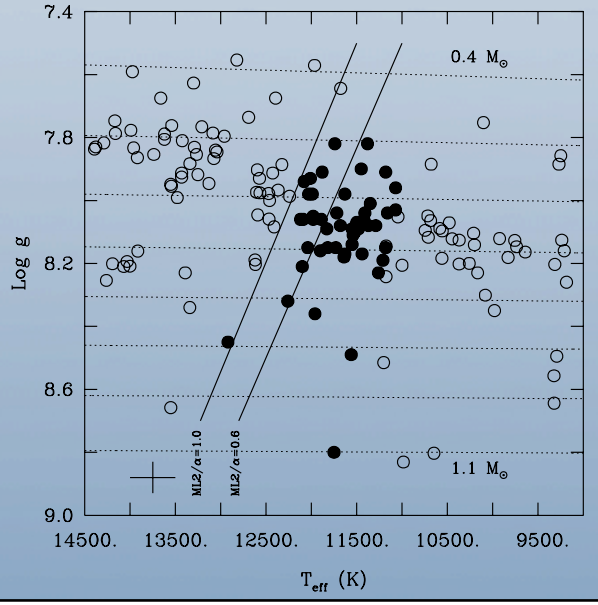


Mullally et al. 2008, ApJ **676** 573

DAVs: Variable, Hydrogen-Atmosphere WDs

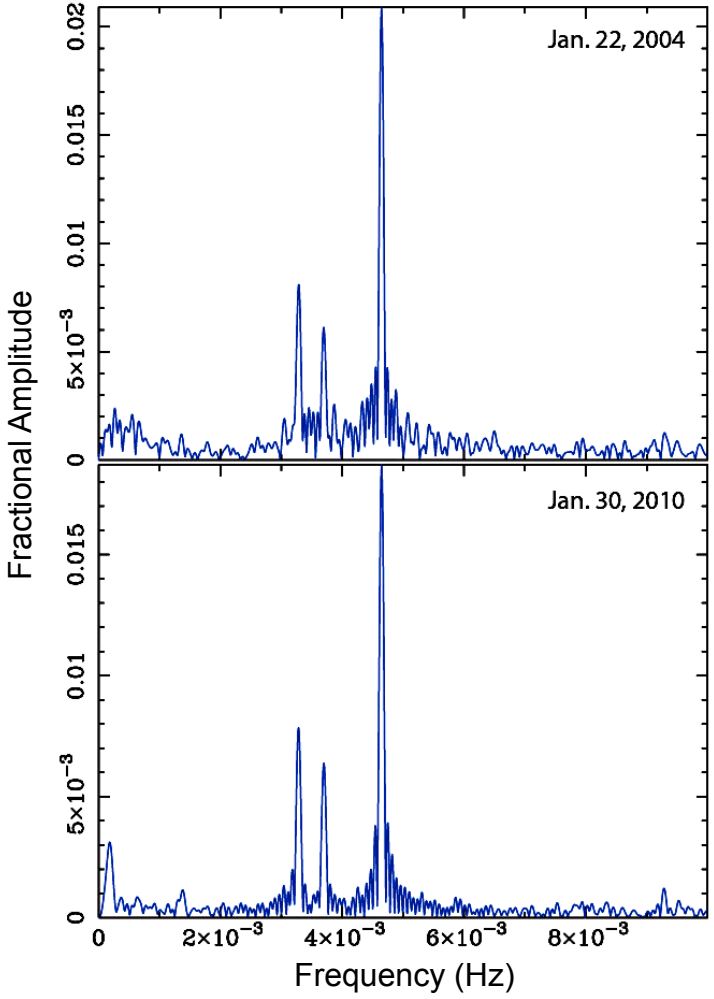
- About 98% of all stars in our Galaxy will become WDs
- Of those, the majority are DA (hydrogen)
- Pulsations are confined to instability strips: partial ionizations zones
  - Recombination → opacity
- Non-radial, *gravity*-modes
- Observed light variations are temperature variations (integrated over the disk)
- DAV instability strip is to date observationally pure
  - Most stars, including our Sun, will eventually pulsate as DAVs
  - See excellent reviews by Fontaine & Brassard 2008, PASP **120** 1043; Winget & Kepler 2008, Ann. Review **46** 157



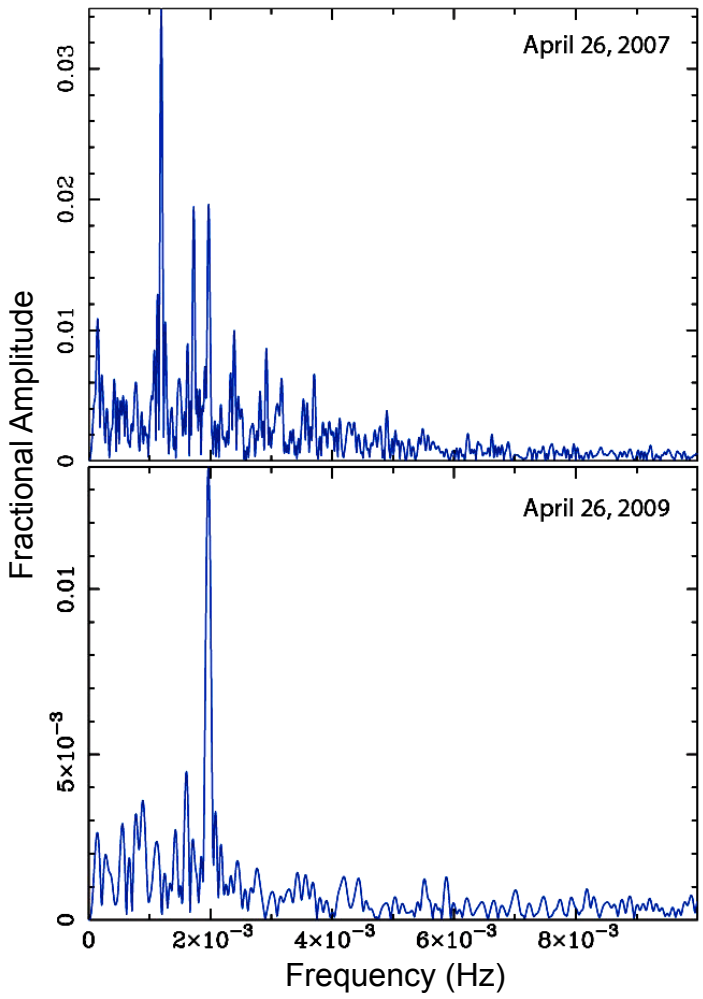


Hotter DAVs Exhibit Pulsation Stability

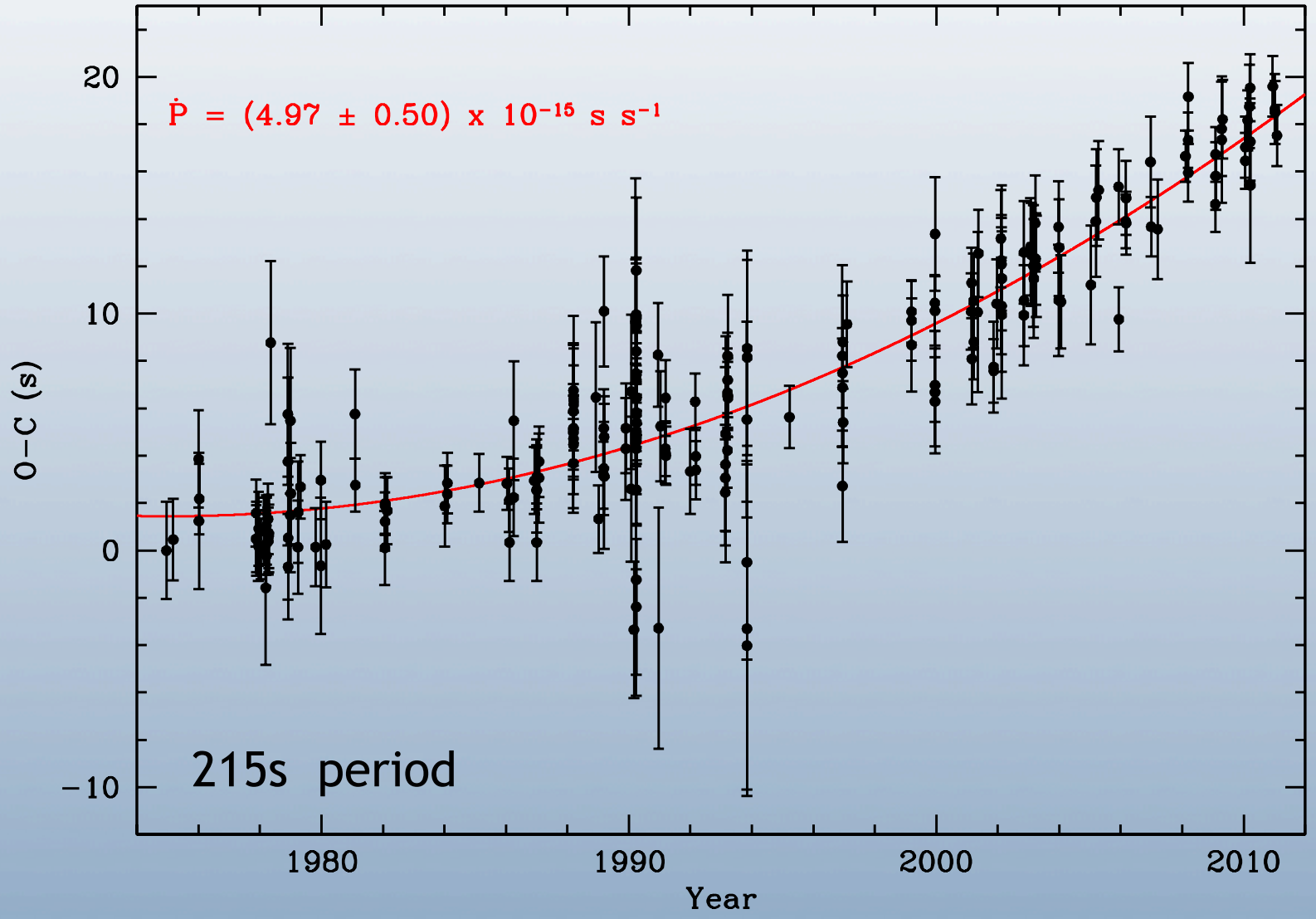
G117-B15A (hDAV, T_{eff} ~ 12kK)



WD1524-0030 (cDAV, ~ 11.6kK)



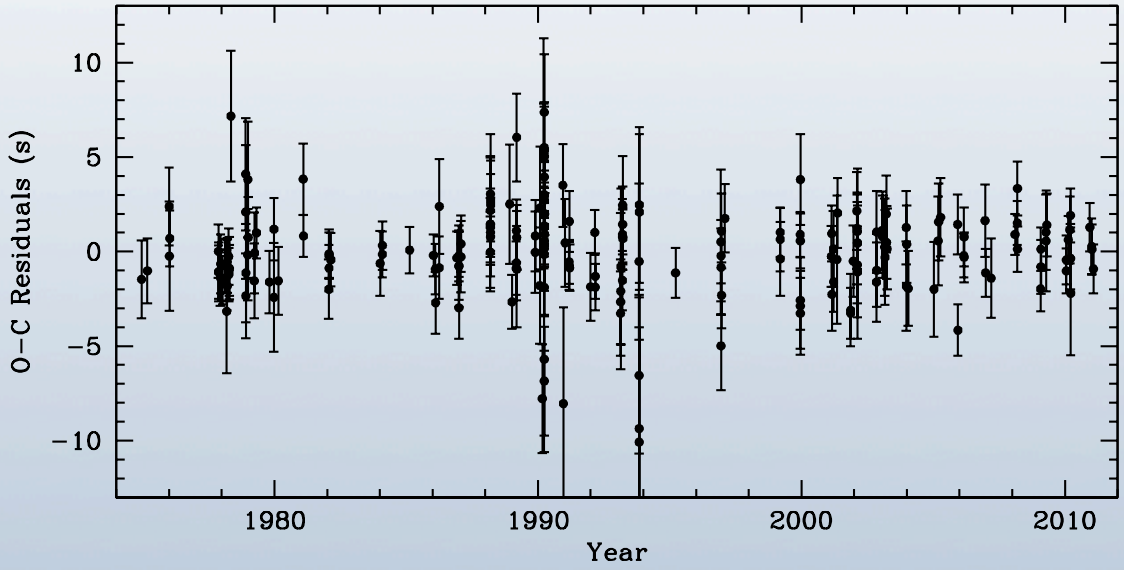
G117-B15A: An Extremely Stable Optical Clock

