Old stars with good tickers: are the beating hearts of white dwarfs regular enough for planet detection?

Steve Kawaler, Iowa State University

Planet-Star Connections in the Era of TESS and Gaia

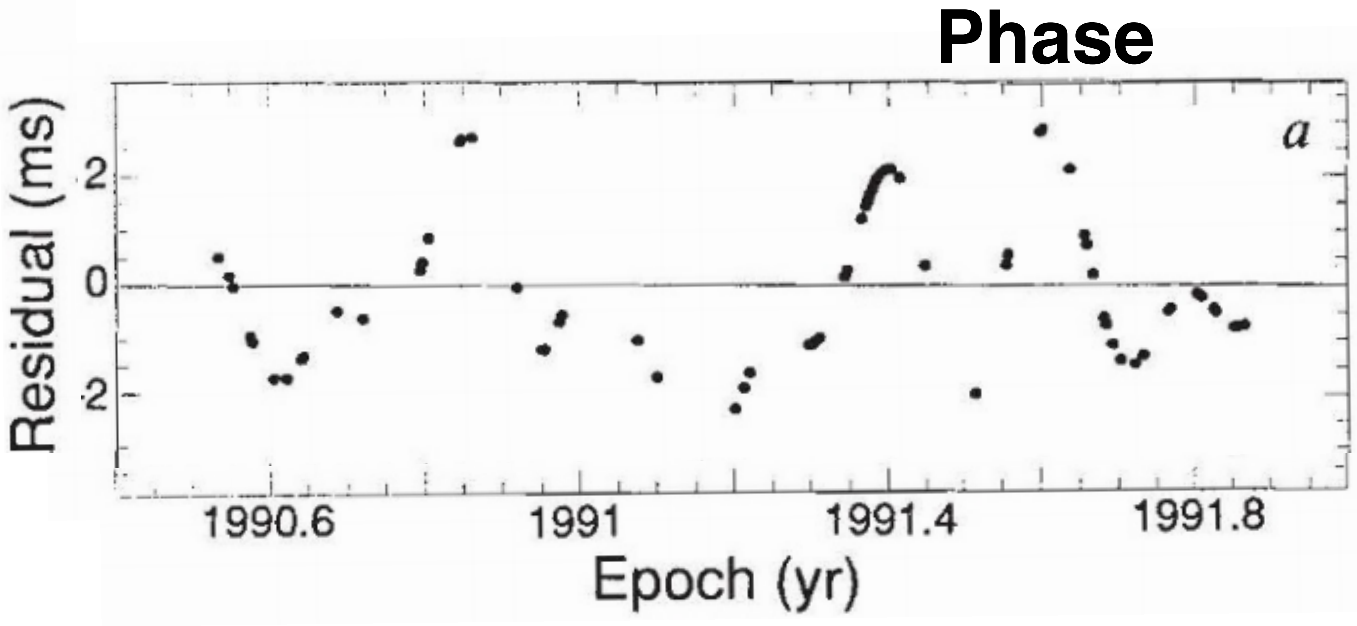
THANK YOU:

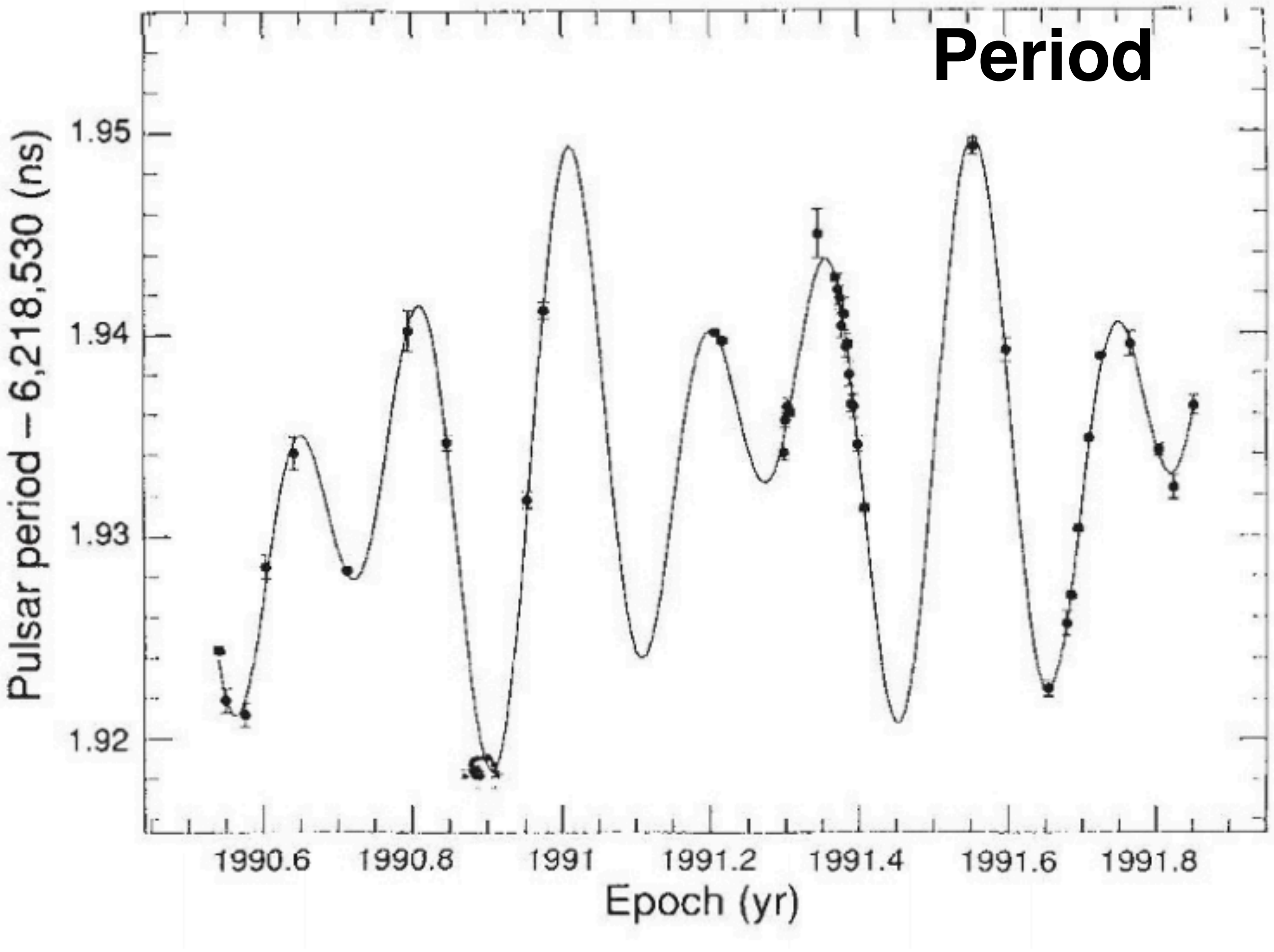
Bekki Dawson
Jim Fuller
Dan Huber
Katja Poppenhaeger
+
KITP Staff

back to the beginning - PSR B1257+12

Wolszczan & Frail 1992

- timing residuals in a millisecond pulsar
- millisecond pulsars best clocks in the Universe
- basic 0th order physics
  - (msp nearly glitch-free)
- dP/dt ~ 10^{-19} (!)
- 1/P dP/dt ~ 2×10^{-17} (s^{-1})

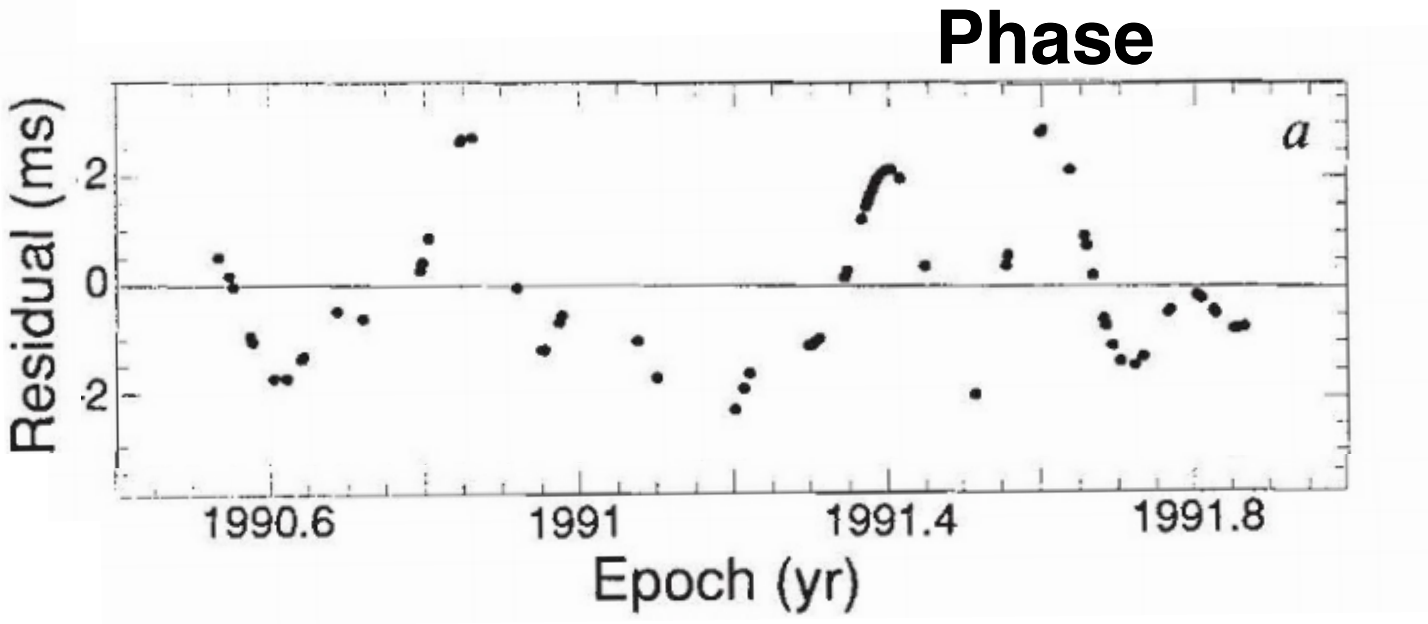

Phase


Period

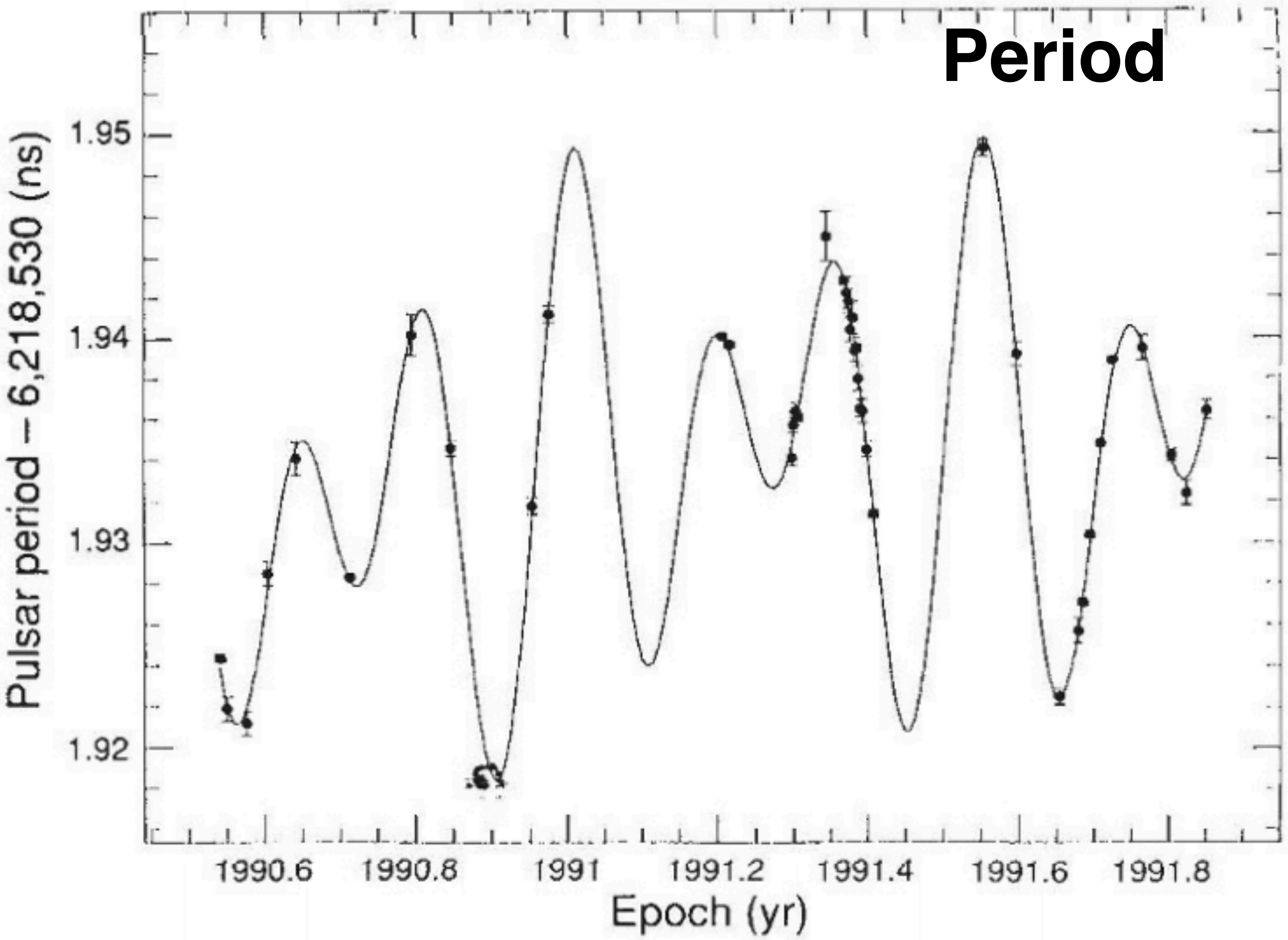
back to the beginning - PSR B1257+12

Wolszczan & Frail 1992

- Phase residuals from orbital motion
- amplitude +/- 3 ms
- amplitude/period ~ 0.5