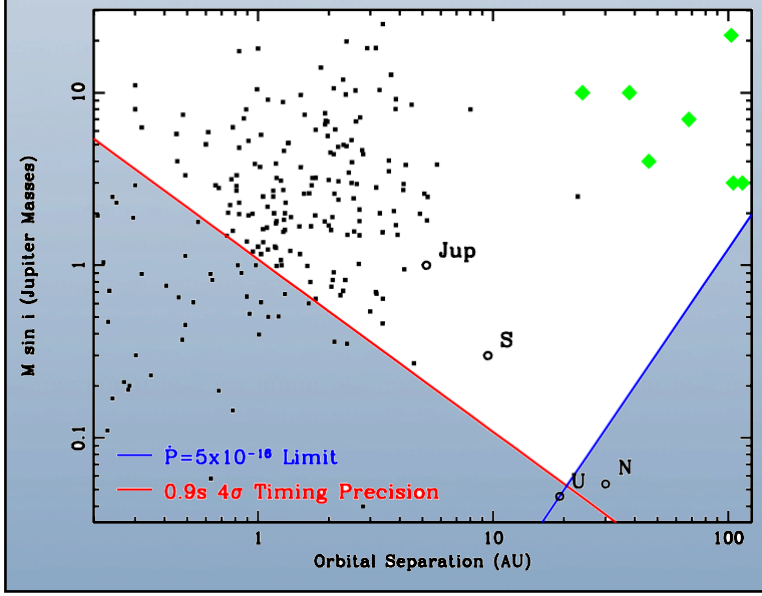


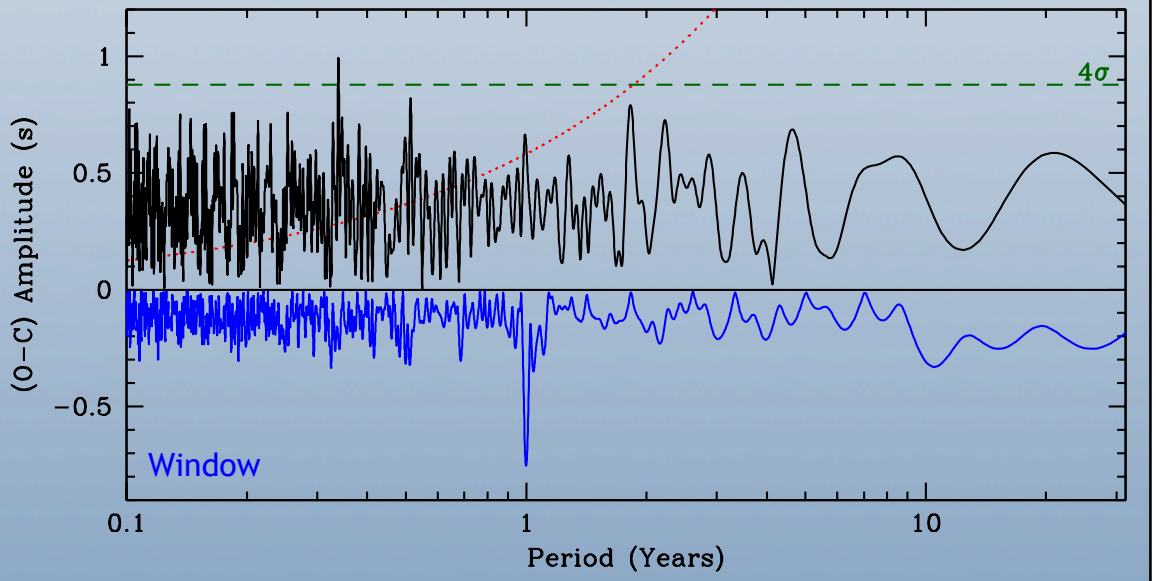
S.O. Kepler 2012, private communication

G117-B15A: An Extremely Stable Optical Clock

- We can remove the secular trend from cooling (and proper motion) and look for periodic modulation
- We are nearly able to exclude Uranus at Uranus distance

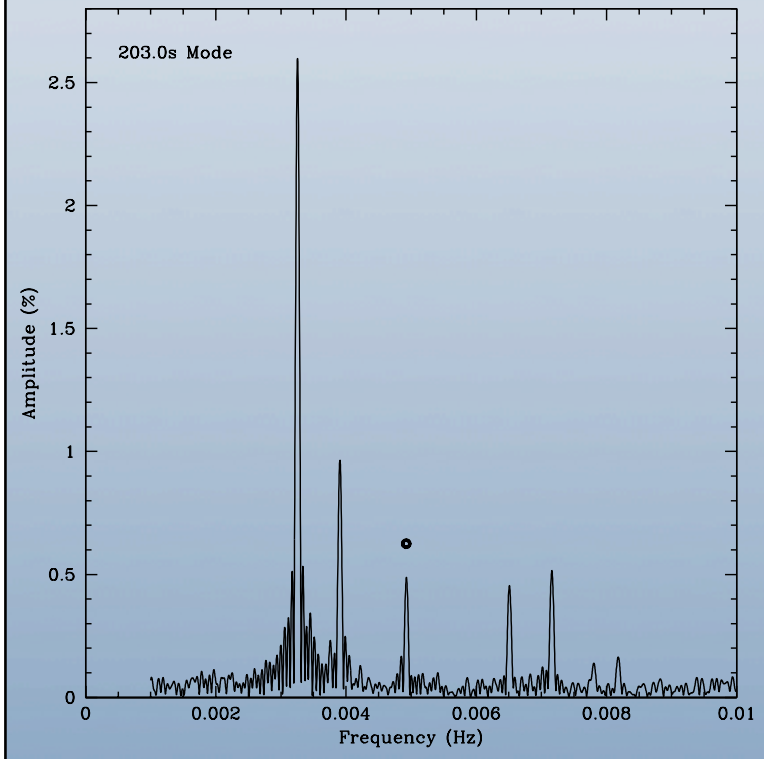


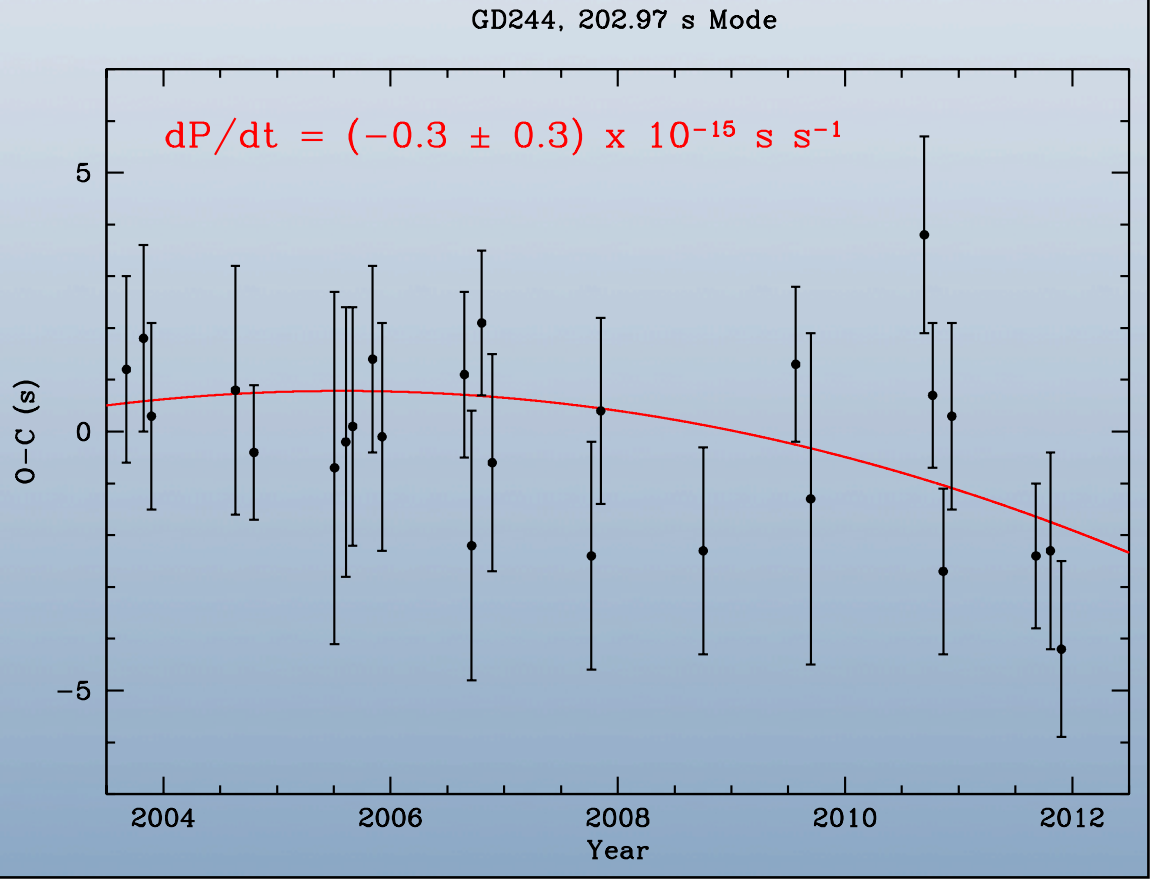




GD244: A Stable, G117-B15A Analogue

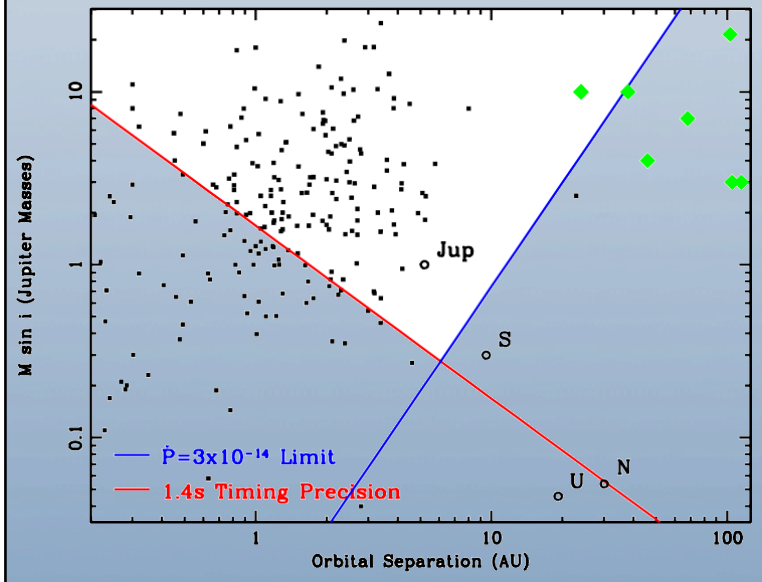
- GD244 behaves as we'd "expect" of a DAV in our sample
- The (O-C) diagram is consistent with flat after 8 years
- Only the 202.97s mode is stable enough for an (O-C) analysis, although this is work in progress

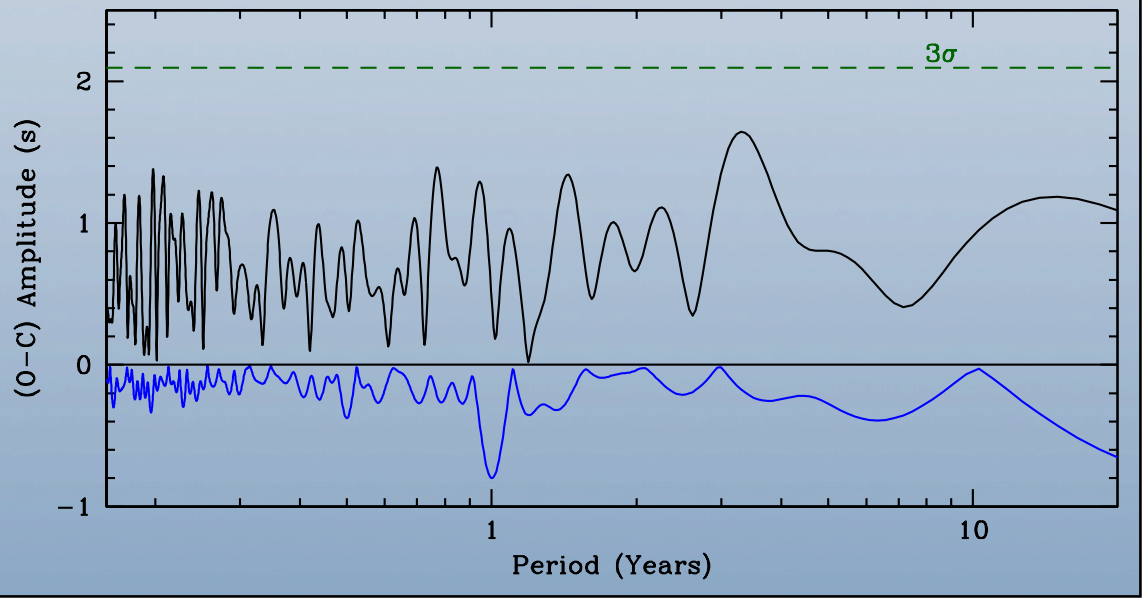




GD244: A Stable, G117-B15A Analogue

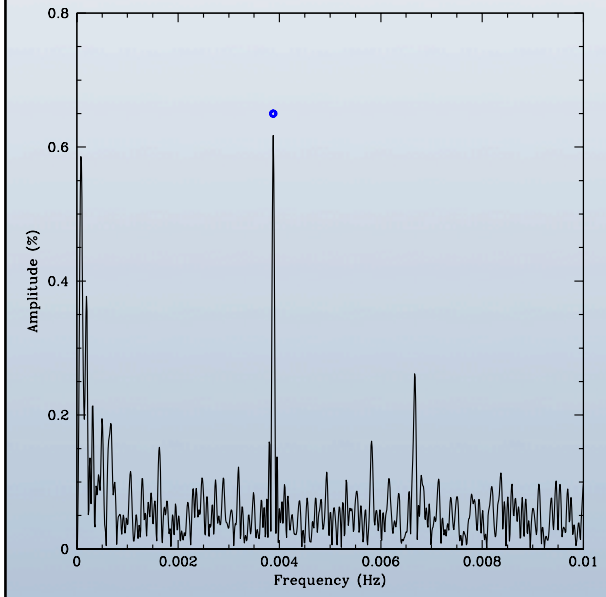
- Using this 202.97s mode we are able to rule out a Saturn-sized planet at Jupiter's orbit, and a Jupiter-mass planet out to 10 AU
- This 0.61(3) $M_\odot$ WD likely had a 1.85(32) $M_\odot$ progenitor (Mullally 2008)
  - We are reaching limits that exclude a $2M_J$ planet at Jupiter's distance, *accounting for* orbital expansion
  - Longer monitoring means measuring a *dP/dt* (sensitive to C/O core composition) and expanding this white region of planet search space

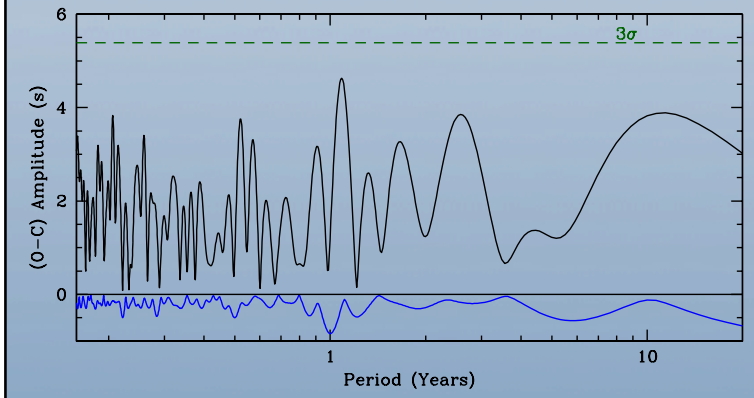


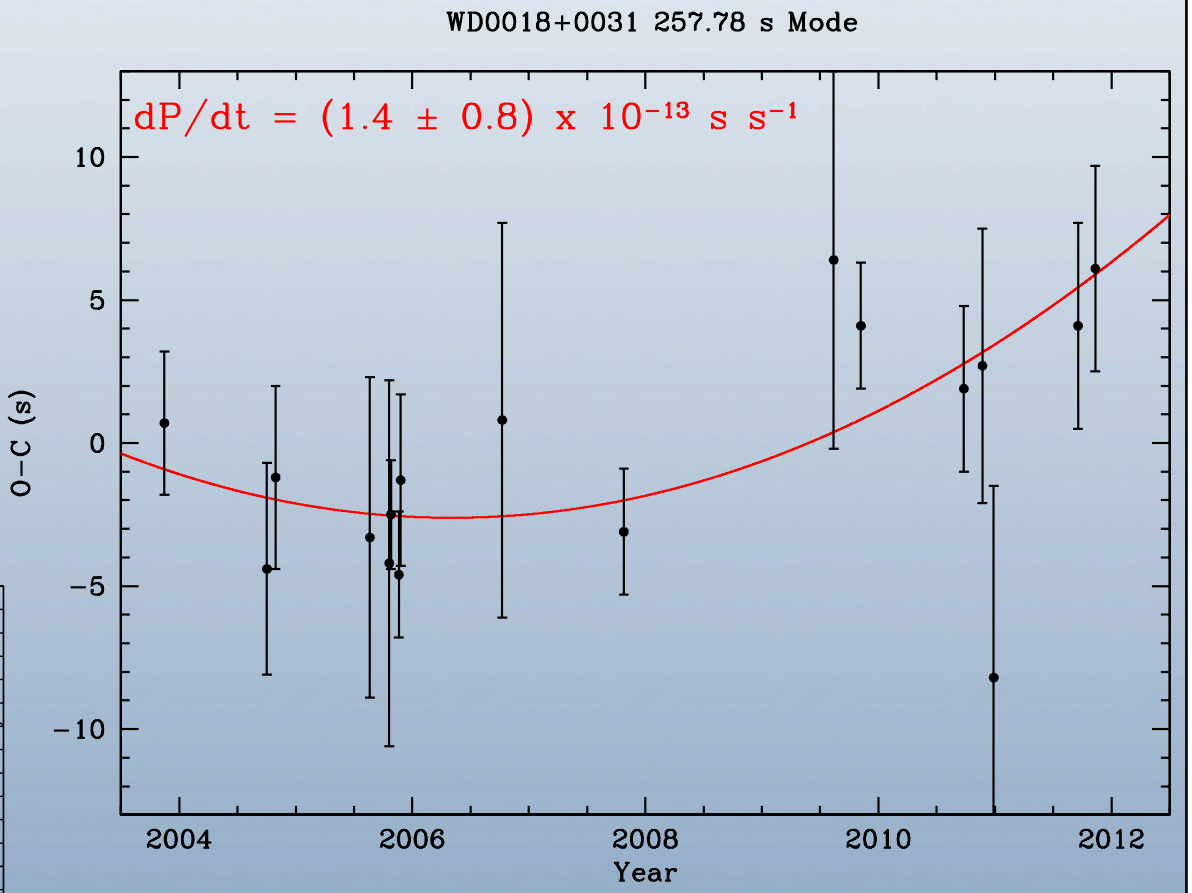


WD0018+0031: A Stable, Low-Amplitude Mode

- A diversion about sines and parabolas

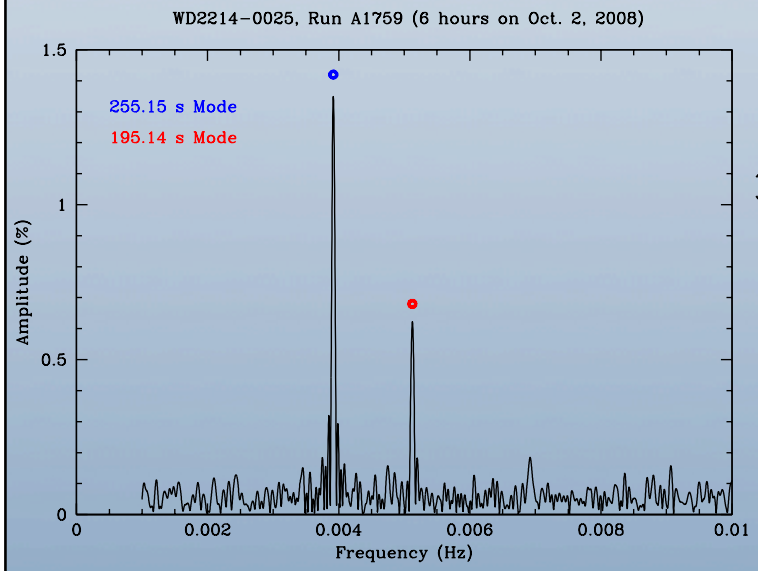


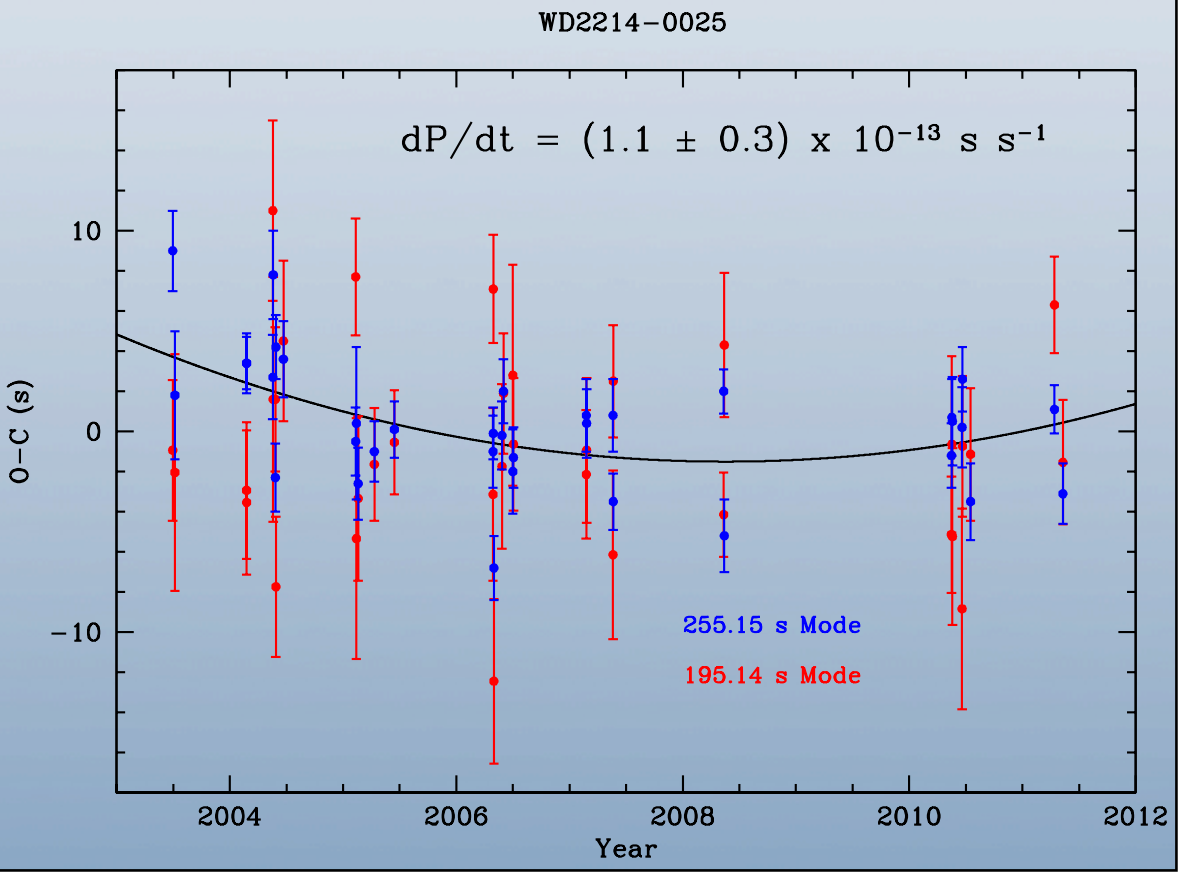




WD2214-0025: 2 Modes in Relative Lockstep

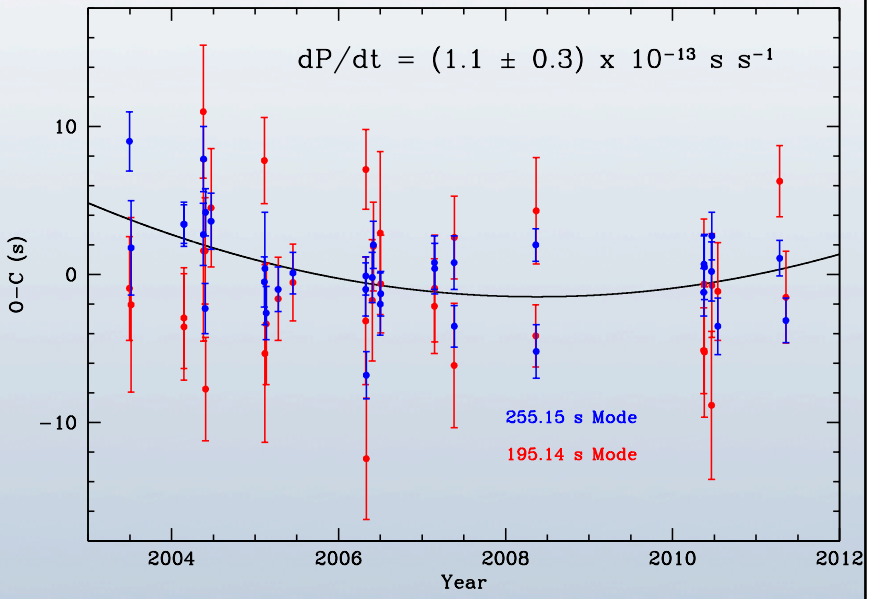
- Another “well-behaved” DAV in our sample, with two modes behaving in unison
- Here again, though, we are running up against a sine/parabola ambiguity