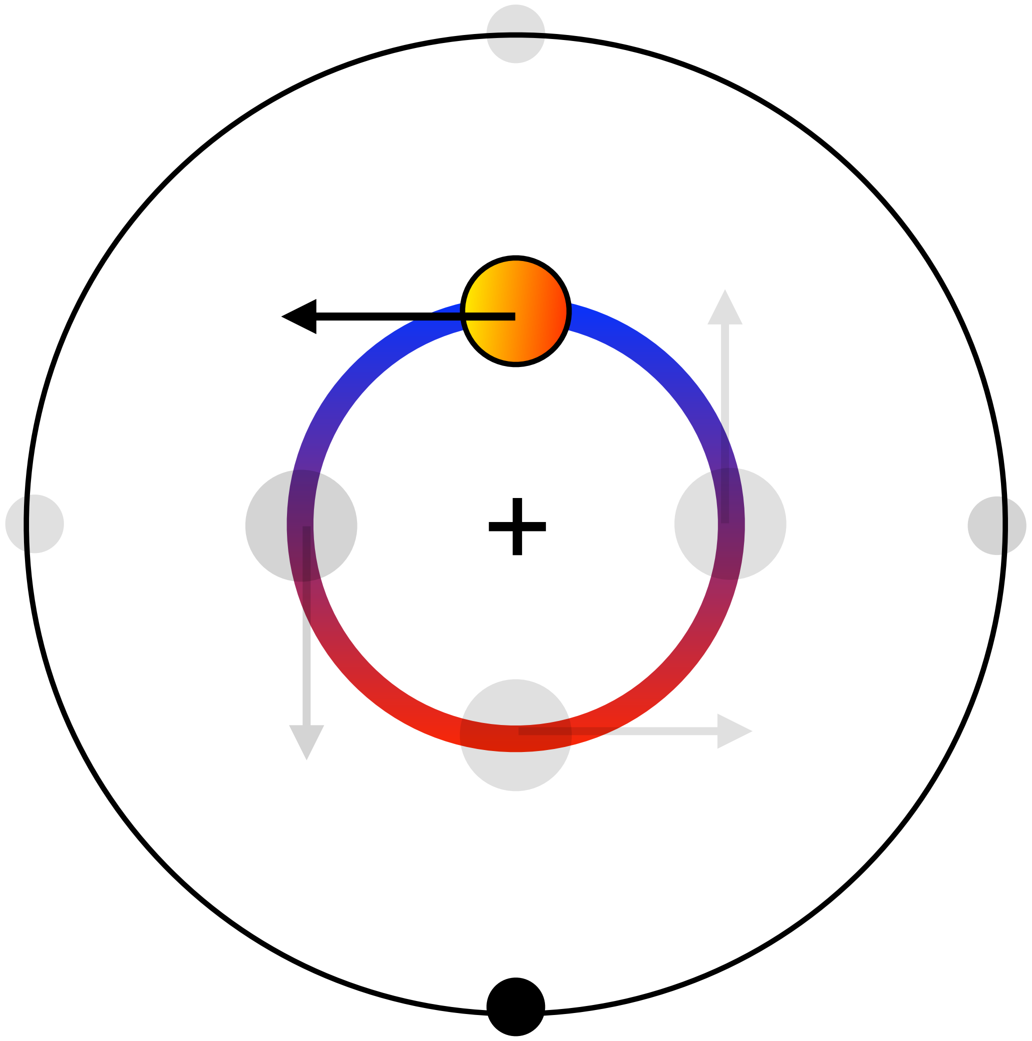


- Period variation (Doppler)
- $\Delta P \sim 2\text{x}10^{-8}$ ms
  - v ~ 1 m/s
- $\Delta P/P \sim 3.3\text{x}10^{-9}$
  - $P/\Delta P \sim 3.3\text{x}10^{8} = 21$d



detecting reflex orbital motion

- binary motion modulates ‘clock’ **period**
- binary motion modulates ‘clock’ **phase**
- **all clock modes affected equally**



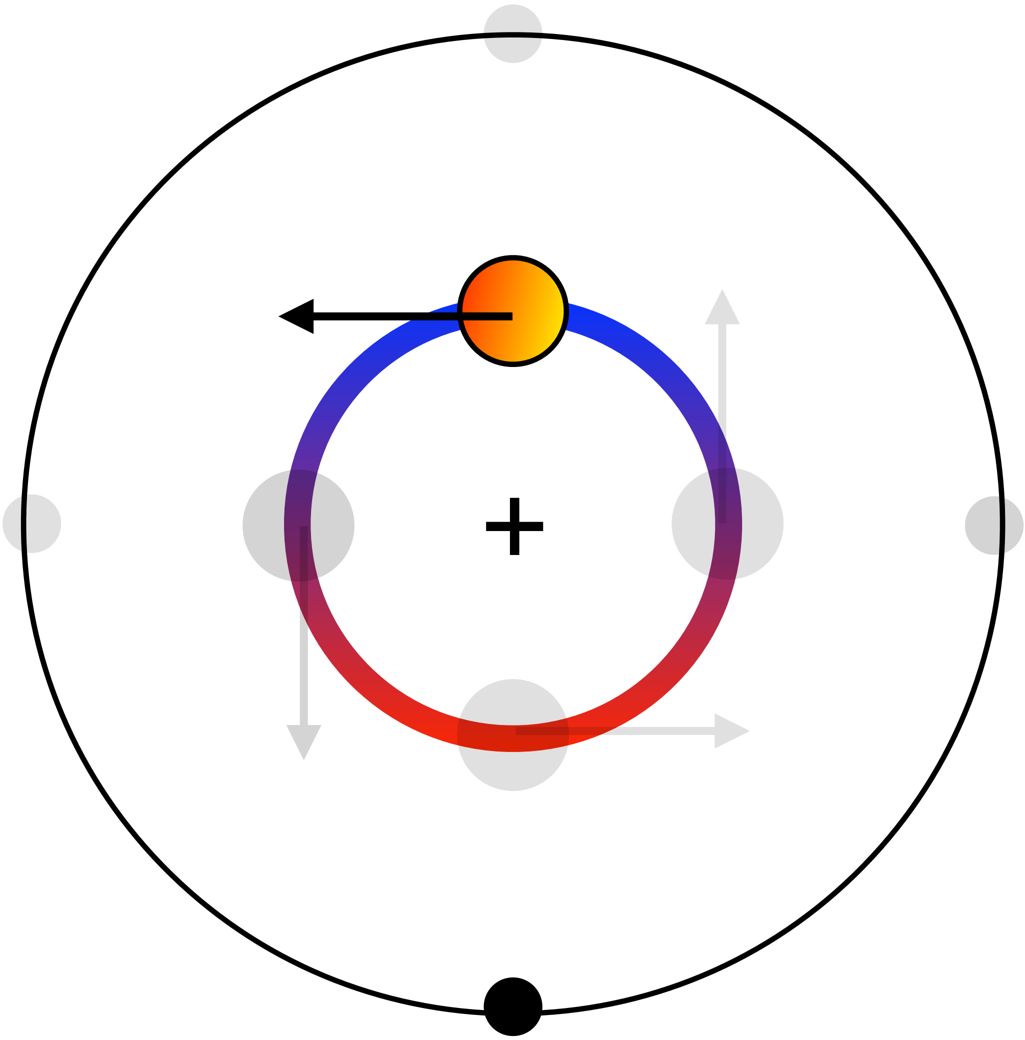
binary motion modulates 'clock' **period**

$$\Delta \mathrm{P} = \frac{v_{\mathrm{orb}}}{c} = \frac{2\pi a}{cP_{\mathrm{orb}}}$$

$P_{obs} = P_o - \Delta P$

$P_{obs} = P_o$

$P_{obs} = P_o + \Delta P$



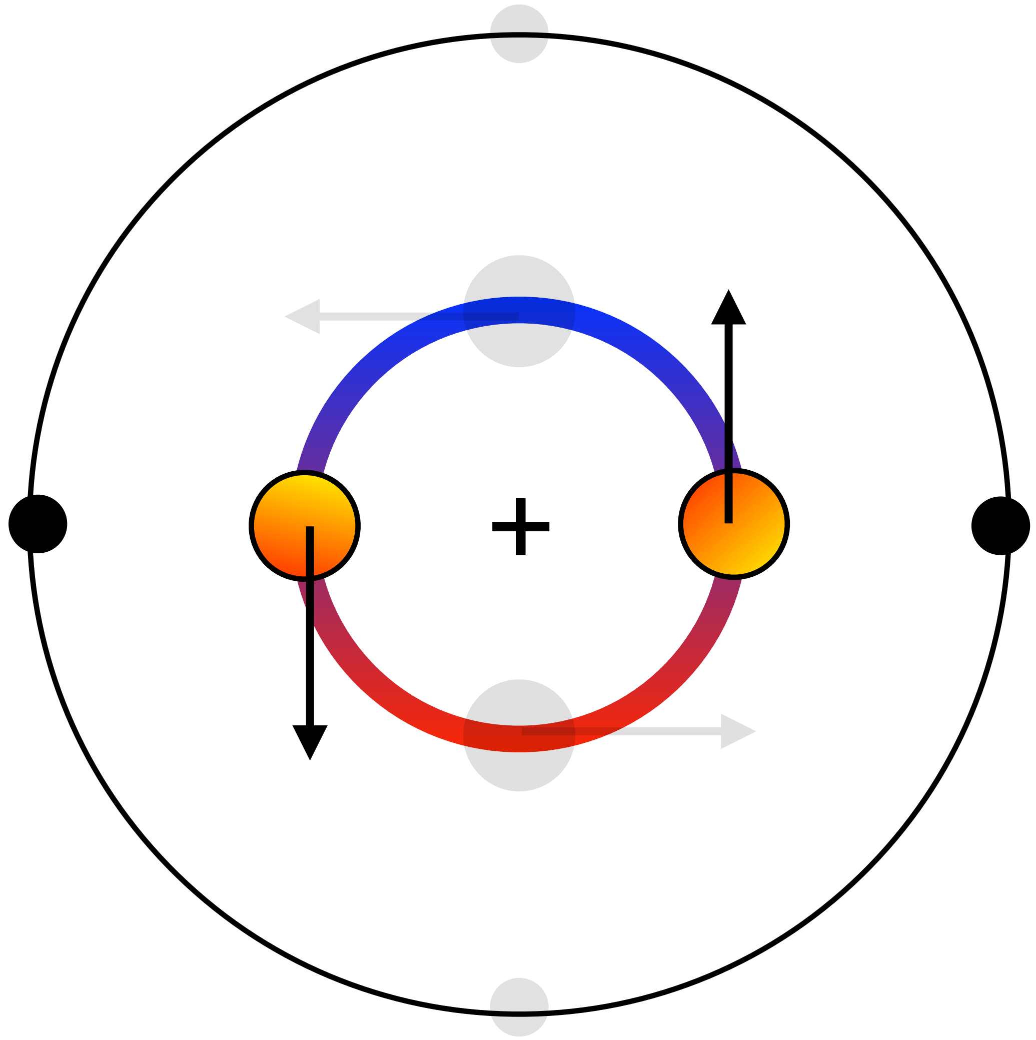
binary motion modulates ‘clock’ **period**

$$\Delta \mathrm{P} = \frac{v_{\mathrm{orb}}}{c} = \frac{2\pi a}{cP_{\mathrm{orb}}}$$

$P_{\mathrm{obs}} = P_{\mathrm{o}} - \Delta P$

$\boldsymbol{P_{\mathrm{obs}} = P_{\mathrm{o}}}$

$P_{\mathrm{obs}} = P_{\mathrm{o}} + \Delta P$



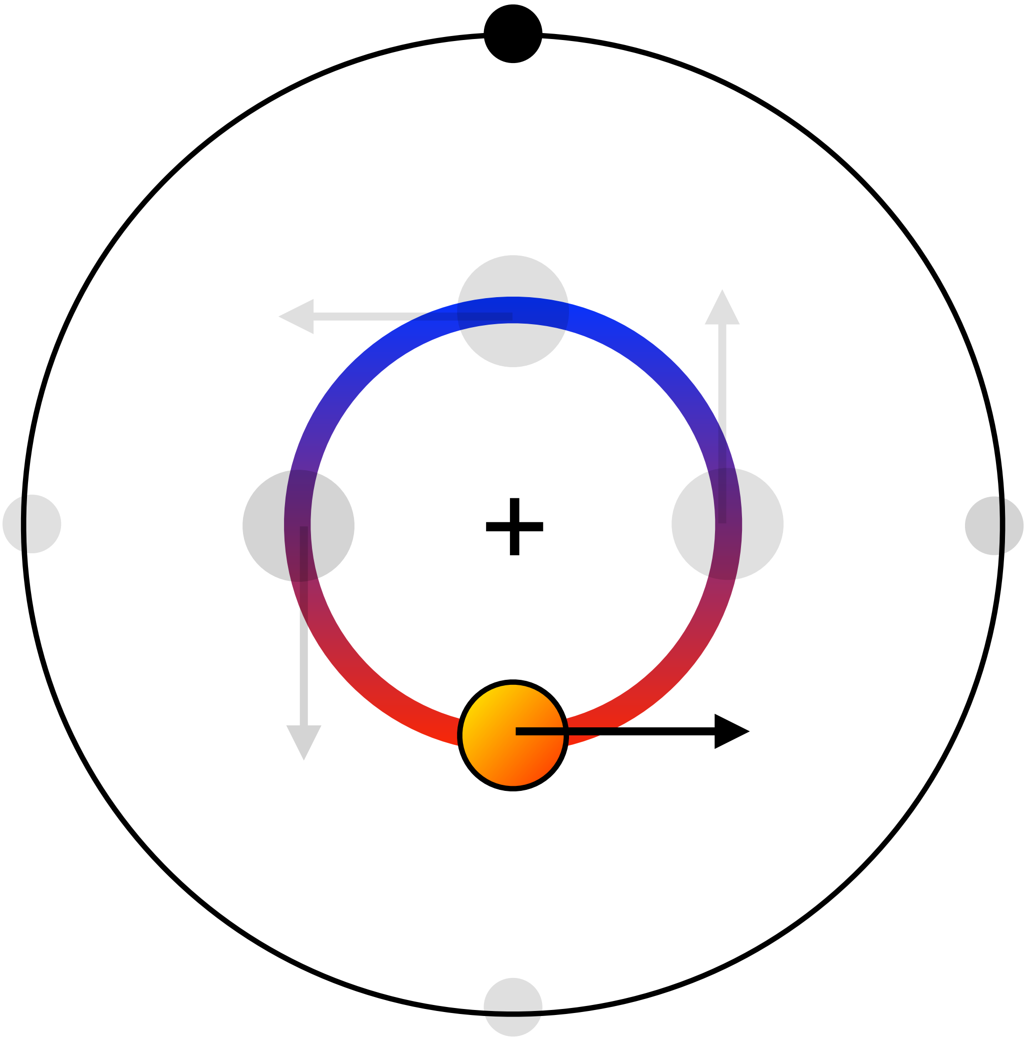
binary motion modulates ‘clock’ **period**

$$\Delta \mathrm{P} = \frac{v_{\mathrm{orb}}}{c} = \frac{2\pi a}{cP_{\mathrm{orb}}}$$

$P_{obs} = P_o - \Delta P$

$P_{obs} = P_o$

$P_{obs} = P_o + \Delta P$



$$\mathrm{P_{obs}} = \mathrm{P_o} + \Delta \mathrm{P} \sin(2\pi \mathrm{T}/\mathrm{P_{orb}})$$

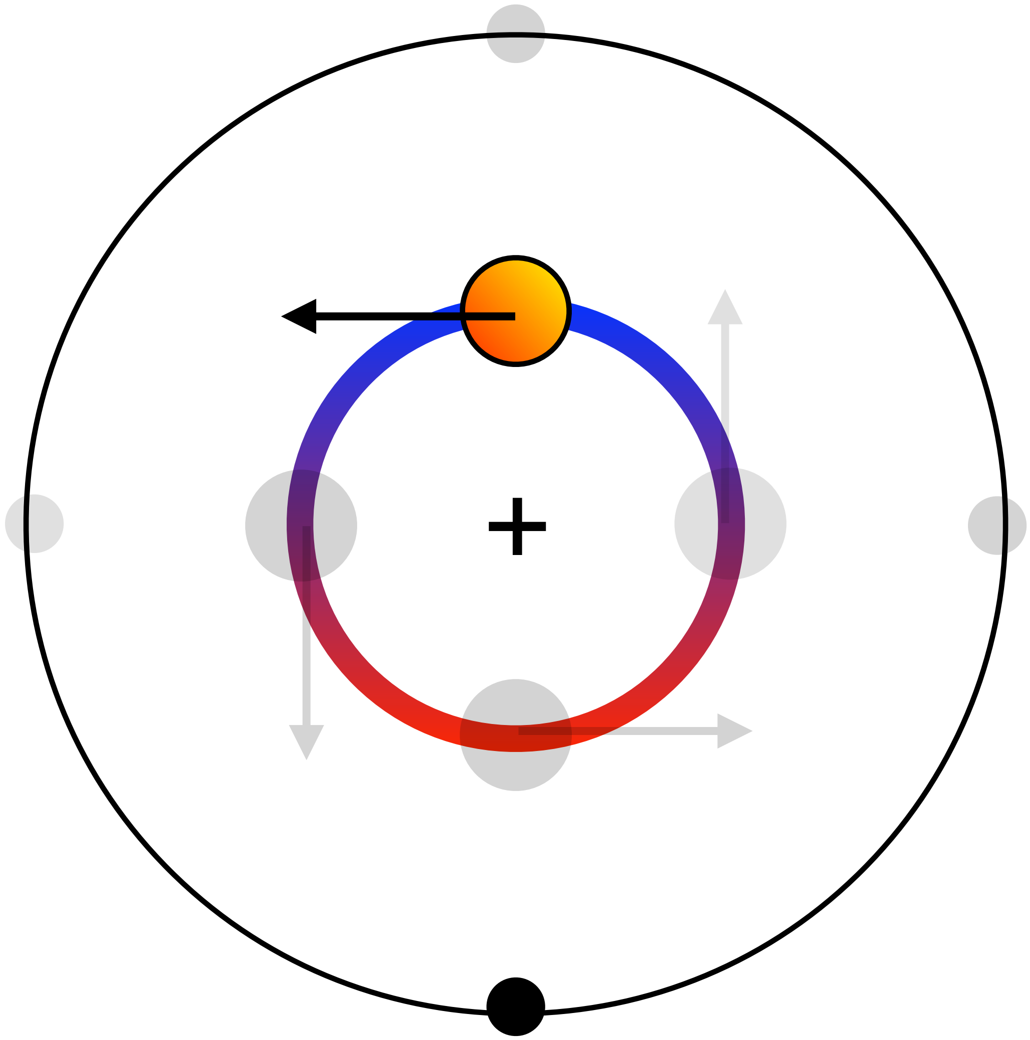
binary motion modulates ‘clock’ **phase**

$$\Delta\phi = 2\pi\frac{a}{cP_o} \quad ; \quad \Delta T_o = \frac{a}{C}$$

$\phi_{\mathrm{obs}} = \phi_{\mathrm{o}}$

$\phi_{\mathrm{obs}} = \phi_{\mathrm{o}} - \Delta\phi$; $\phi_{\mathrm{obs}} = \phi_{\mathrm{o}} + \Delta\phi$

$\phi_{\mathrm{obs}} = \phi_{\mathrm{o}}$



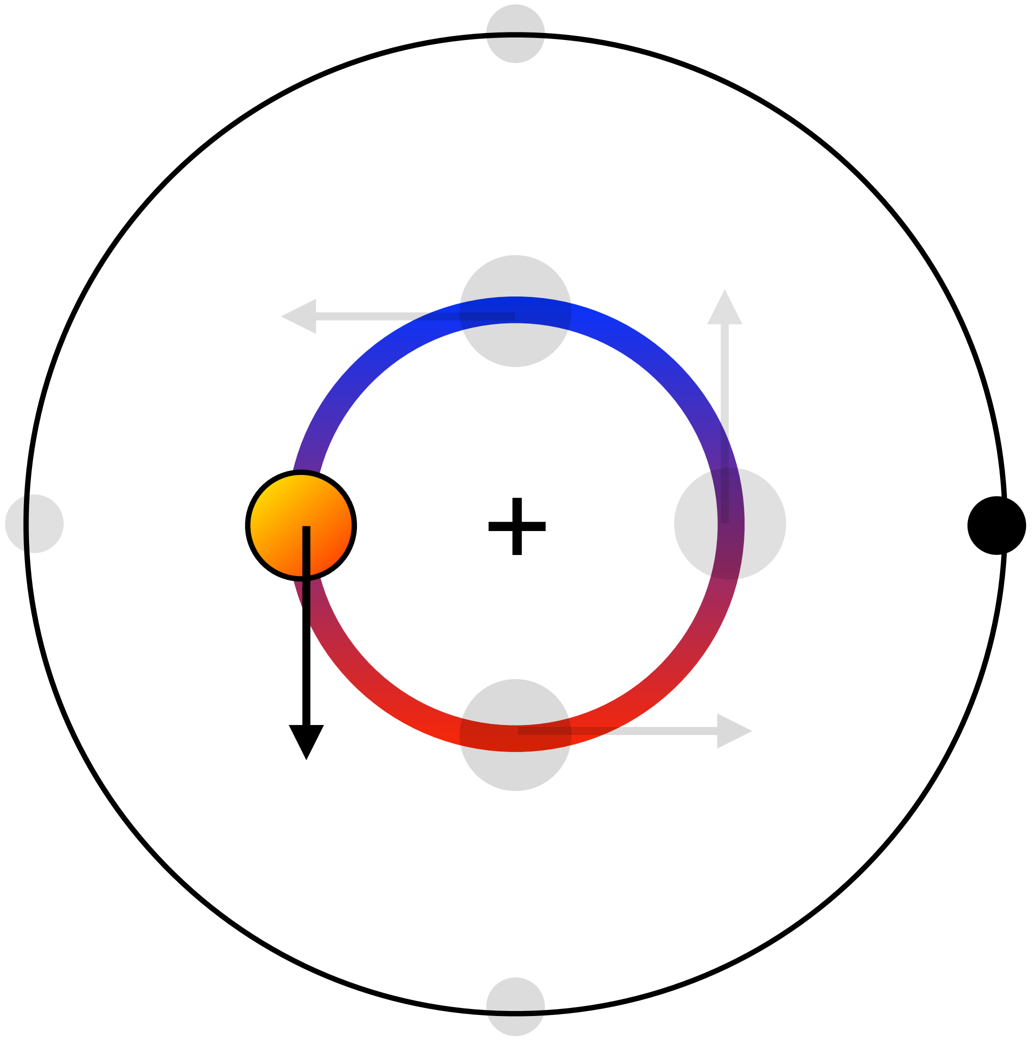
binary motion modulates ‘clock’ **phase**

$$\Delta\phi = 2\pi\frac{a}{cP_o} \quad ; \quad \Delta T_o = \frac{a}{C}$$

$\phi_{\text{obs}} = \phi_o$

$\phi_{\text{obs}} = \phi_o - \Delta\phi$; $\phi_{\text{obs}} = \phi_o + \Delta\phi$

$\phi_{\text{obs}} = \phi_o$



binary motion modulates ‘clock’ **phase**

$$\Delta\phi = 2\pi\frac{a}{cP_o} \quad ; \quad \Delta T_o = \frac{a}{C}$$

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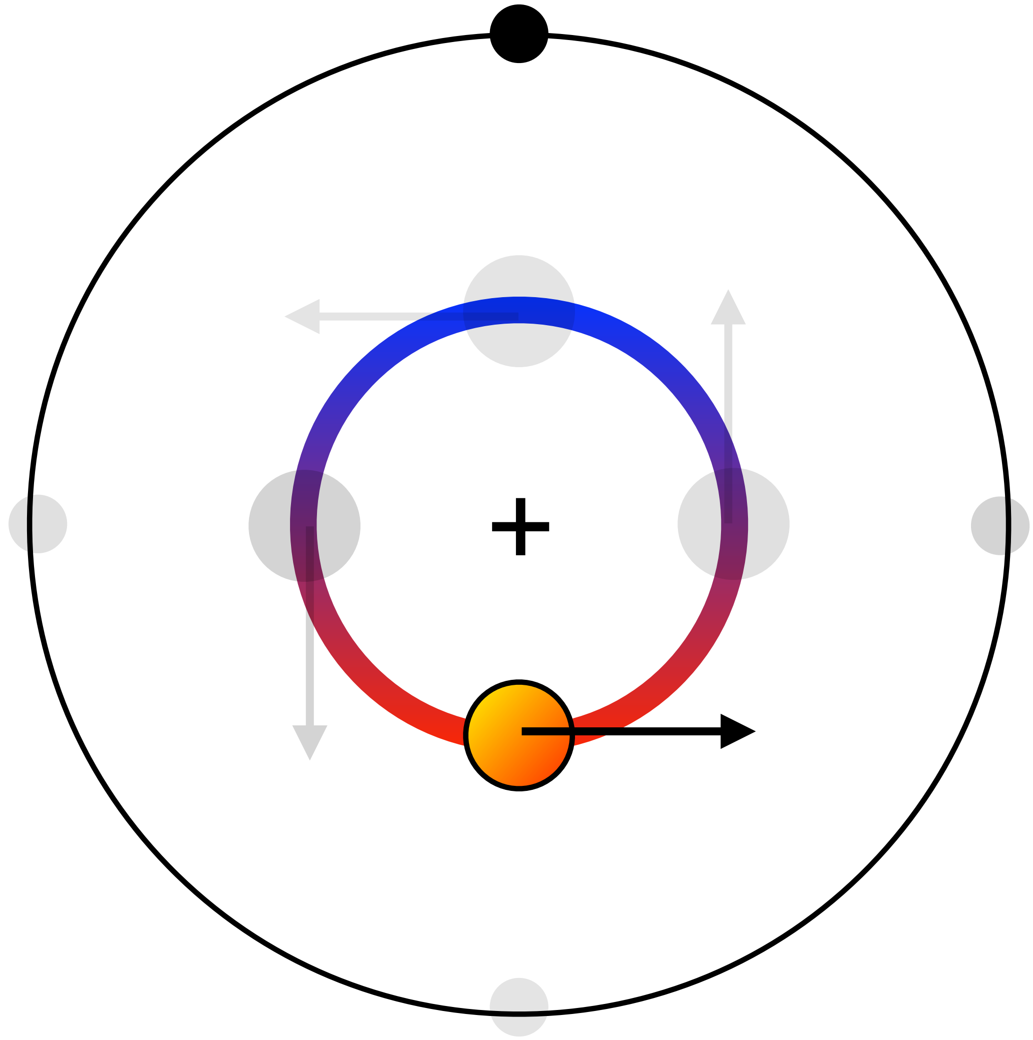


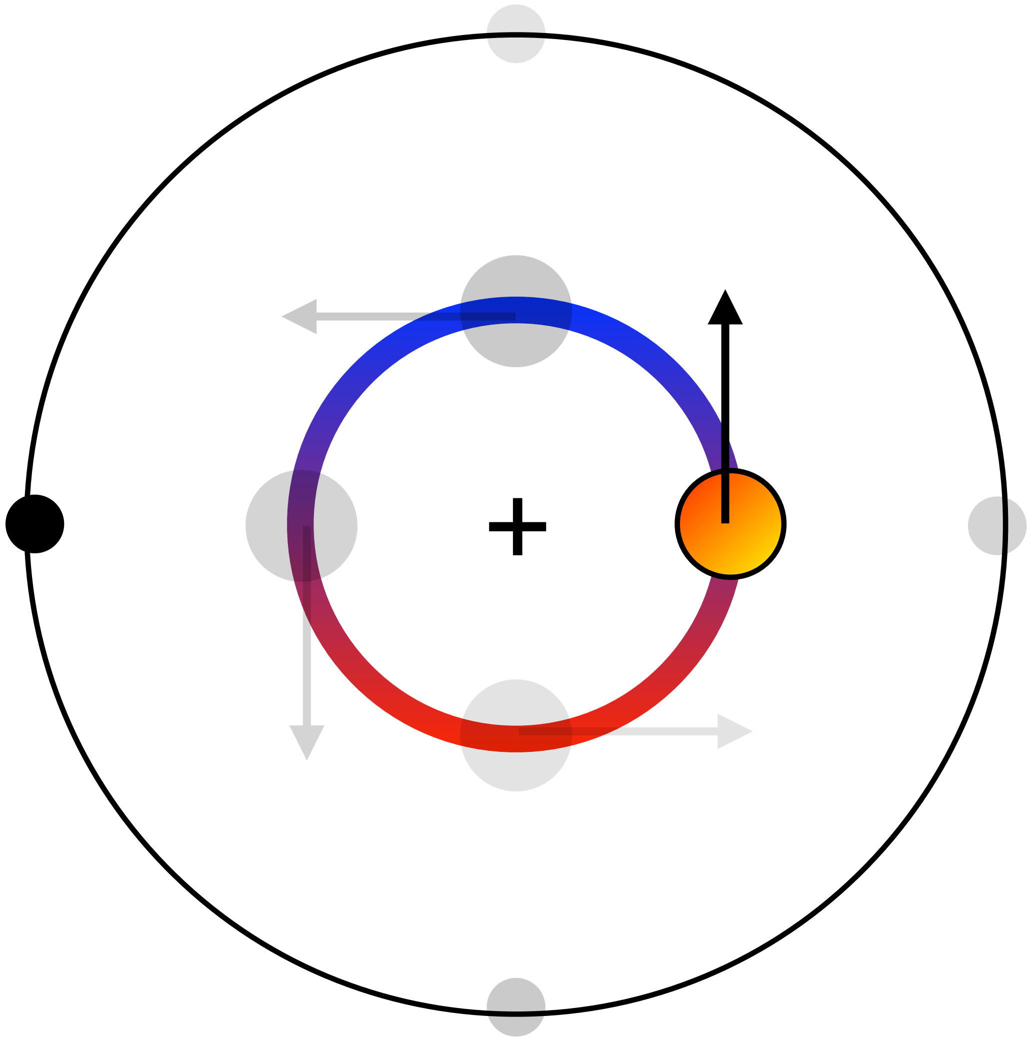
binary motion modulates ‘clock’ **phase**