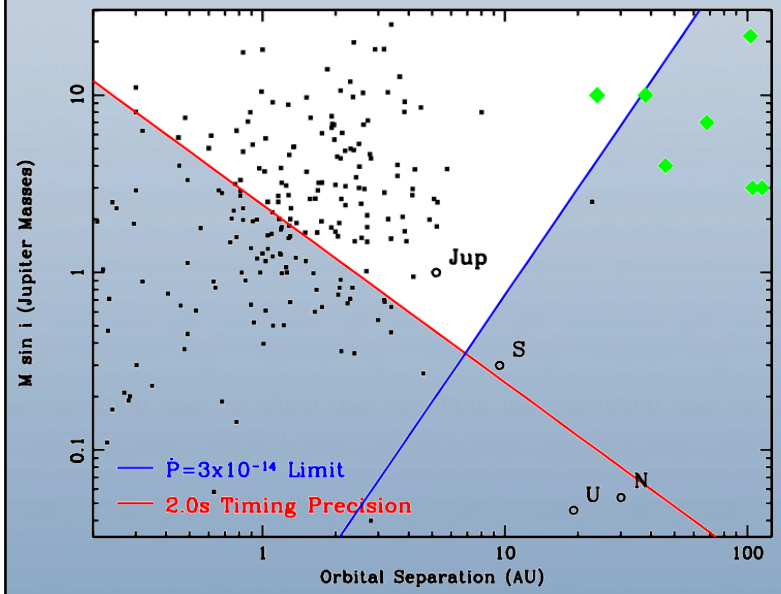


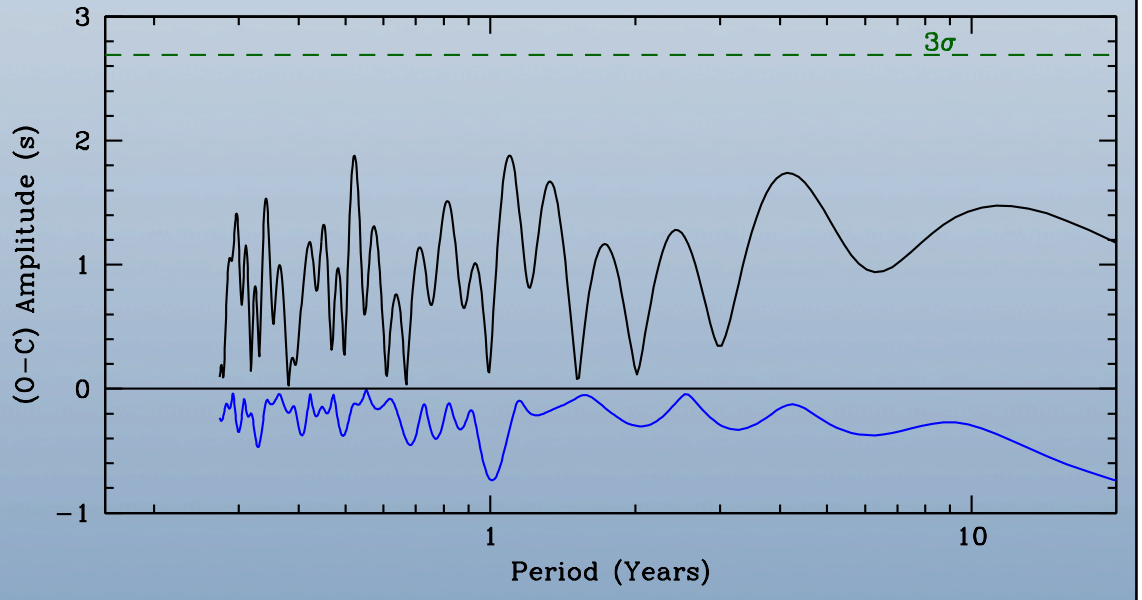


WD2214-0025: 2 Modes in Relative Lockstep

- Regardless, we are still putting stringent limits on the lack of a sub-stellar companion around this star throughout an extensive part of parameter space
- Perhaps, also, we are really measuring *dP/dt*

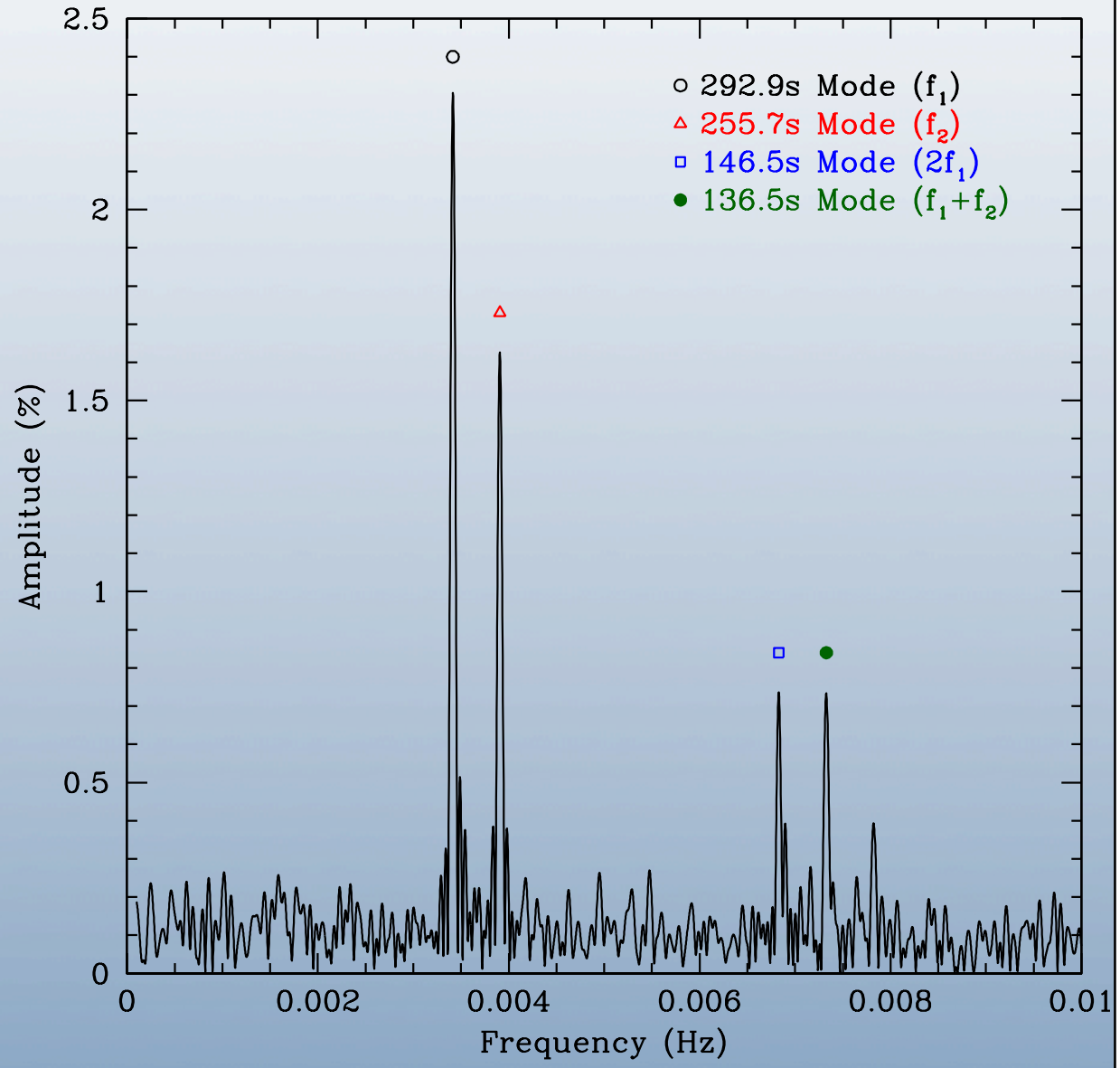




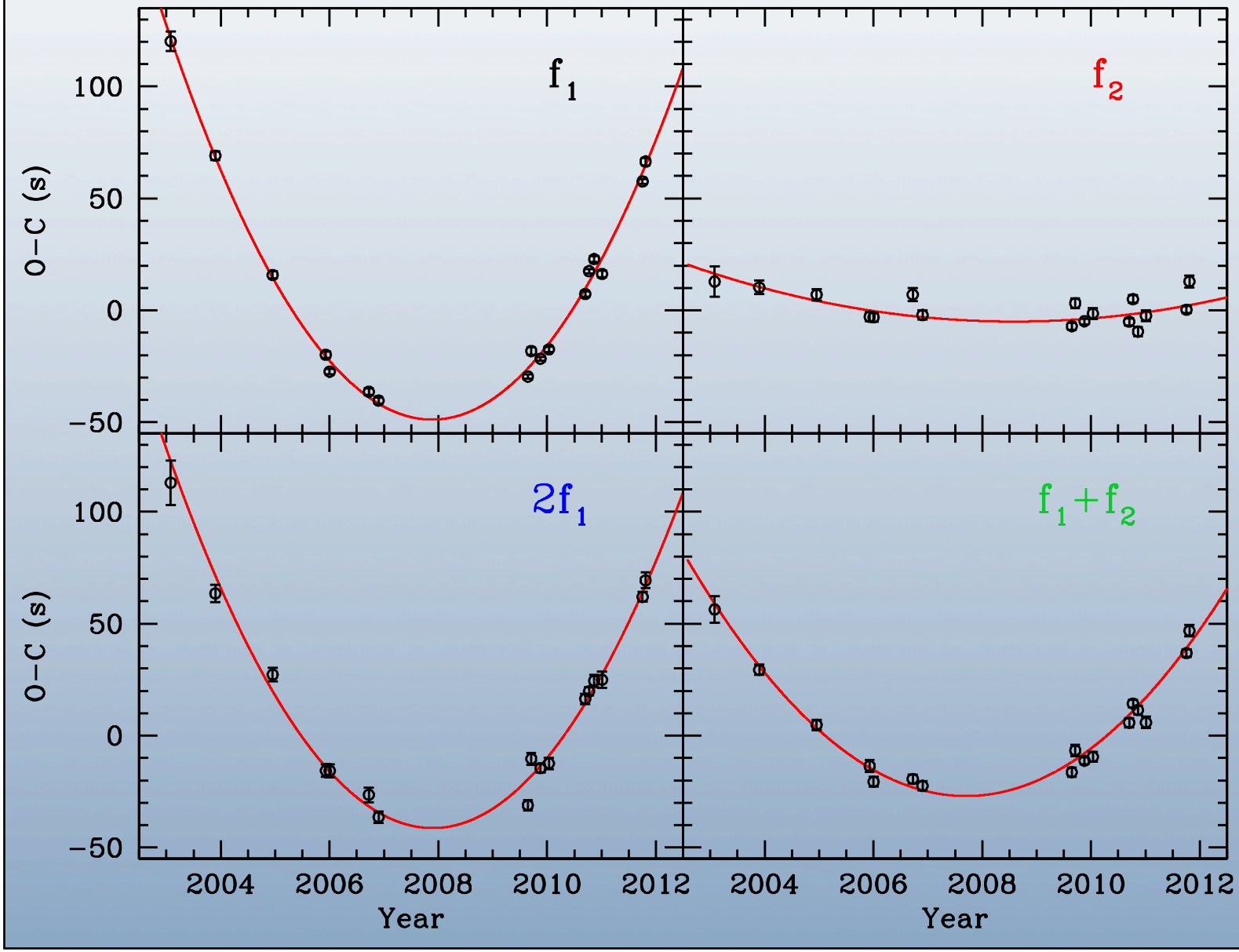


WD0111+0018: A New Timescale for *dP/dt*

- DA evolution should be simple, dictated by cooling
- Expected rate of ~ (2-9) x 10^{-15} s/s for all l,k (Bradley et al. 1992, ApJ **391** L33)
- The main mode in G117-B15A has us expecting all modes to behave this way
- However, the WDs have some surprises in store