$$\Delta\phi = 2\pi \frac{a}{cP_o} \quad ; \quad \Delta T_o = \frac{a}{C}$$

$\phi_{obs} = \phi_o$

$\phi_{obs} = \phi_o - \Delta\phi$; **$\phi_{obs} = \phi_o + \Delta\phi$**

$\phi_{obs} = \phi_o$

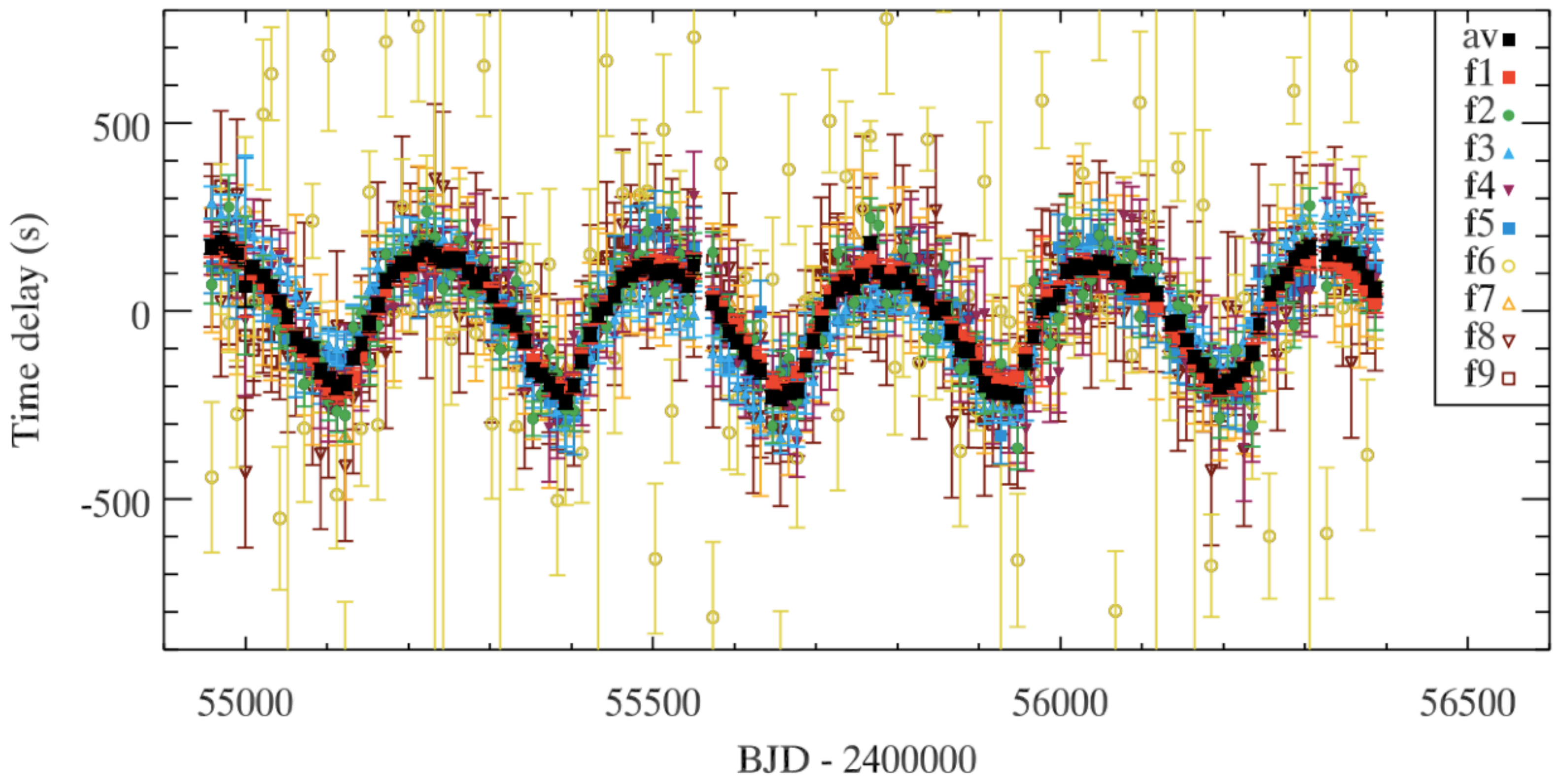


$$T_{o,obs} = T_o - \Delta T_o \cos(2\pi T/P_{orb})$$

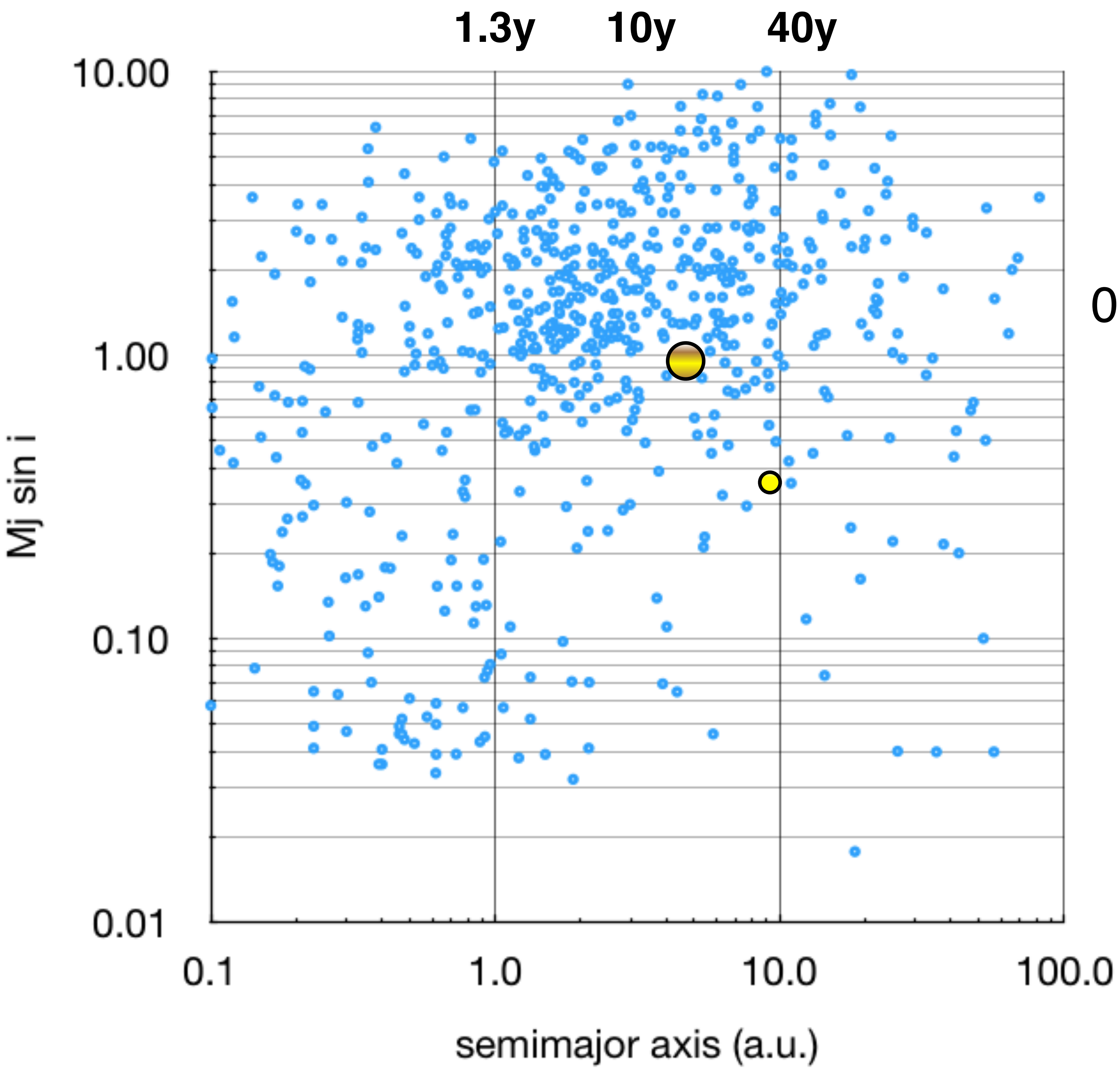
multimode pulsators:
identical phase variations

- light travel time across (projected) orbit is same for all modes
- modulation amplitude / phase / period must match
- “instant” verification of extrinsic process
- Example: KIC 9651065 - 9 modes, P ~ 300d

(Murphy & Shibahashi 2015)

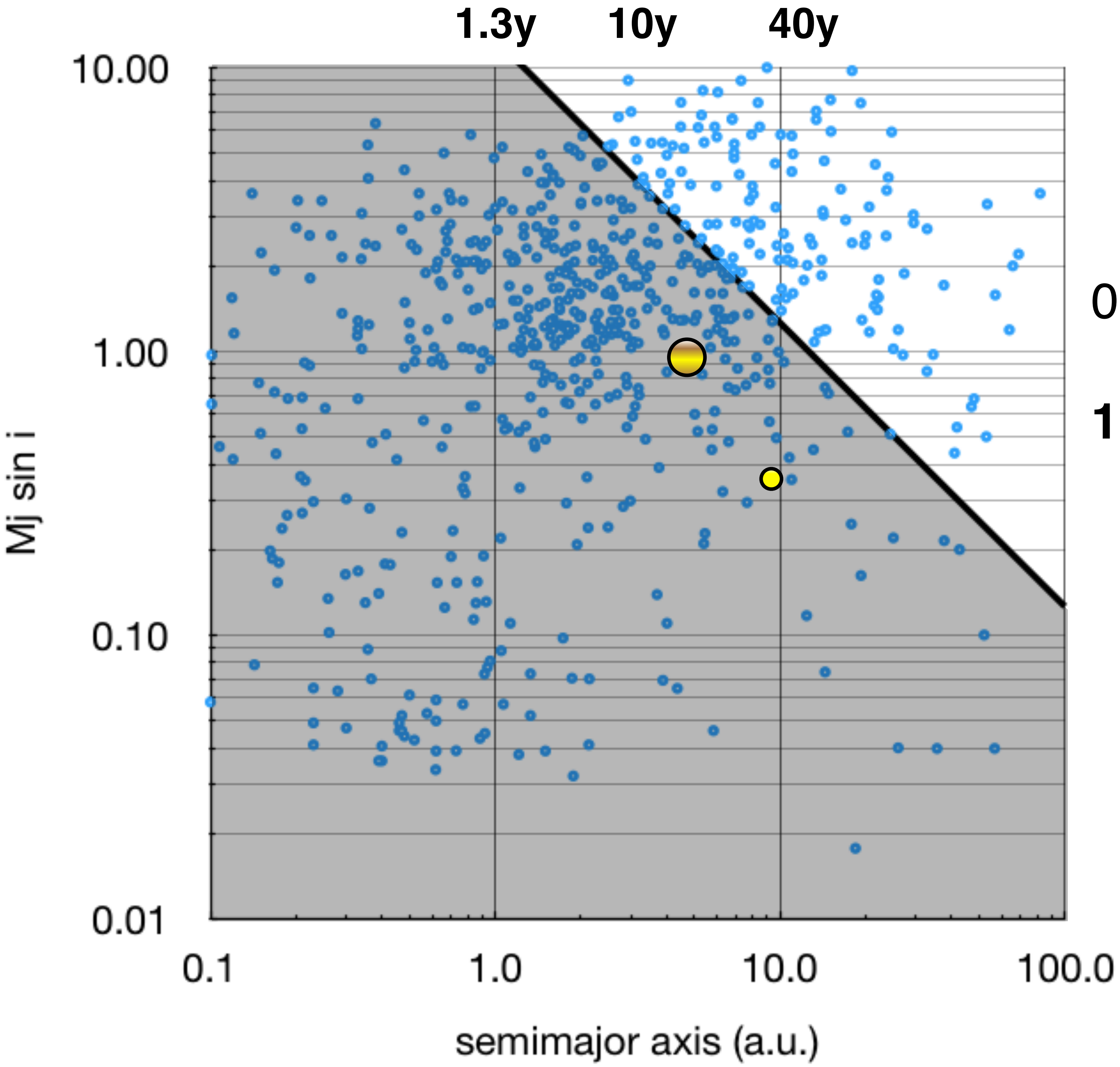


some numbers



0.6M$_o$ primary

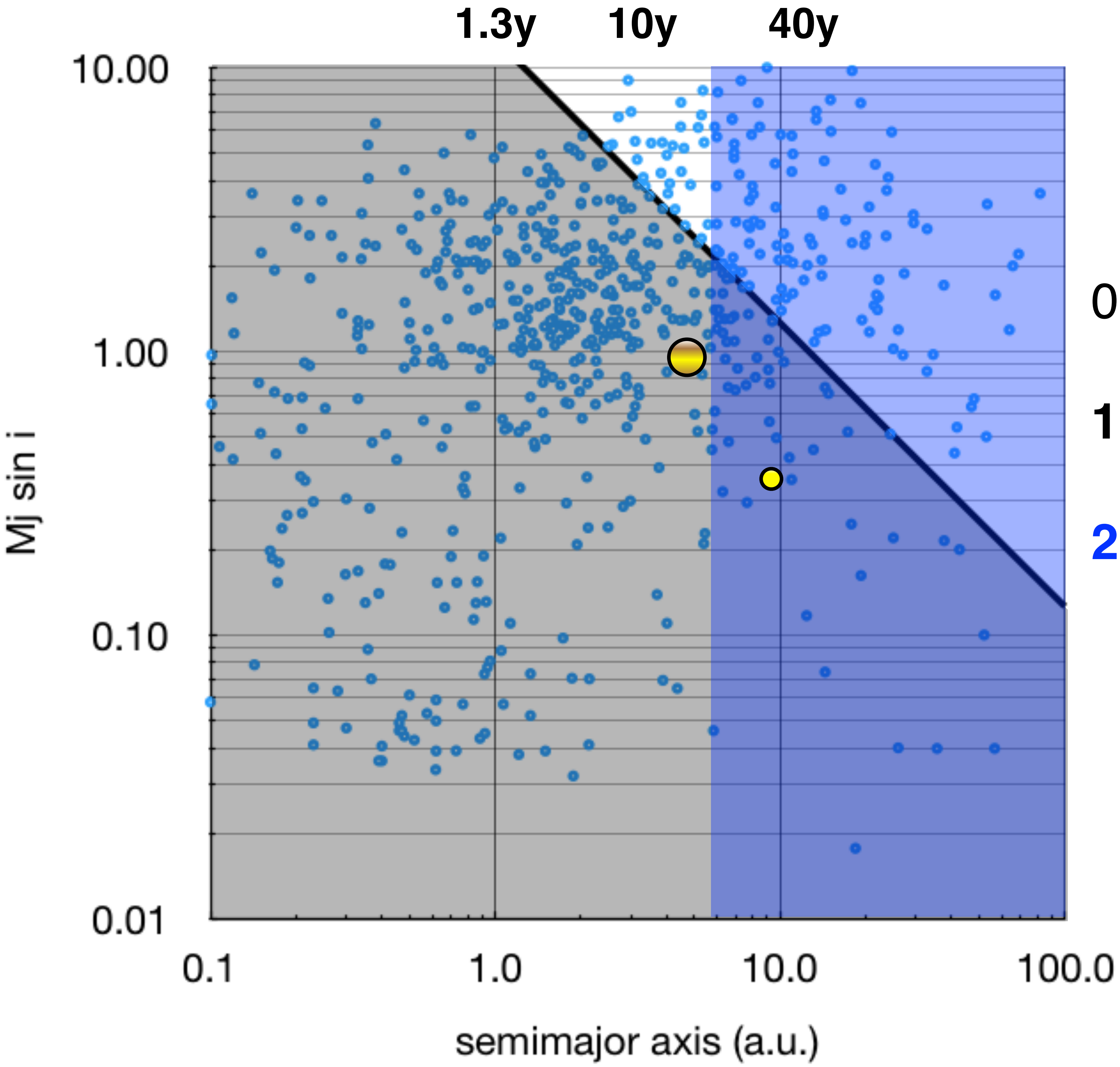
some numbers



0.6Mₒ primary

10 s (O-C) timing

some numbers

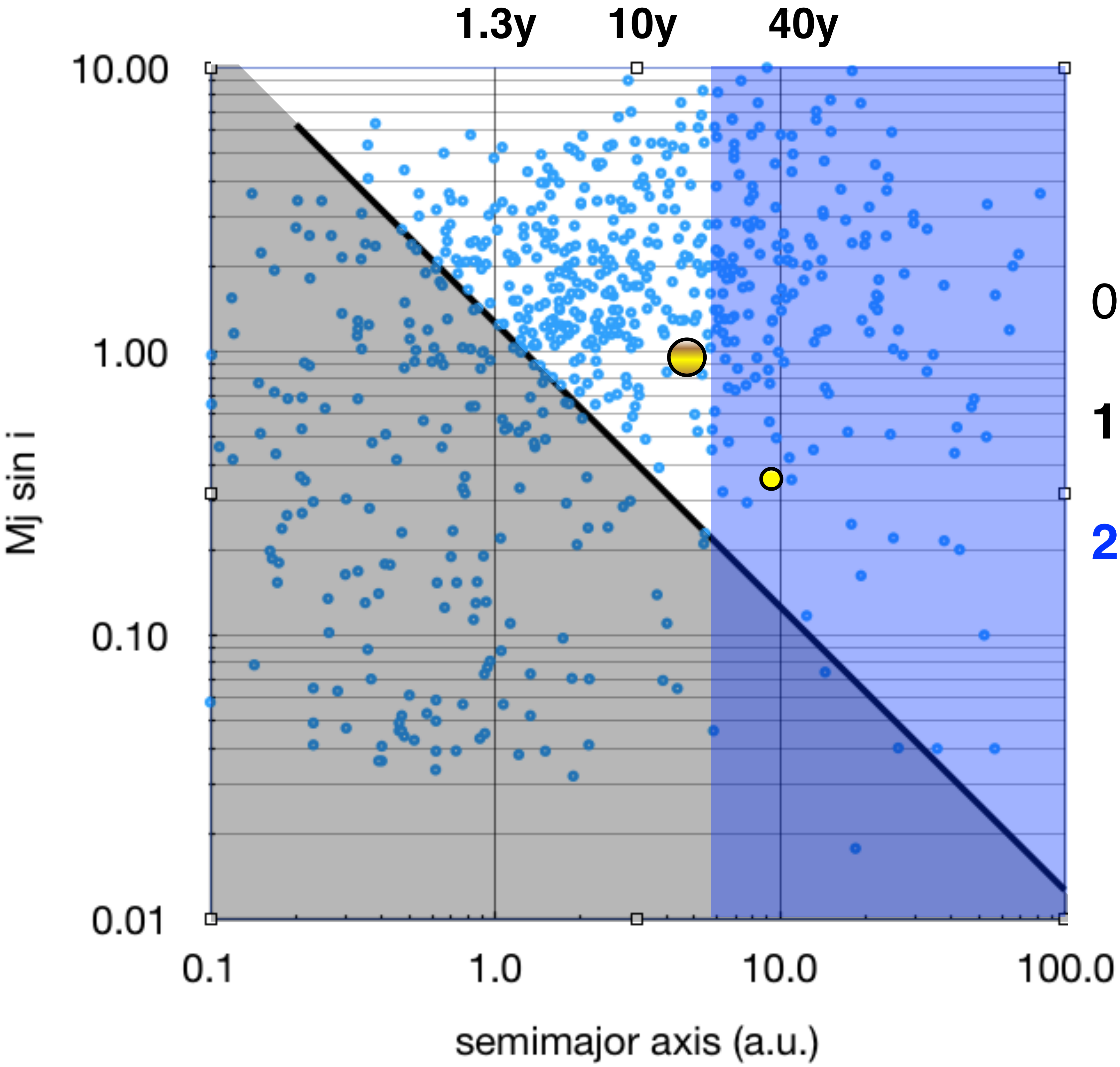


0.6M$_\odot$ primary

10 s (O-C) timing

20 year span

some numbers



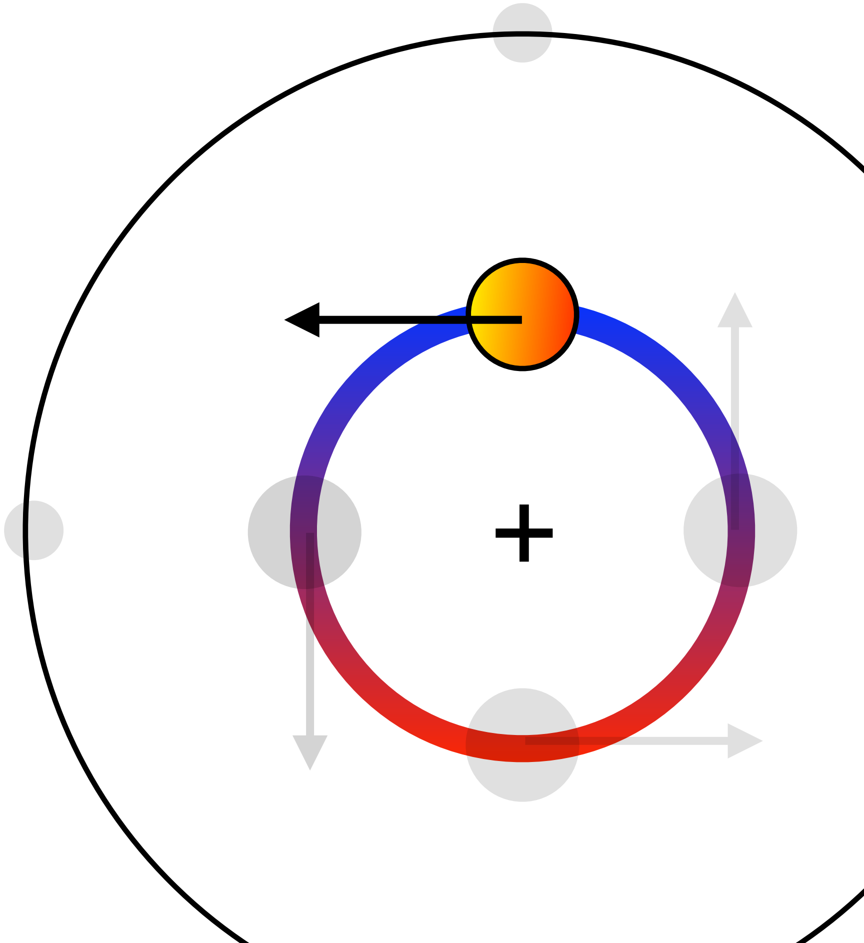
$0.6M_o$ primary

1 s (O-C) timing

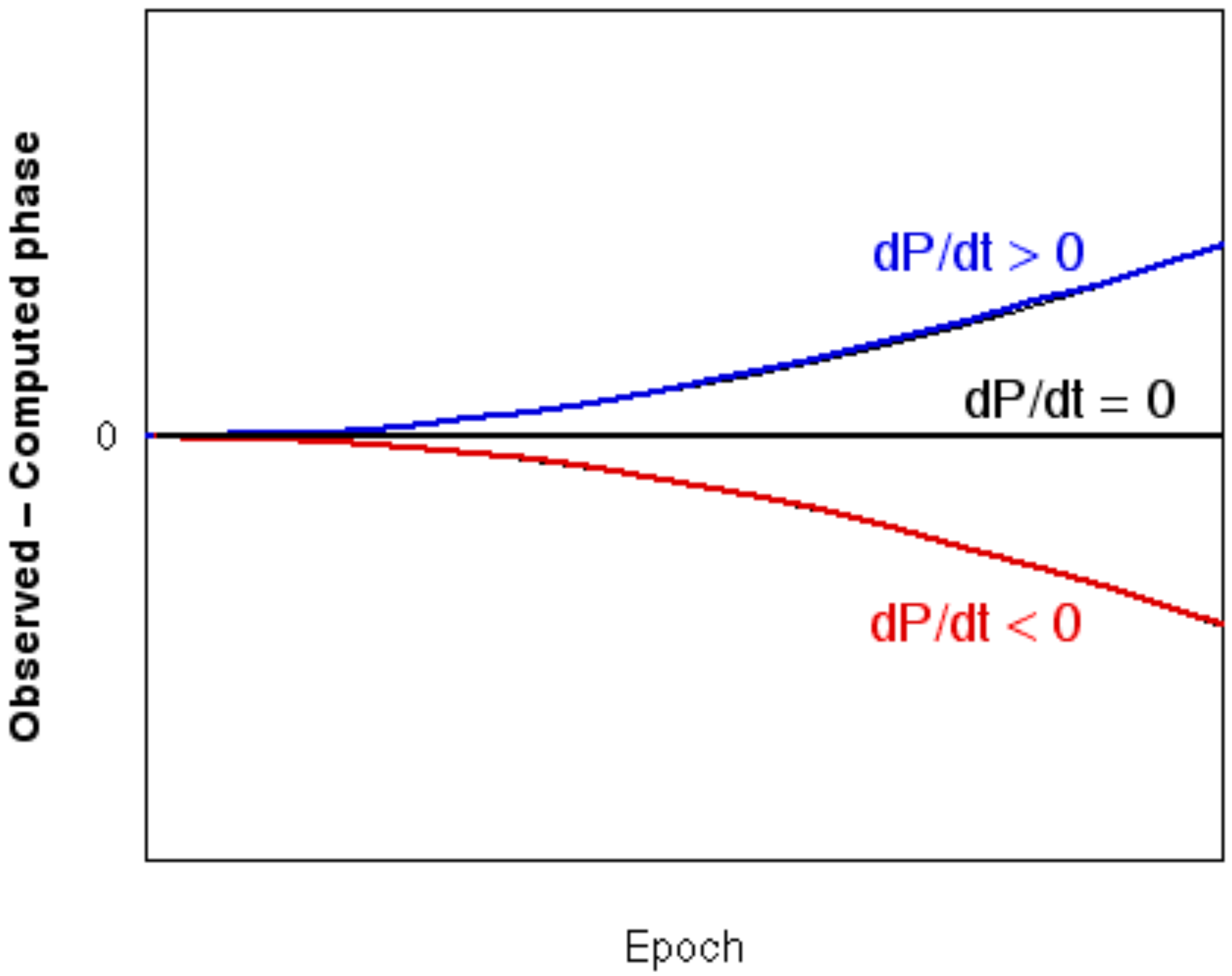
20 year span

detecting reflex orbital motion

- binary motion modulates ‘clock’ **period**
- binary motion modulates ‘clock’ **phase**
- **all clock modes affected equally**
- **minimize intrinsic pulsation ‘noise’**
  - secular period changes
  - stochastic phase variation
  - stochastic amplitude variation
  - other evil effects



stellar evolution drives period changes: revealed by (O-C) diagram



- secular change via stellar cooling - stellar evolution while you watch
- reflex orbital motion - low-mass companions

$$(O - C) = (\Delta t)^2 \frac{1}{P} \frac{dP}{dt}$$

Period changes with time - evolution!

- if period is constant with time:

$$t_{\mathrm{max,i}} = t_{\mathrm{max,0}} + (i \times P_0)$$

- but, if period changes (at a fixed rate), then

$$\frac{dt_{\mathrm{max,i}}}{dt} = i\frac{dP}{dt}$$

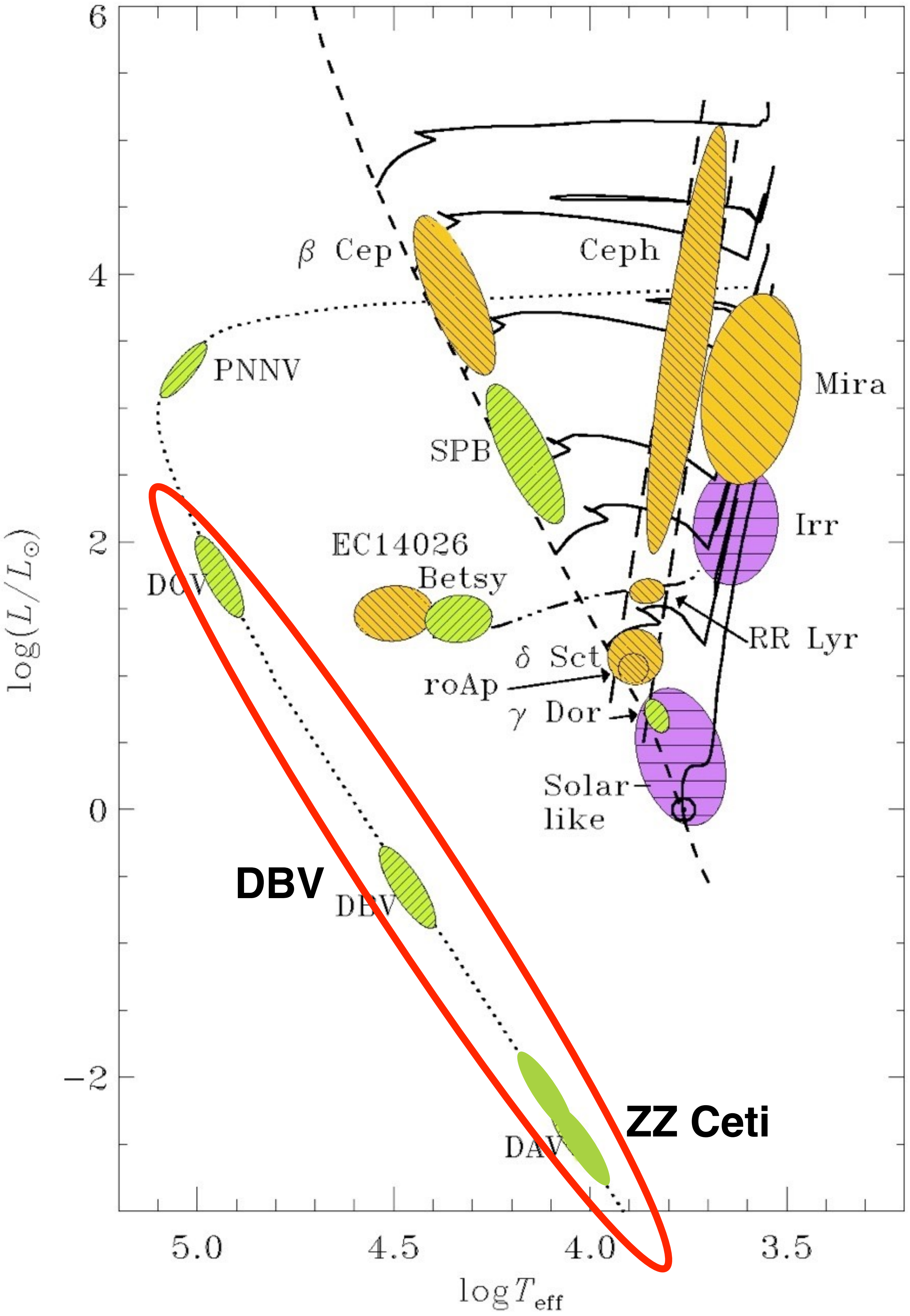
and

$$t_{\mathrm{max,i}} = t_{\mathrm{max,0}} + iP_0 + i^2 P\frac{dP}{dt}$$

- so the difference between the computed maximum and observed time is:

$$(O - C) = (\Delta t)^2 \frac{1}{P}\frac{dP}{dt}$$

Pulsating stars in the HR diagram



▨ p modes heat engine

▨ g modes heat engine

▤ solarlike oscillations

from J. Christensen-Dalsgaard

for nonradial pulsations (g-modes) in WDs

$$\frac{1}{P}\frac{dP}{dt} = \boxed{\frac{a}{R}\frac{dR}{dt}}\boxed{-\frac{b}{T}\frac{dT}{dt}}$$

- **contraction** —> period decrease with time

  (expansion - period increase with time)

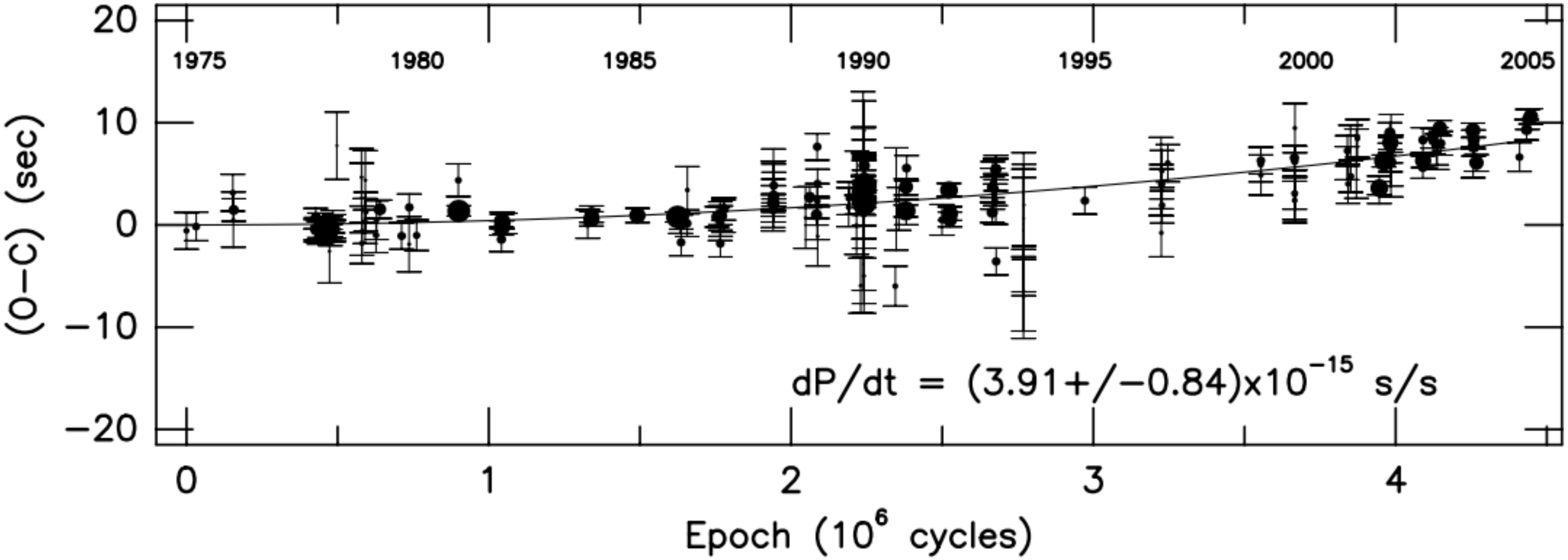
- **cooling** —> period *increase* with time
  - thermal loss via photons
  - neutrino / axion cooling processes
  - rotational spin-up or spin-down

G117-B15A

(S.O. Kepler et al. 2005)

- 40+ years of monitoring
- dP/dt ~ 4 x 10^{-15}

- P = 215 s; $\sigma_{P,mo}$ <~ 3ms
  - P/ΔP ~ 7×10^5 ; v > 0.4 km/s



planet limits around G117-B15a

Fergal Mullally - (2007 PhD Thesis)