Lesson 1: Not All DAVs Have $dP/dt \sim 10^{-15}$ s/s



dP/dt f_1 (s/s):
$(4.34 \pm 0.04) \times 10^{-12}$

dP/dt f_2 (s/s):
$(0.36 \pm 0.06) \times 10^{-12}$

dP/dt $2f_1$ (s/s):
$(2.08 \pm 0.04) \times 10^{-12}$

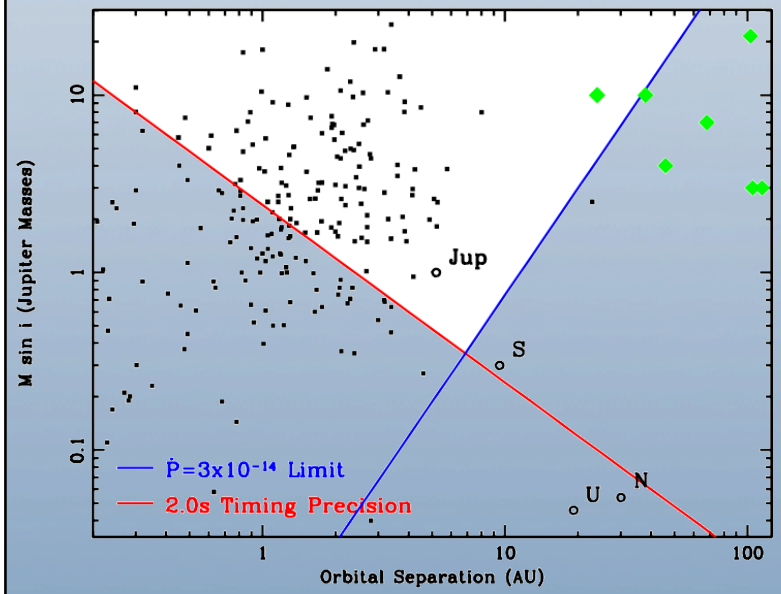
dP/dt f_1+f_2 (s/s):
$(1.10 \pm 0.03) \times 10^{-12}$

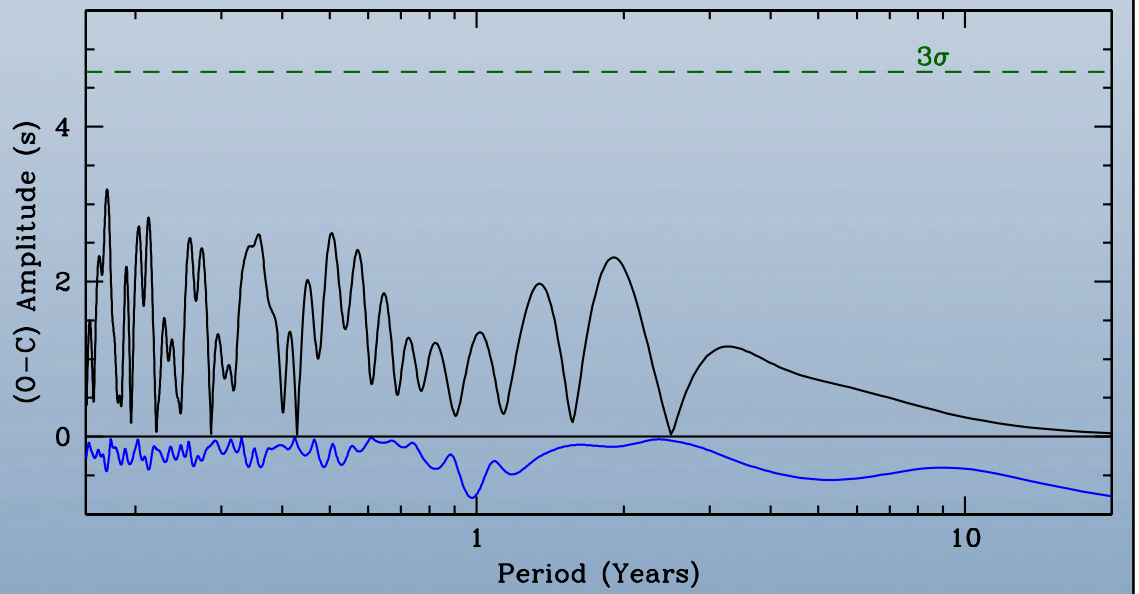
These are not 2σ detections!

This proves that these nonlinear combination freqs. are not independent modes but tied to their parent modes

WD0111+0018: A New Timescale for *dP/dt*

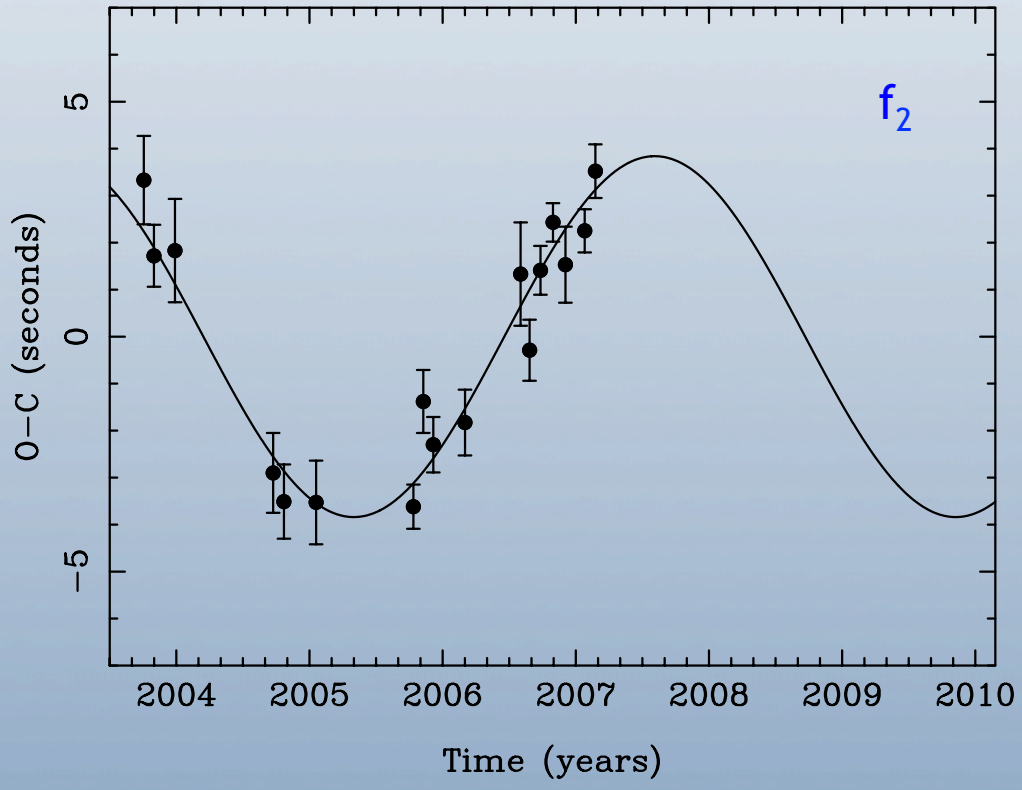
- The assumption that it will take 30 years to make a *dP/dt* detection (if *dP/dt* < 10^{-15} s/s) in a DAV is not universal
- This being a talk about our planet search, though, we can remove these large parabolas and search for periodicity in the four modes
- Again, we rule out Jupiter-mass planets over a wide range of possible orbits (at least 3-10 AU)





GD66: An Update on the "Candidate"

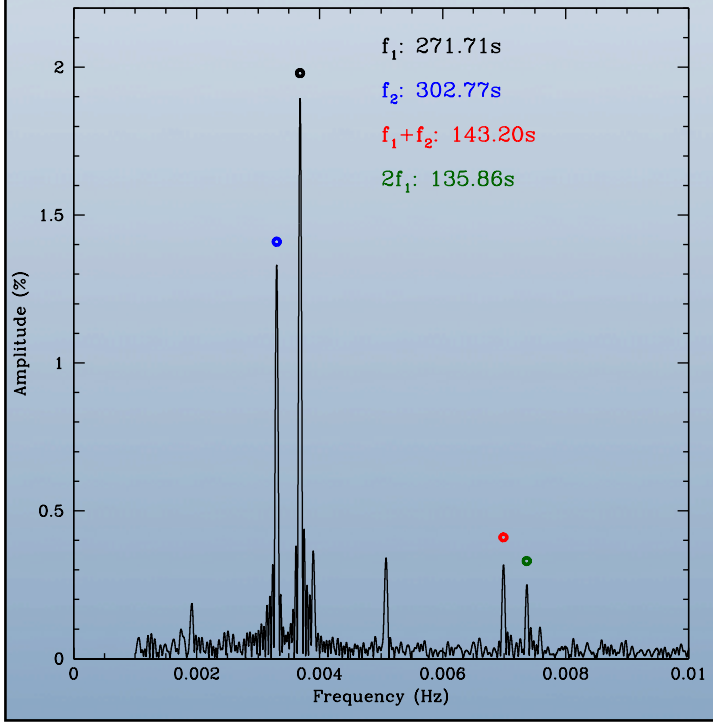
- The 302.77s mode showed evidence for periodic behavior, and a $2M_J$ planet in a 4.5-year orbit was posited
- 8 years on, how is "GD66b" looking?

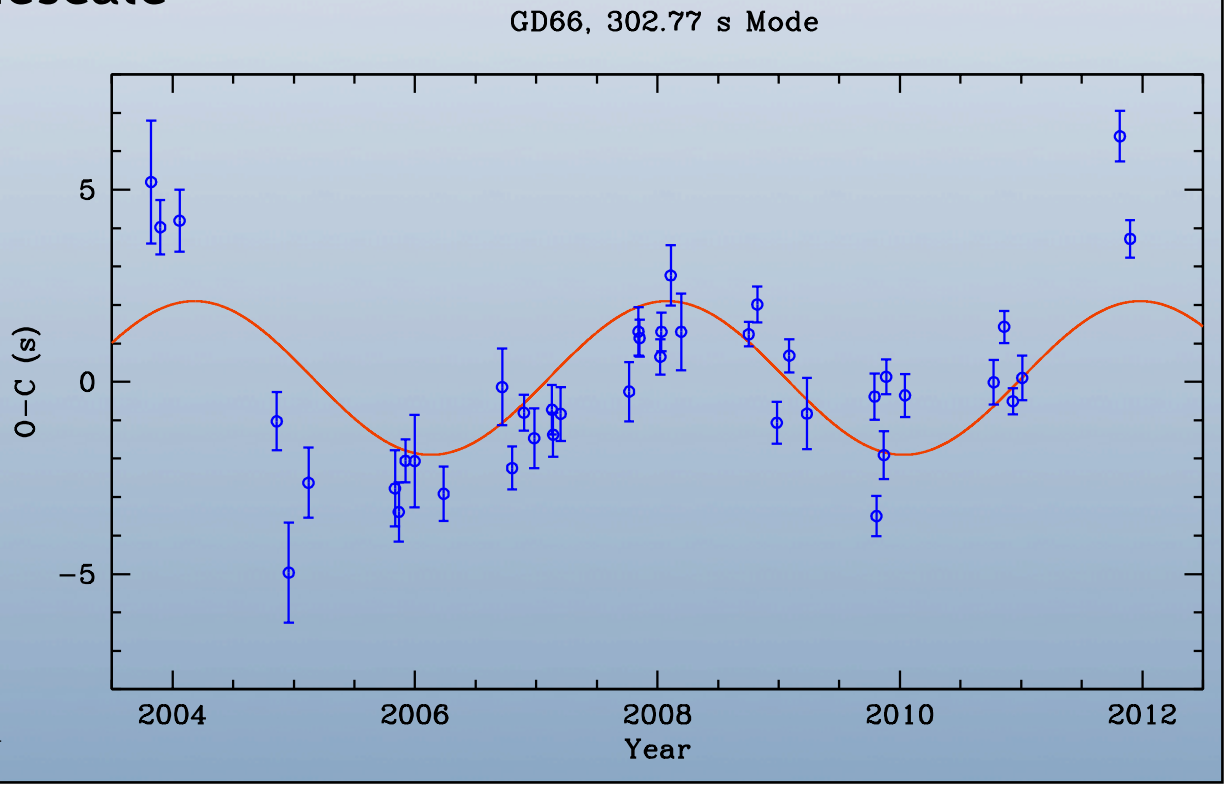


Mullally et al. 2008, ApJ 676 573

GD66: An Update on the "Candidate"