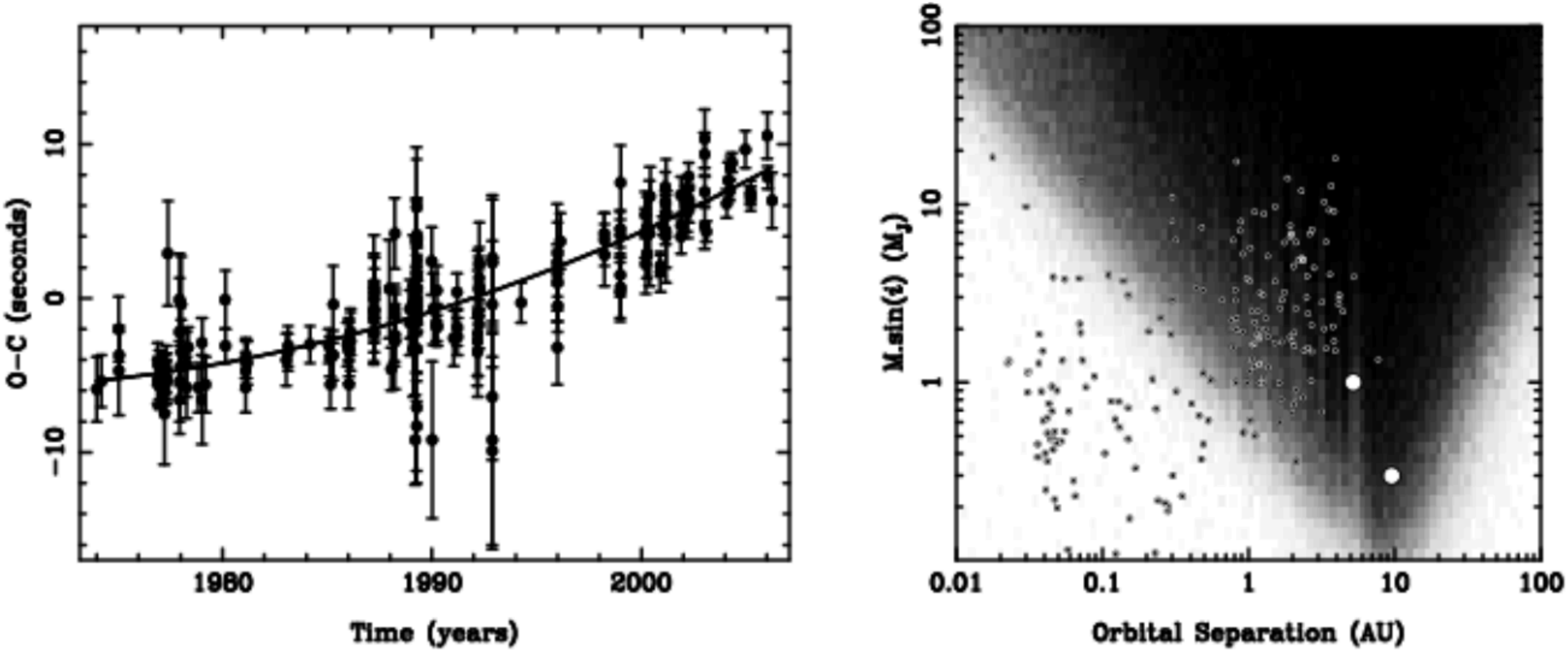
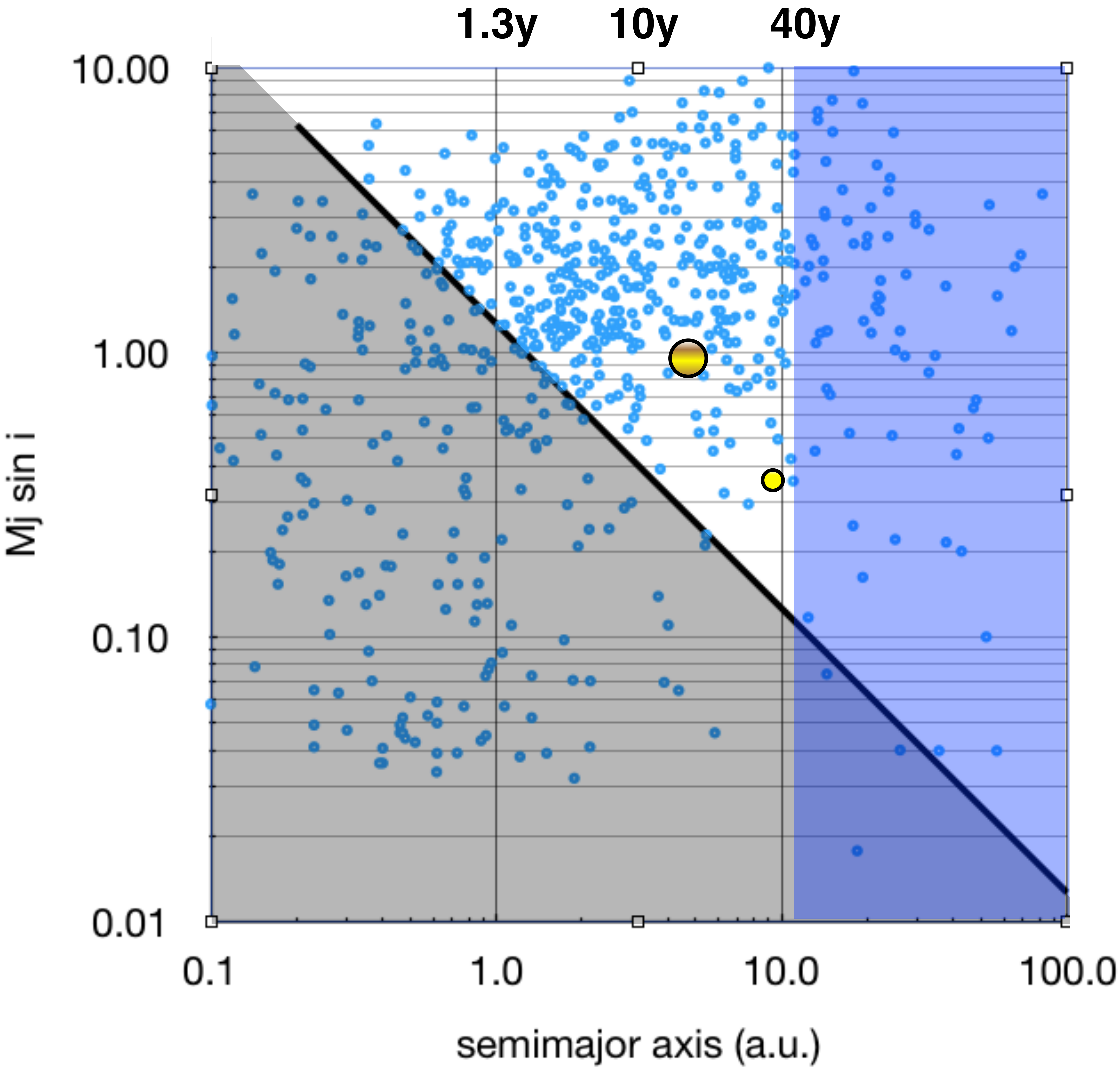


Figure 4.11 G117−B15A

G117-B15A - planet limits



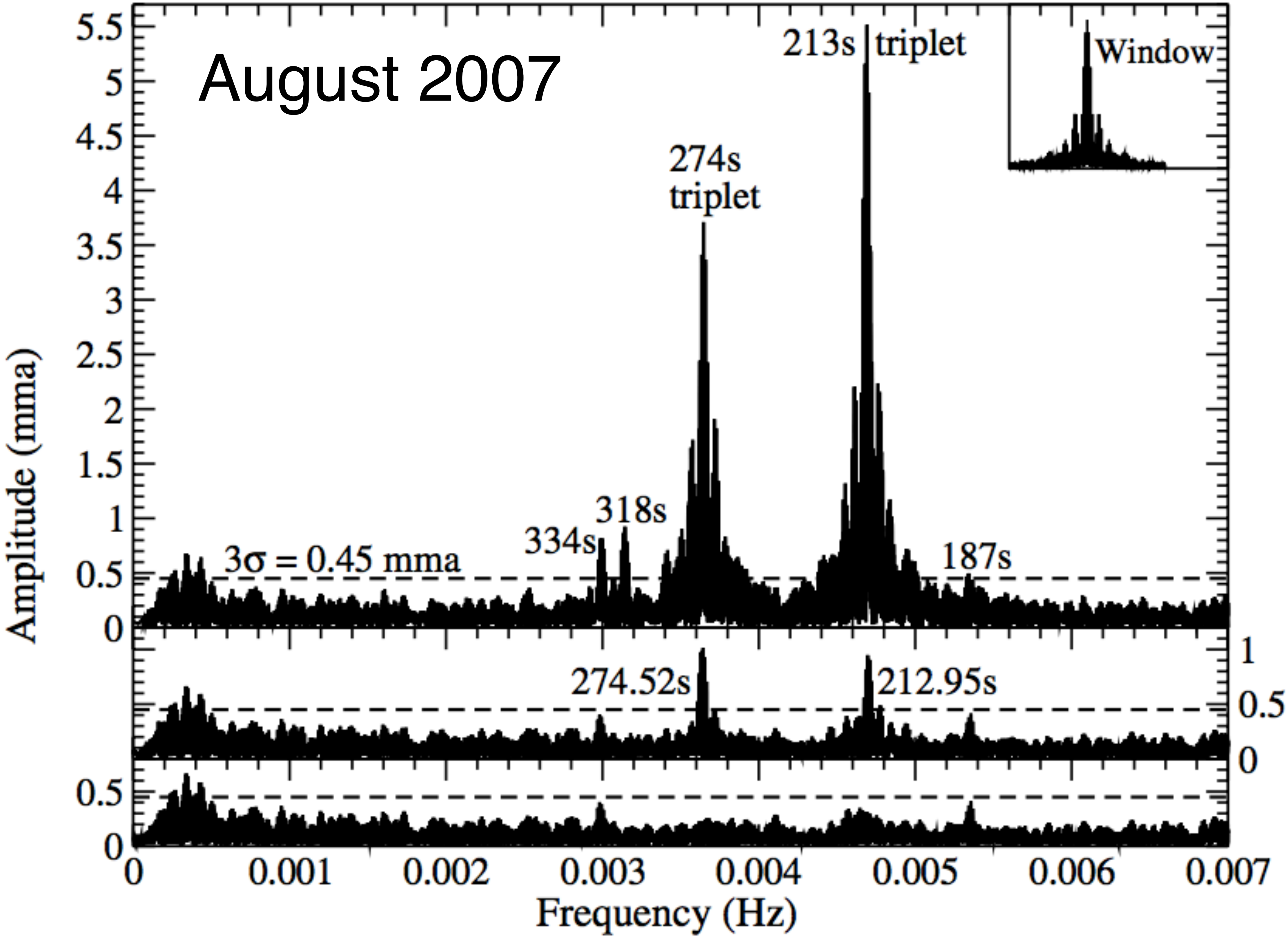
0.6M_o primary

1 s (O-C) timing

40 year period

ZZ Ceti (R548)

Mukadam et al. (2013)



ZZ Ceti (R548)

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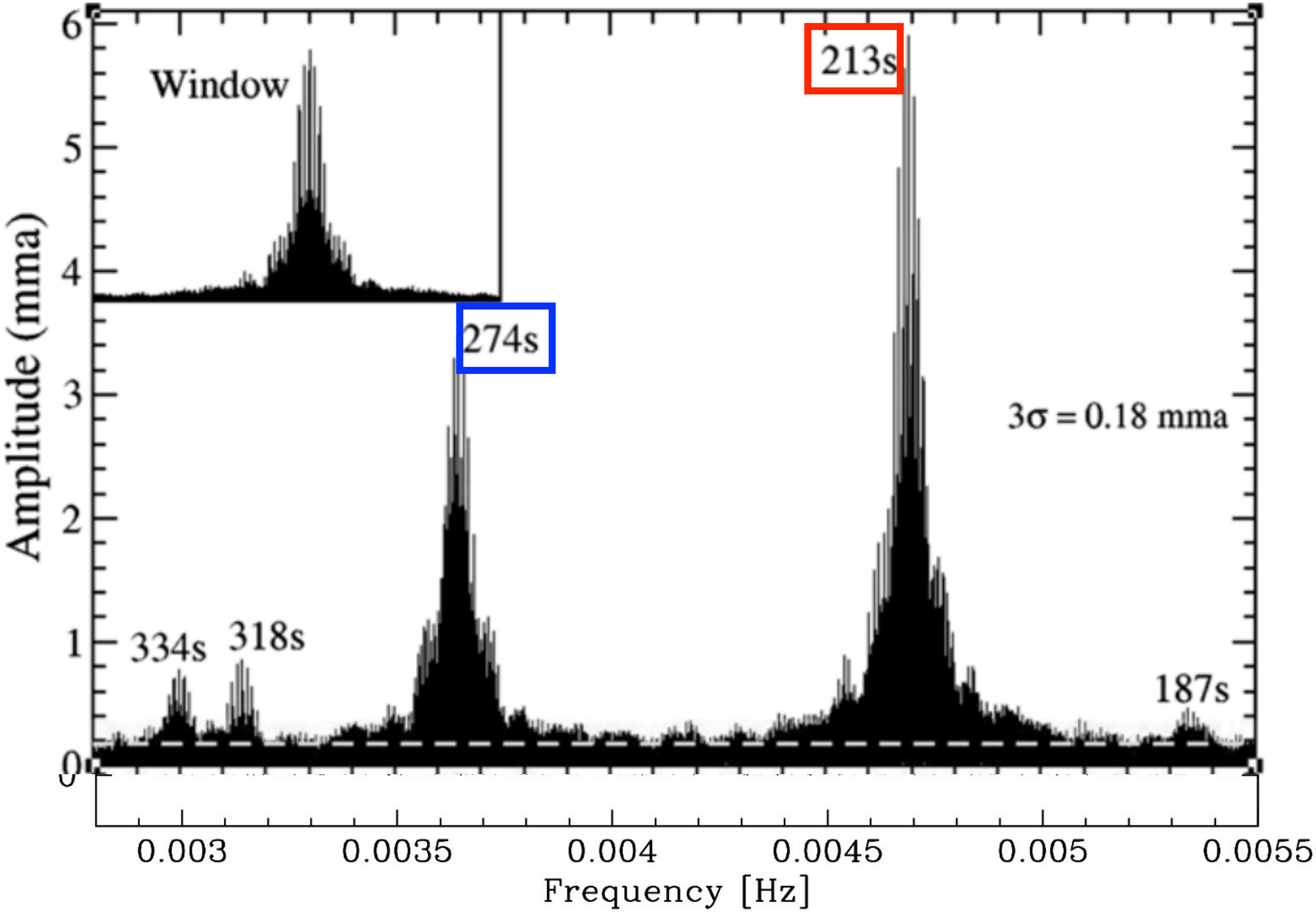
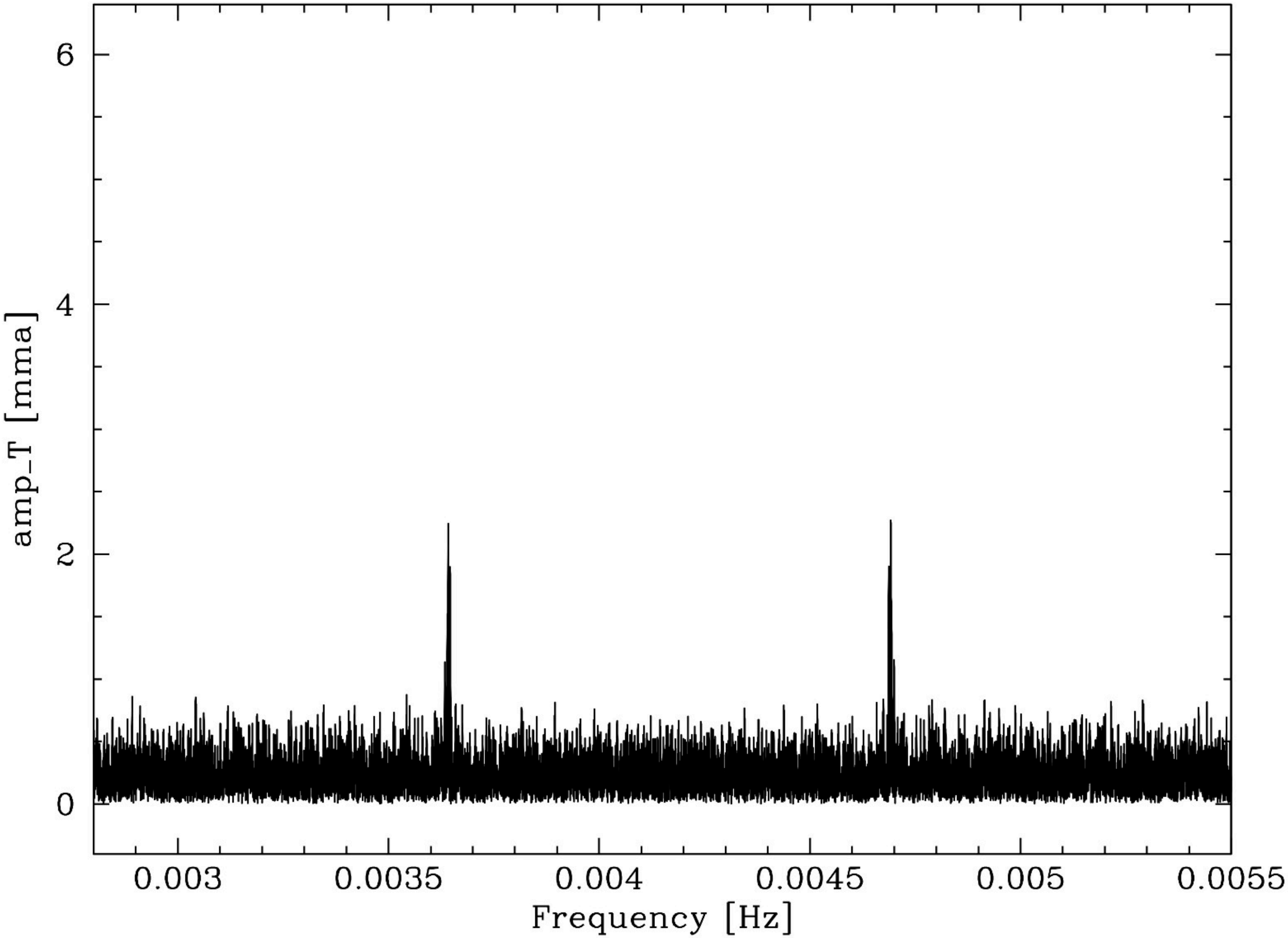


August 2007 - January 2012

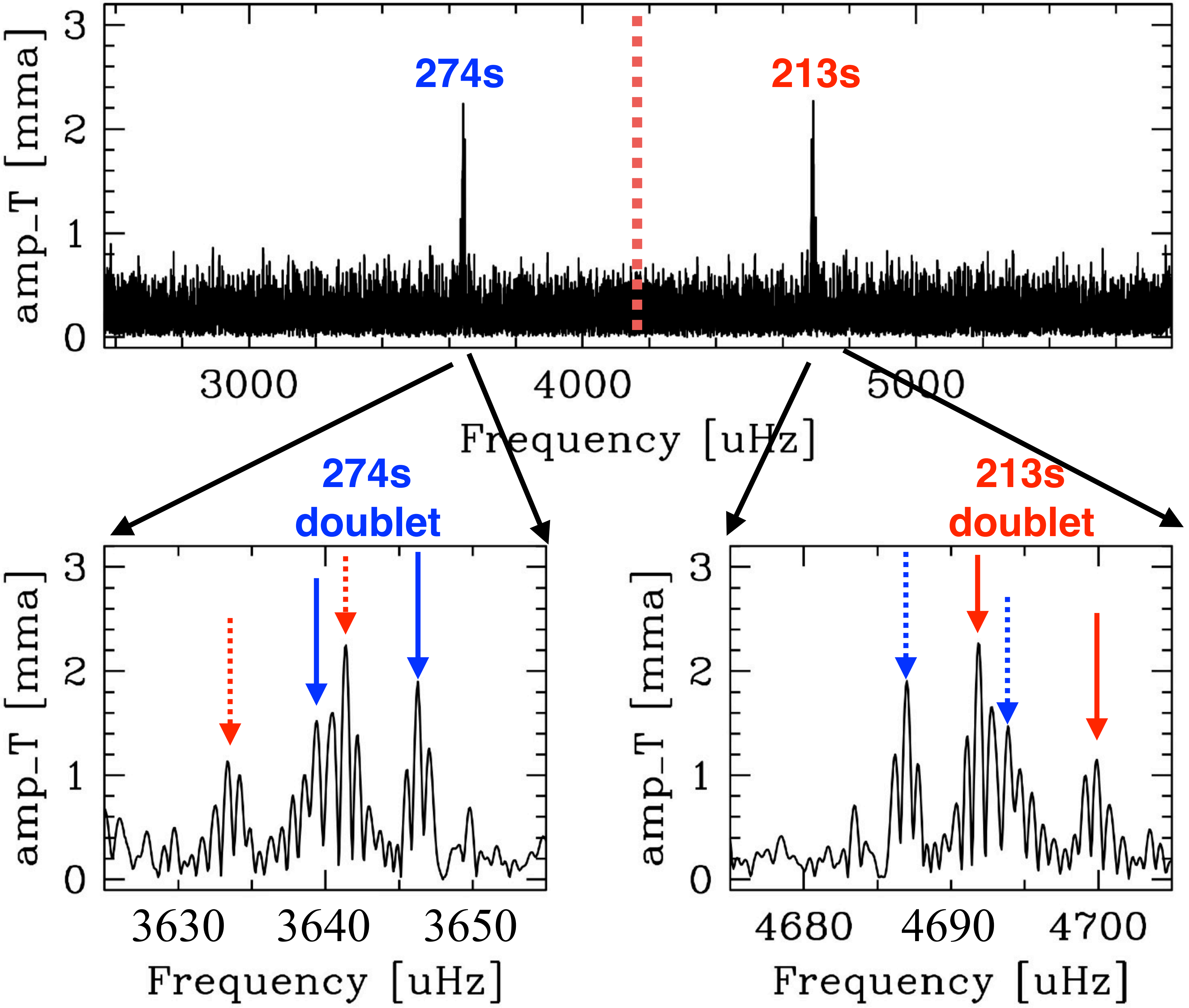
ZZ Ceti (R548)



TESS Sector 1 (~ 20 days)

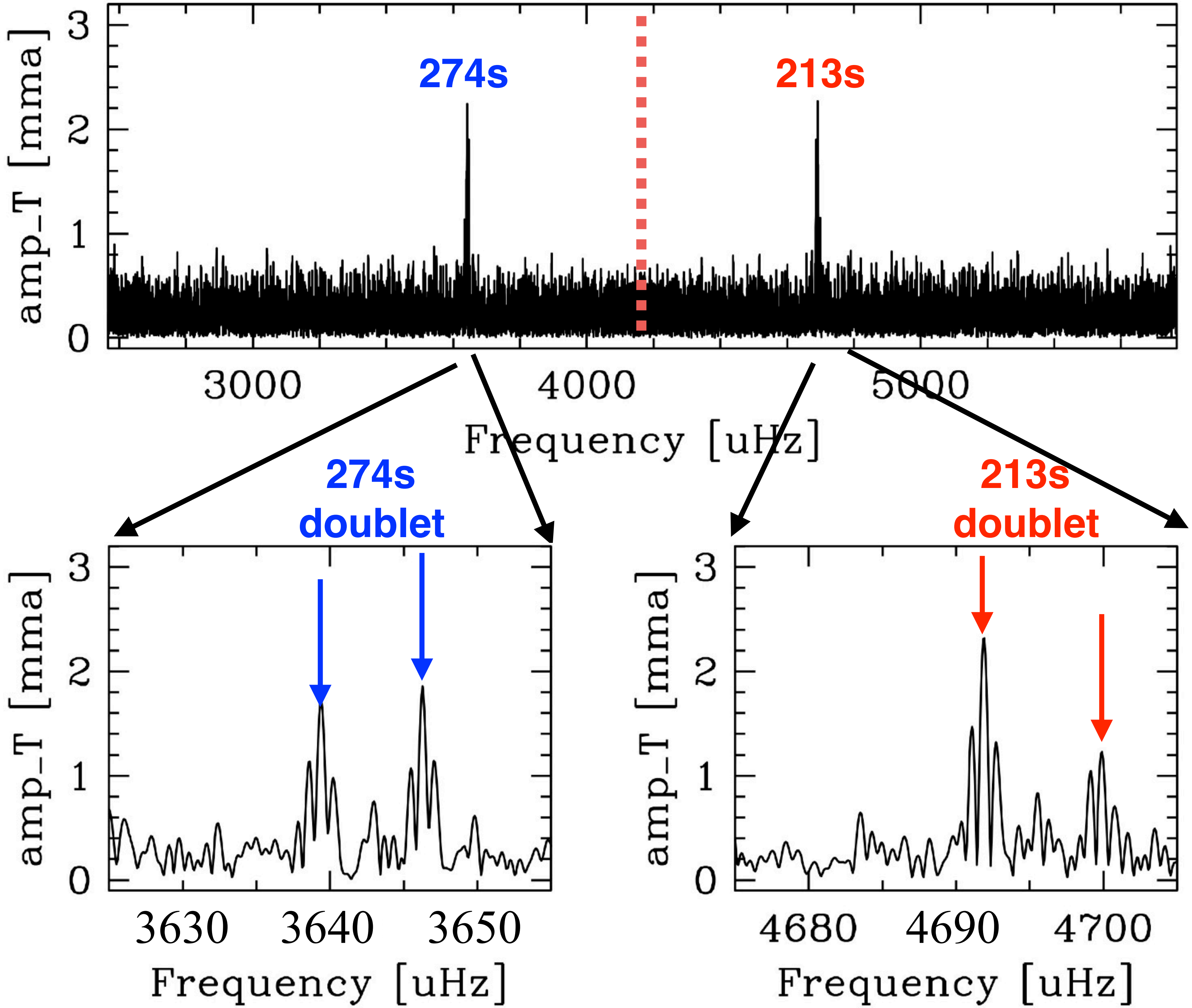
ZZ Ceti (R548)

Cory Schrandt, ISU MS thesis, 2019

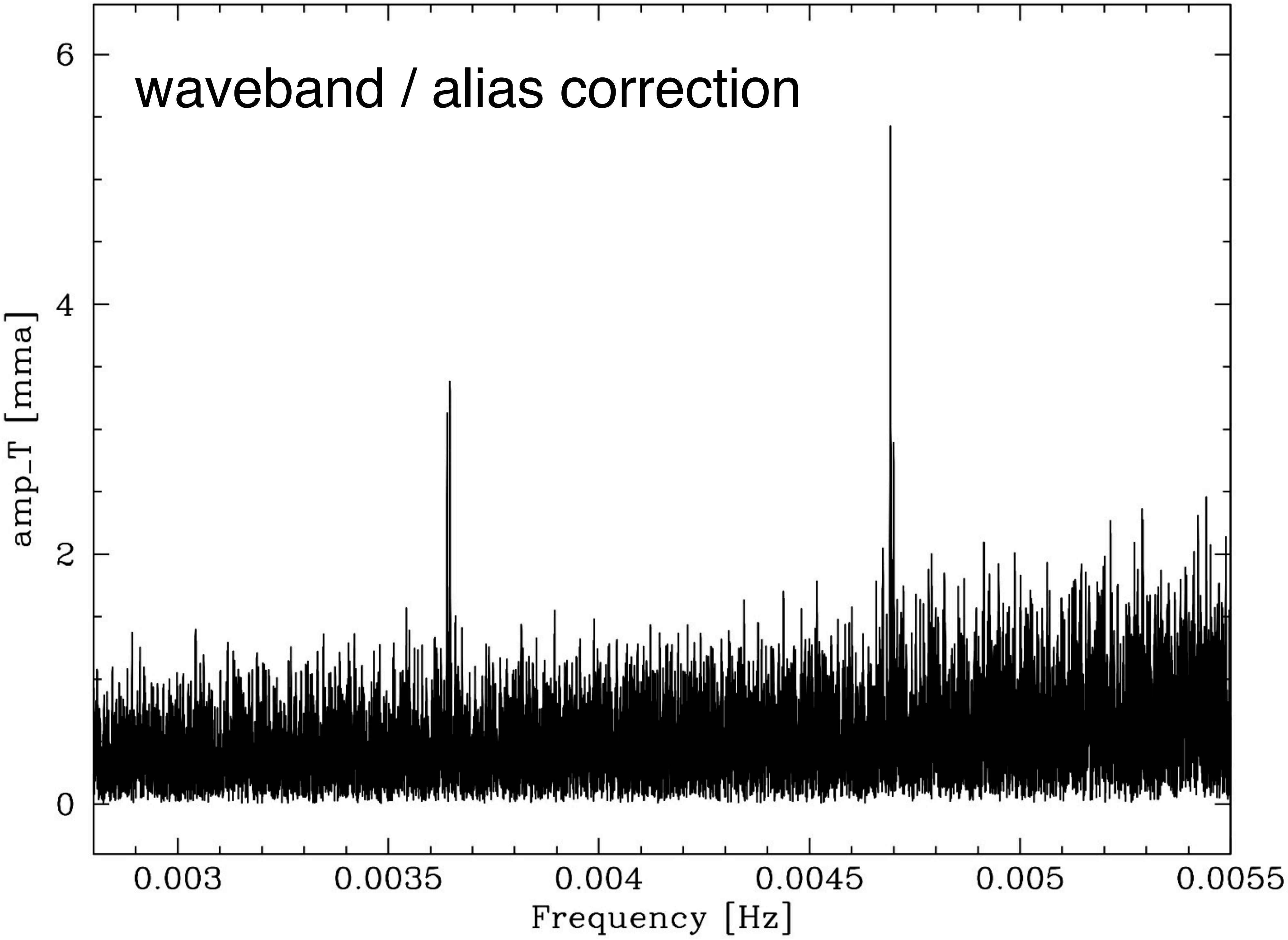


ZZ Ceti (R548)

Cory Schrandt, ISU MS thesis, 2019



ZZ Ceti (R548)



TESS Sector 1 (~ 20 days)

ZZ Ceti (R548)

Mukadam et al. (2013)