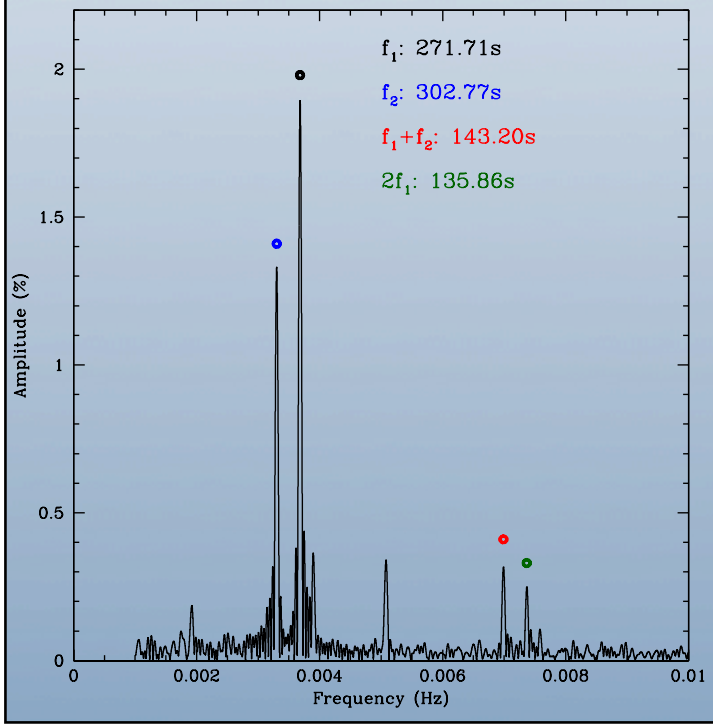
- As "expected" the (O-C) diagram for f_2 has turned over, and there is clearly a periodic modulation to the phase of this mode
  - The period, P_0, has been refined slightly, which mimics a linear trend
- This modulation is currently consistent with a 1.2(2) M_J sin *i* planet at 2.2 AU (4.0(3) yr); there is no amplitude modulation, especially on this timescale

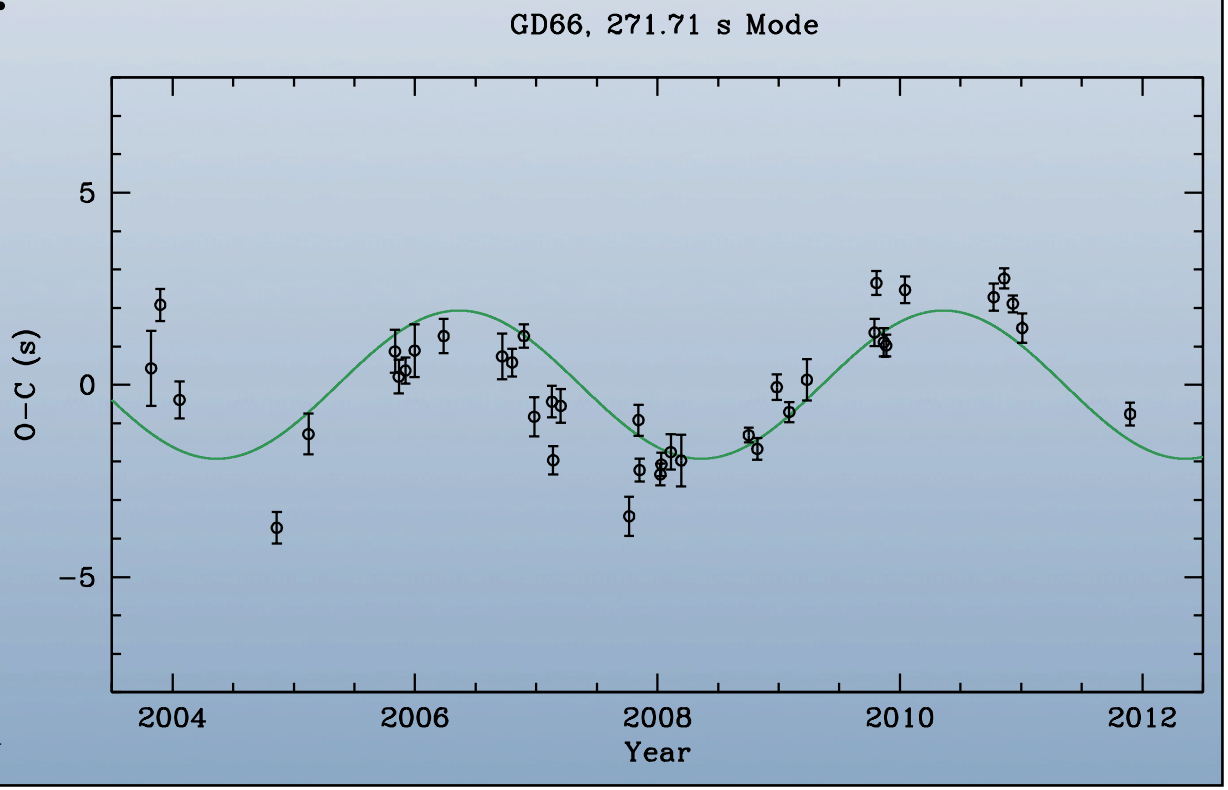




GD66: An Update on the "Candidate"

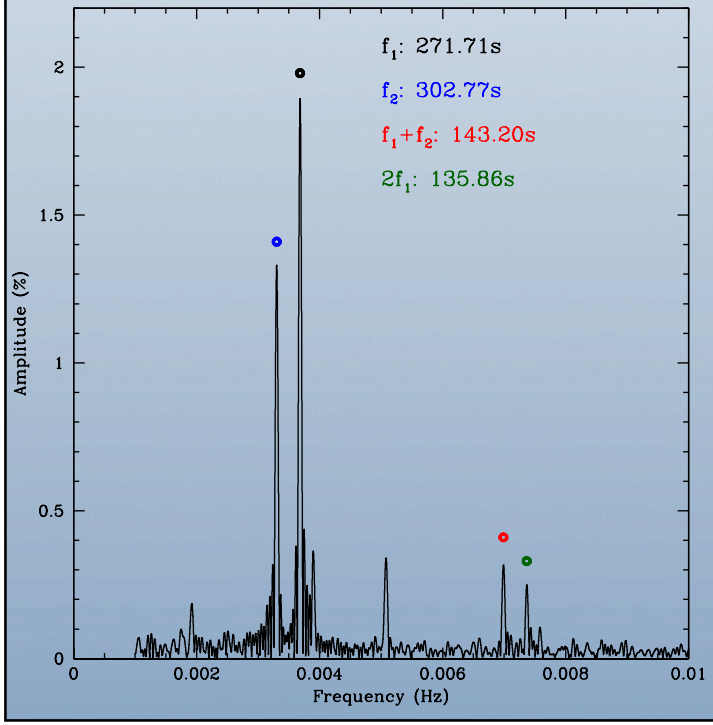
- We have been able to construct an (O-C) diagram for the highest-amplitude mode at 271.71s, which is the m=0 component of a detected triplet (we simultaneously fit all 3 peaks, using several nights of data such that each is >1 mma)
- This mode also shows a 3.9(2) year modulation consistent with a 1.3(2) M_J sin *i* planet!

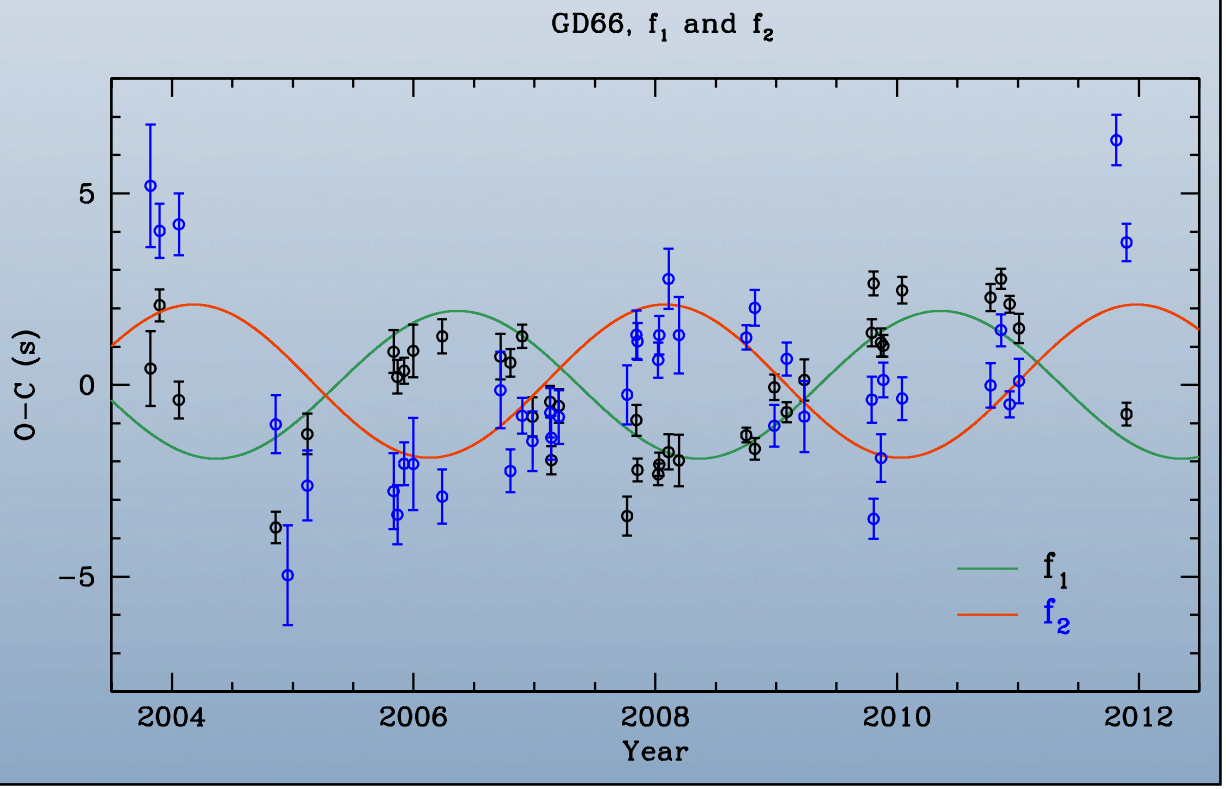




GD66: A Complication to the "Candidate"

- Uh oh: The best-fit sine curves to f_1 and f_2 are π out of phase
- An external companion would modulate all modes *identically*
- While discouraging for the planetary hypothesis, this is likely telling us something very interesting about the star. But what?!



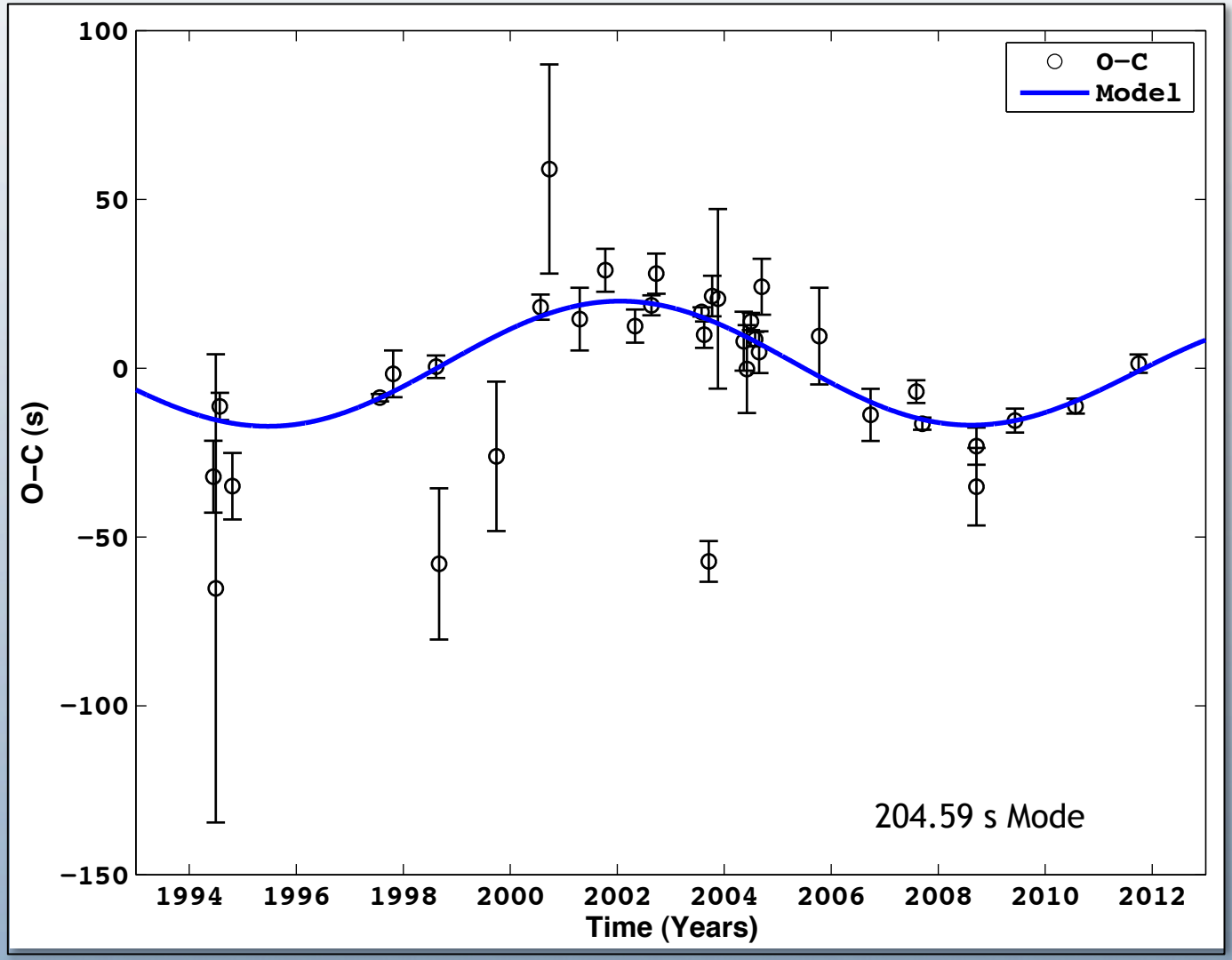


Lesson 2: Planets Are One Way to Modulate an O-C

- Our planet search has vastly expanded the number of stars with data sets long and dense enough to probe these timescales
- GD66 yields empirical evidence that there may be internal effects acting to cause a periodic signal in an (O-C) diagram
  - We don't yet have a model to explain GD66, but it certainly establishes the need to observe *identical* periodic behavior in more than one mode before claiming a planet around a pulsating star (perhaps even sdBs)
  - Repeat refrain: Planets are but one explanation
- GD66 is not the only pulsating white dwarf that shows such behavior over similar timescales:
  - James Dalessio (U. Delaware) has observed a similar effect in a DBV (He atmosphere), EC20058-5234

EC20058-5234: The GD66 DBV Analogue

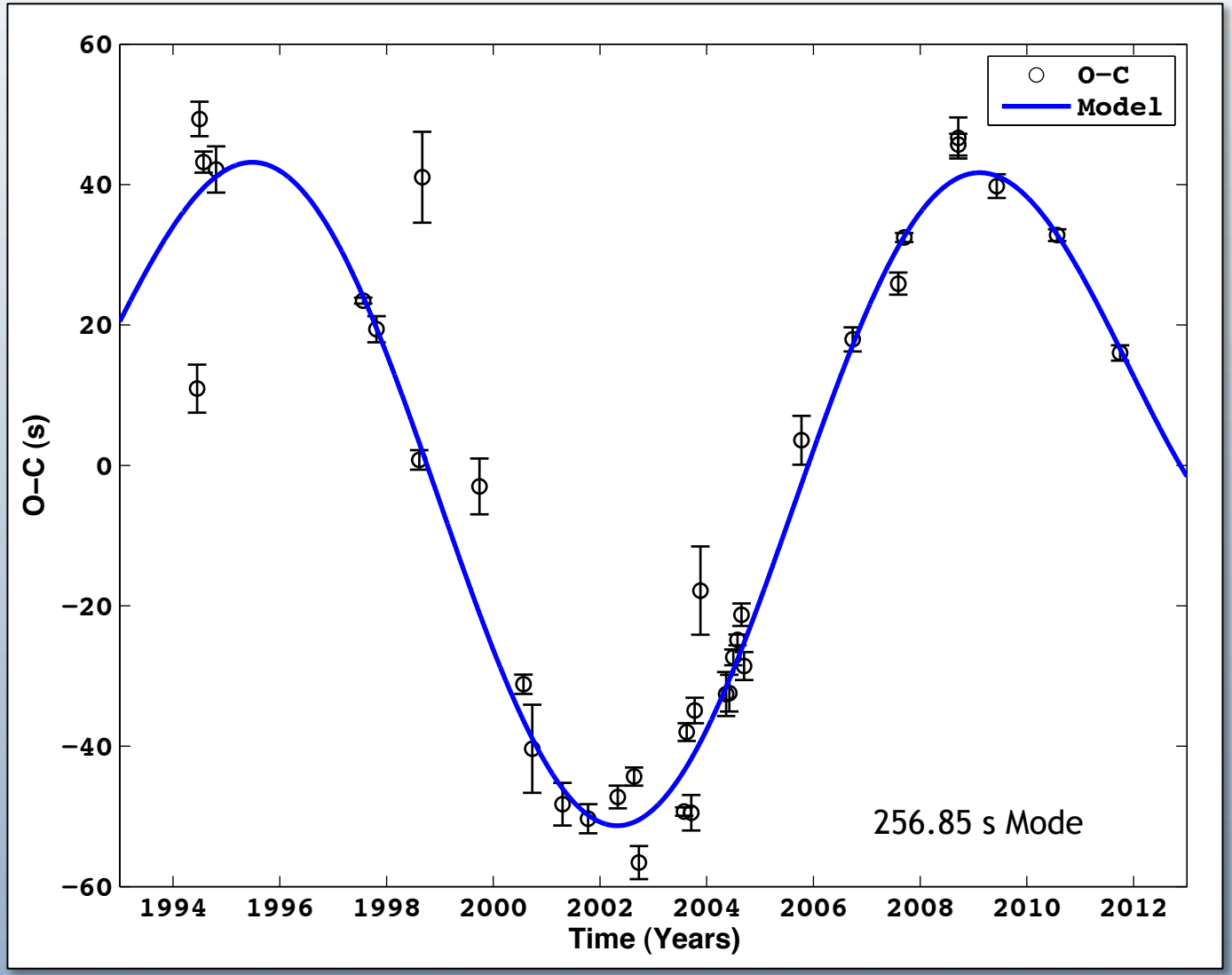
- But the (O-C) diagrams are hardly simple parabolas from cooling
- Here is f_{10}
- Taken alone, we might get excited for the planet hypothesis



Dalessio et al. 2012, in prep.

EC20058-5234: The GD66 DBV Analogue

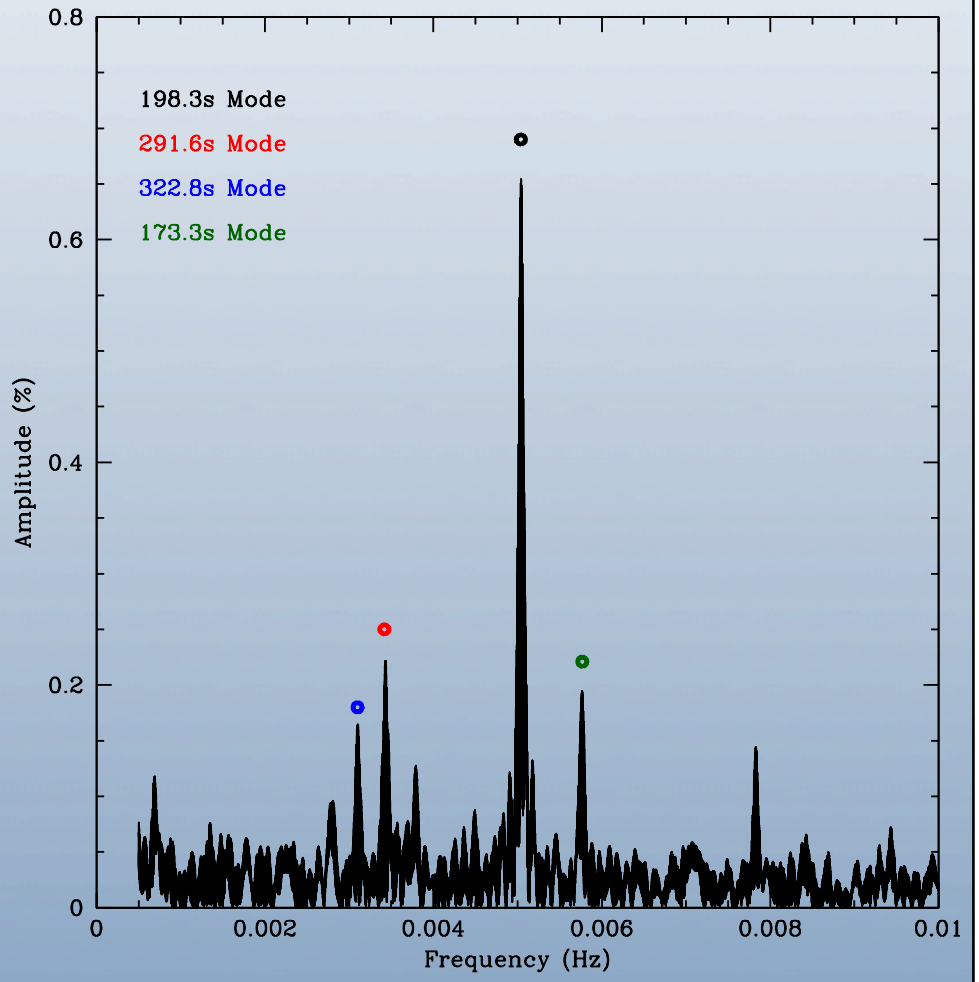
- But f_8 provides a sobering sight
- Again, the fit is π out of phase



Dalessio et al. 2012, in prep.

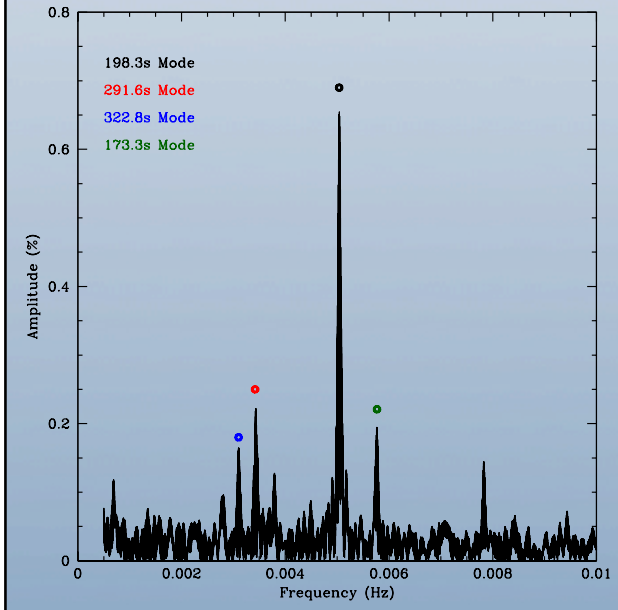
WD1354+0108: A New Hope

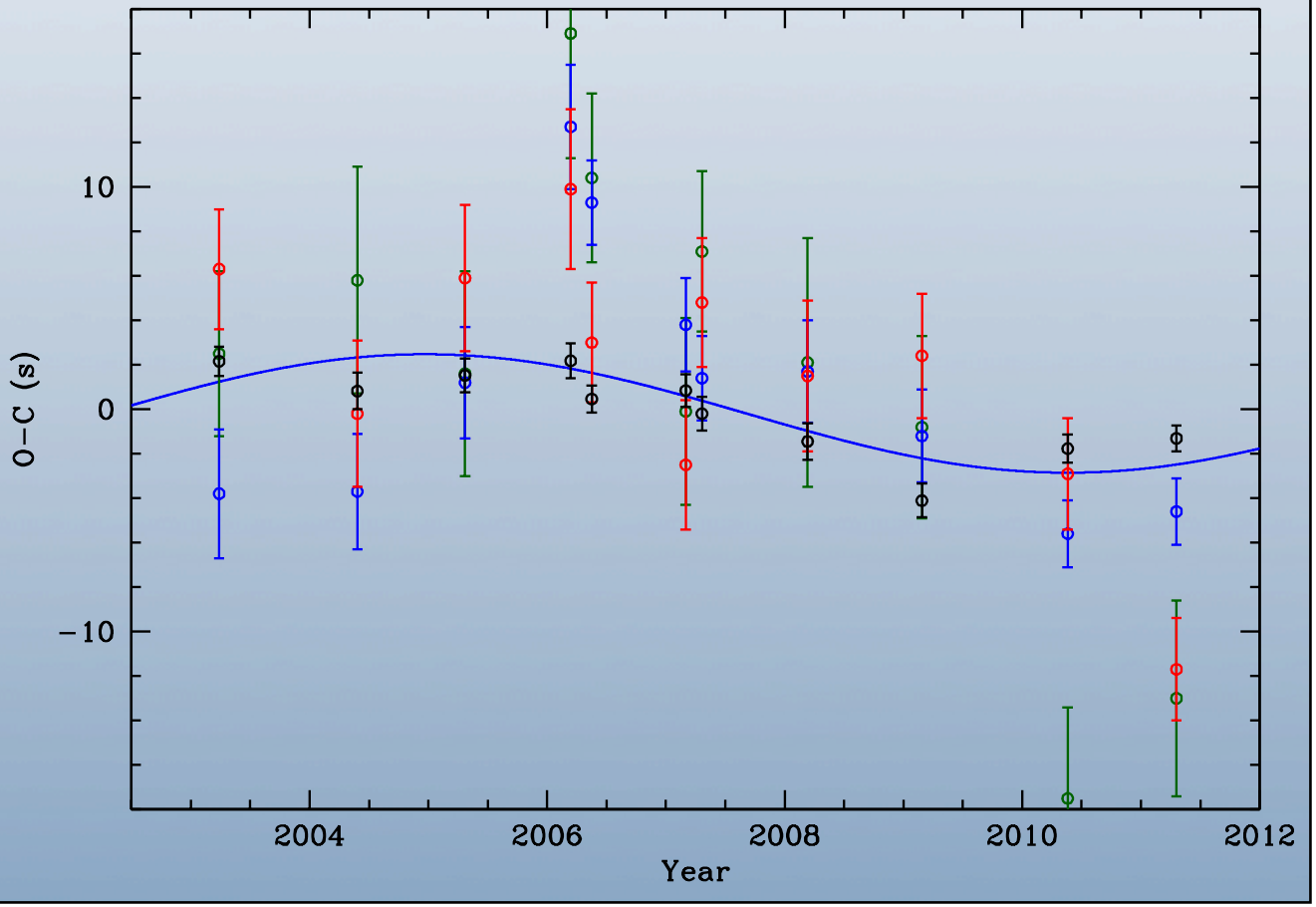
- Despite the complications with GD66 and EC20058, let's not be wet blankets by constantly rejecting the planet hypothesis
- Did all of the progenitors to the WDs in our sample lack >1M_J planets inside 3 AU?
- We have found an interesting behavior in this relatively bright (V=16.4) DAV
- The pulsation spectrum has several low-amplitude modes, four of which can be used to construct a stable (O-C) diagram
- The four modes act in relative lockstep



WD1354+0108: 4 Modes in Relative Lockstep

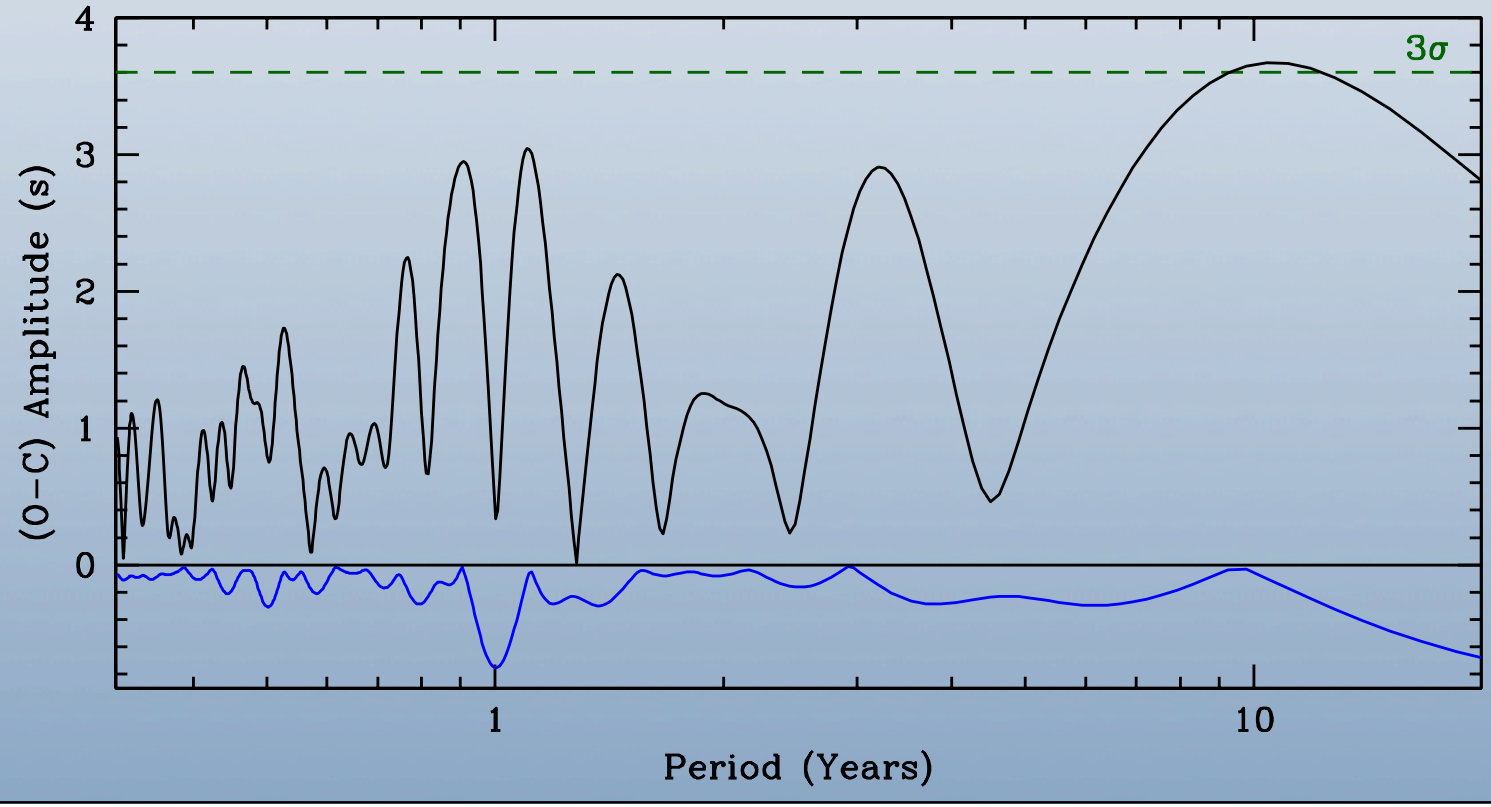
- That trend appears sinusoidal, with an 10.8(1.5)-yr period
- Such a modulation would be consistent with a 0.8(2) M_J sin *i* planet at 4.1(4) AU
- Quick: We need a Wikipedia entry!





WD1354+0108: 4 Modes in Relative Lockstep

- We are nearing coverage of a full cycle, by 2014
- Our weighted Lomb-Scargle periodogram peaks for 10.8 years above 3 times the average amplitude: significant?

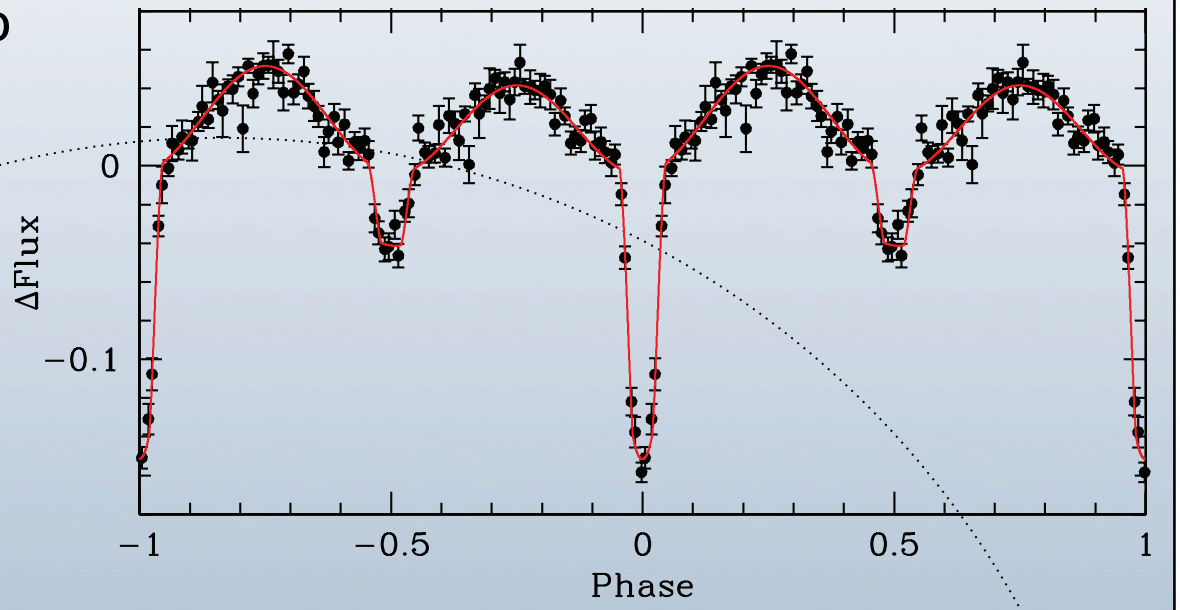


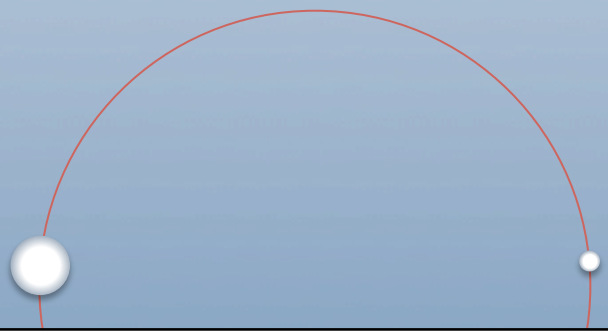
Conclusions and Future Prospects

- We have empirical evidence that two assumptions we had going into this planet search don't always hold:
  - 1. Not every DAV has a $dP/dt < 10^{-15}$ s/s
    - WD0111+0018 (Hermes et al. 2012, *in prep*) is proof positive that dP/dt can exceed 10^{-13} s/s
  - 2. The planetary hypothesis is not the only explanation for a periodic signal in a pulsating WD (O-C) diagram
    - GD66 (a DAV) and EC20058 (a DBV) both show periodic phase changes, but not all modes are in phase with one another
- Still, we have continued our search for sub-stellar companions to pulsating DA white dwarfs, extending our baseline 8+ years
  - G117-B15A has a 35+ year baseline, with no clear evidence of a companion
- Perhaps this search will yield useful *exclusion* statistics: We can currently exclude $>1M_J$ companions out to 9 AU for 12/13 DAVs
- We have focused our search sample to accommodate some exciting new science, which may also be used to put limits on planets around WDs...

J0651+2844: A 12.75-min Detached Binary

- 0.25 $M_\odot$ WD + 0.55 $M_\odot$ WD
- The systems is inclined to show primary and secondary eclipses
- We are currently (as in, tonight!) observing this system to construct an (O-C) diagram of mid-eclipse times, starting from April 2011
- $dP/dt_{orbit} < -8 \times 10^{-12}$ s/s
  - These WDs are **strongly** emitting gravitational radiation
- We get out a planet search for free!





Brown et al. 2011, ApJL 737 L23