- 2 stable oscillation modes
- 41 years of data
- dP/dt = 0.5 - 1 x 10^{-15}

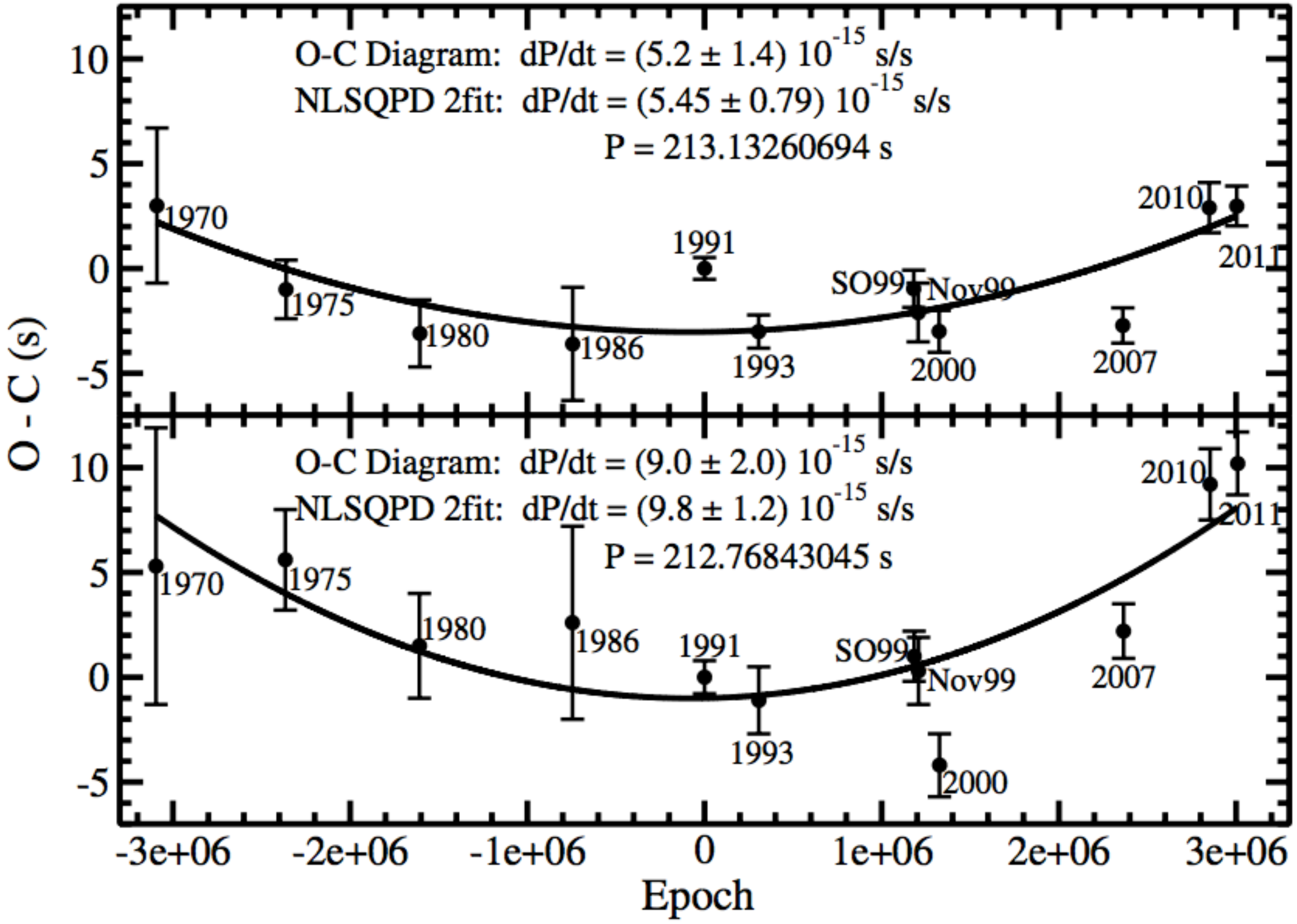
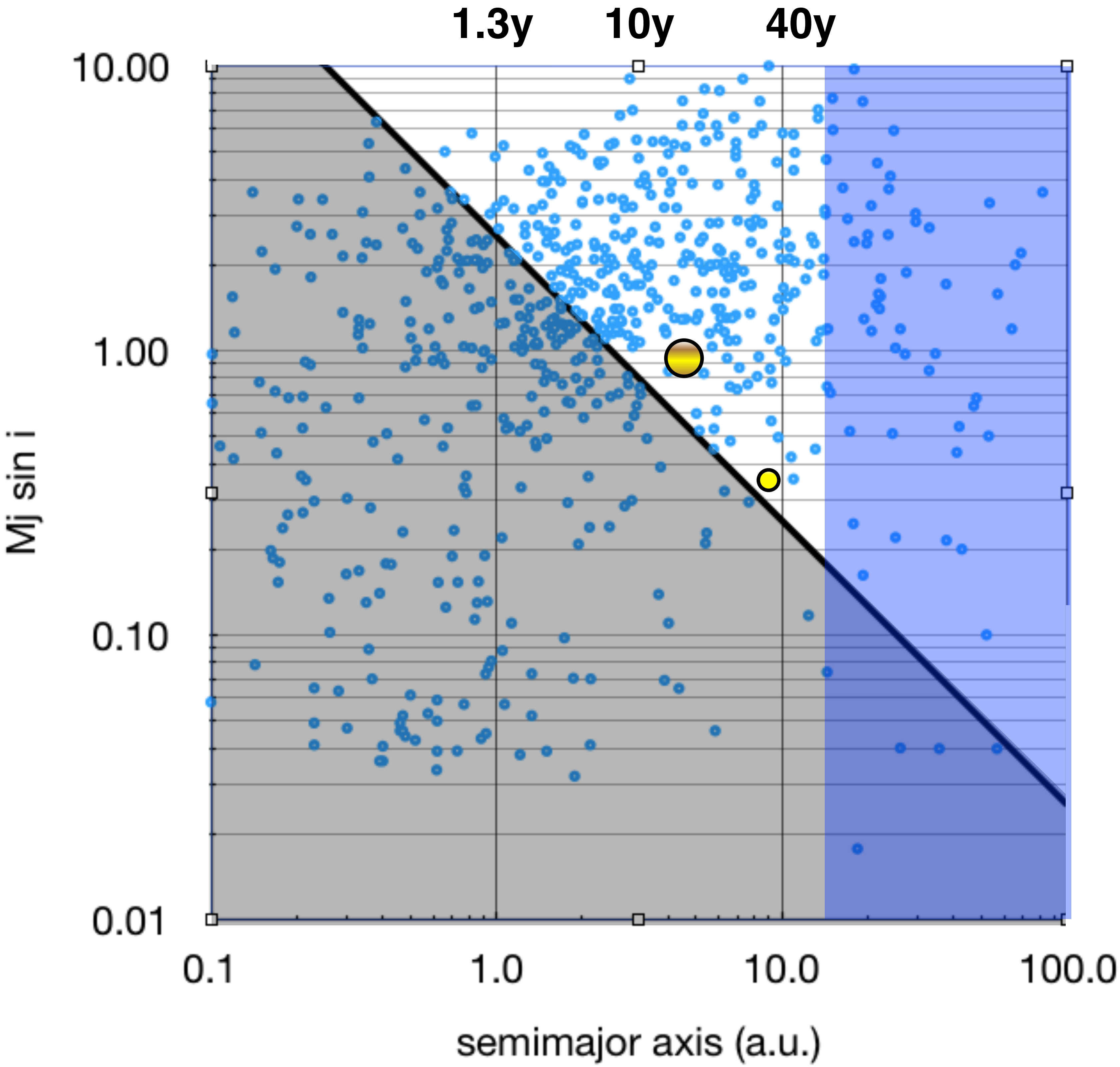


Figure 5. *O* − *C* diagrams obtained for the 213.13260694 s and 212.76843045 s periods.

ZZ Ceti - planet limits

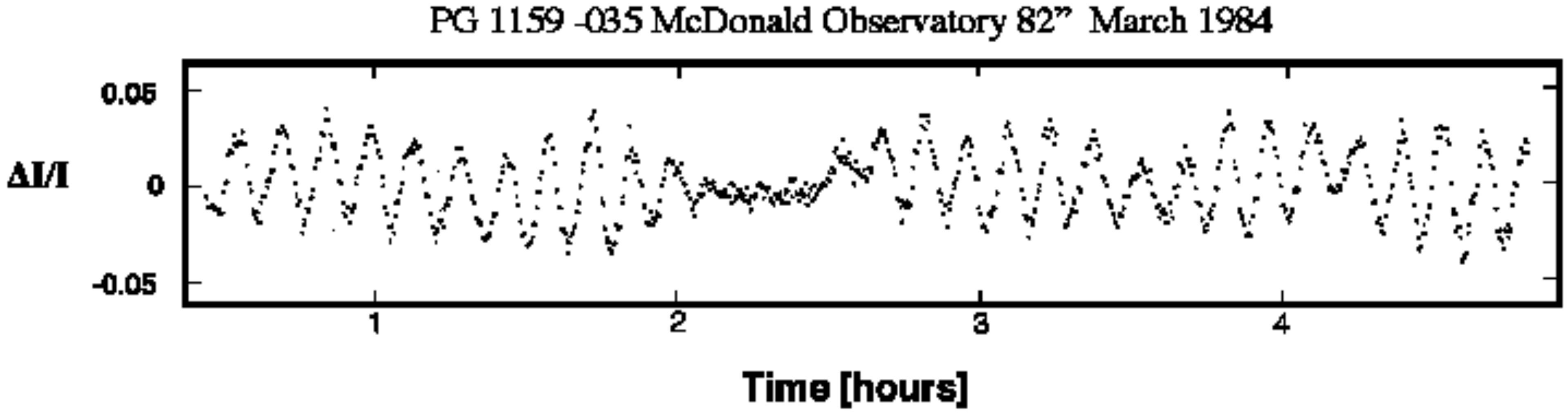


0.6M$_{o}$ primary

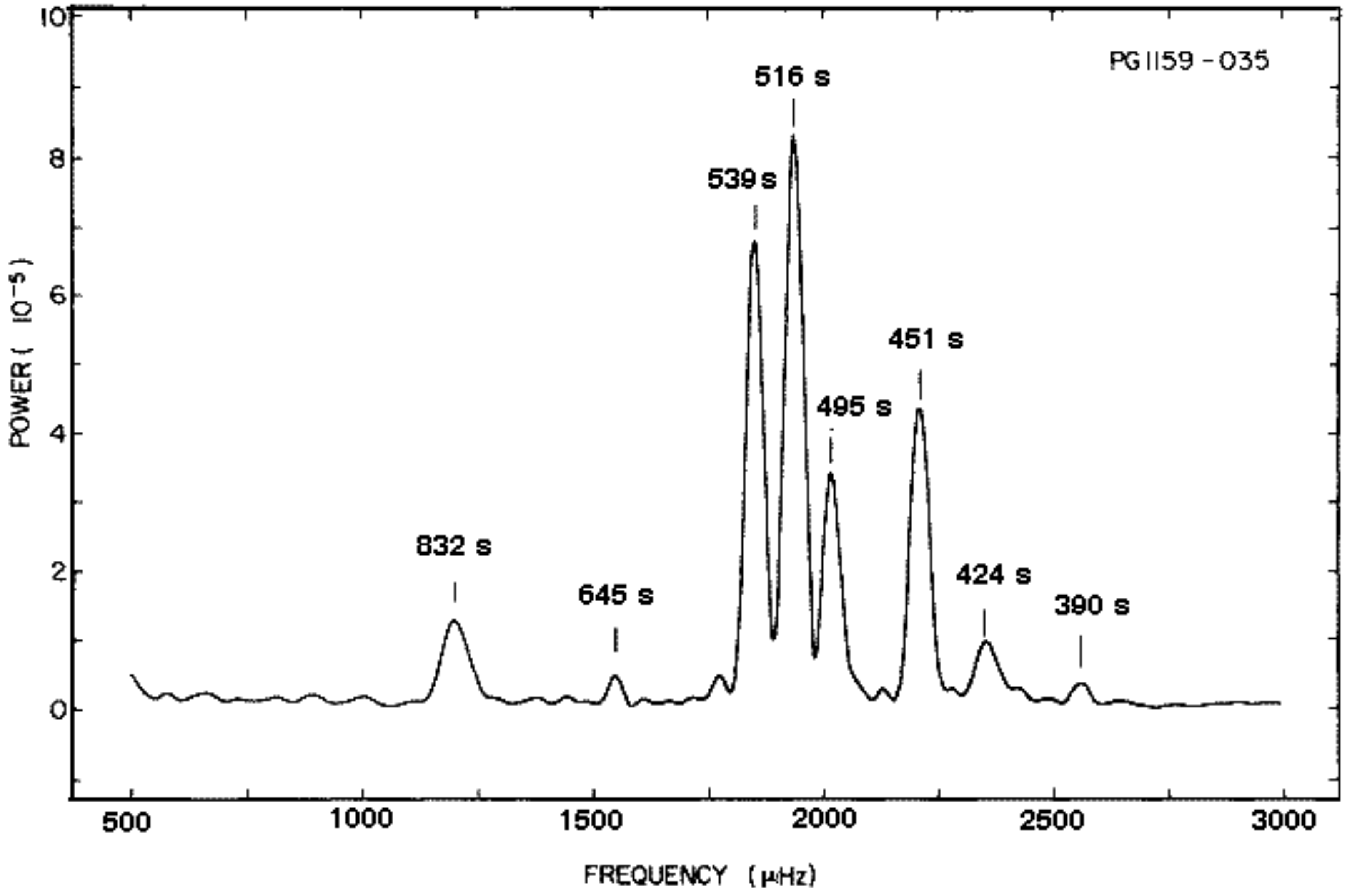
2 s (O-C) timing

50 year span

hot white dwarf PG 1159-035:
a g-mode pulsator

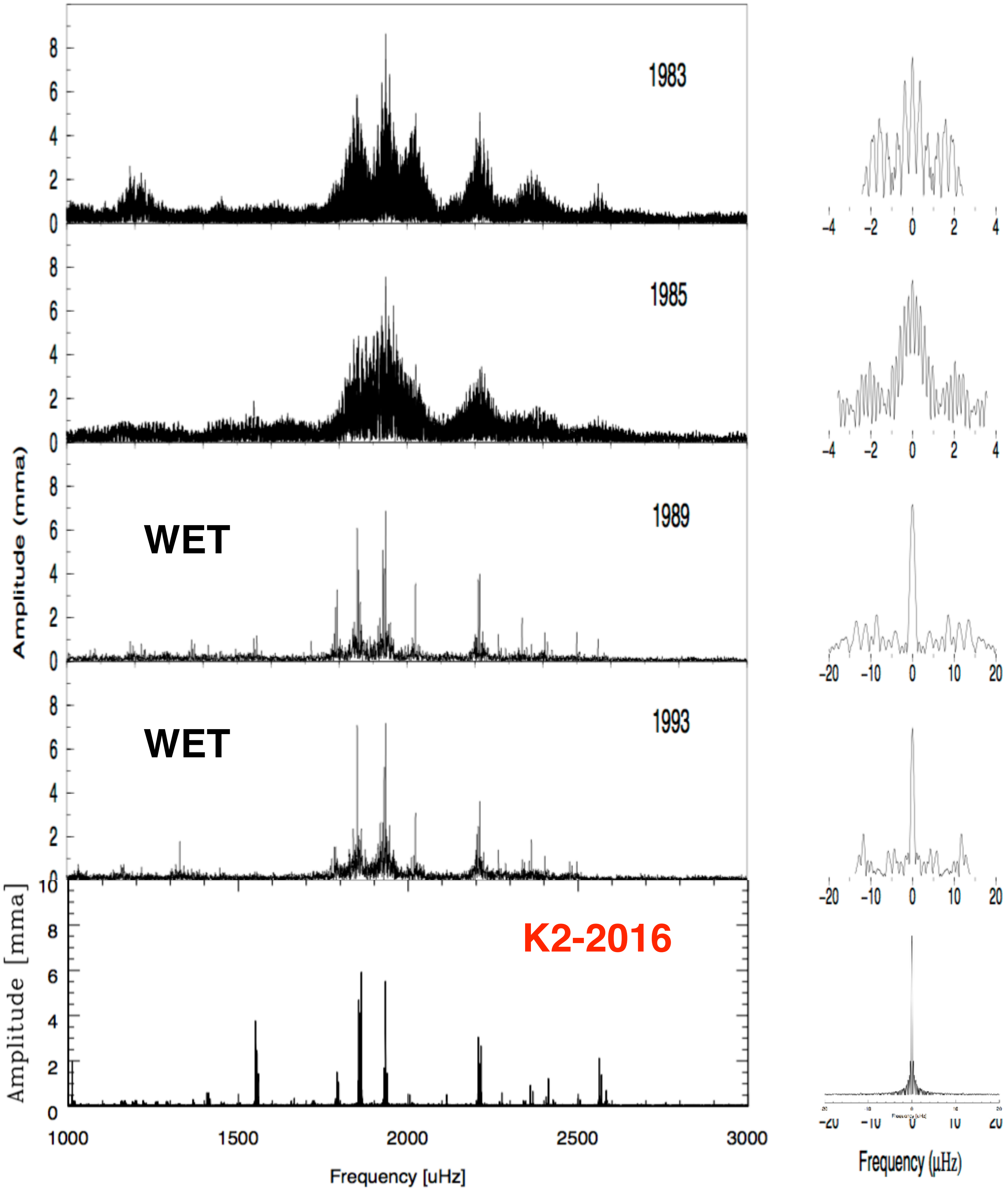

PG 1159 -035 McDonald Observatory 82" March 1984

March 1984



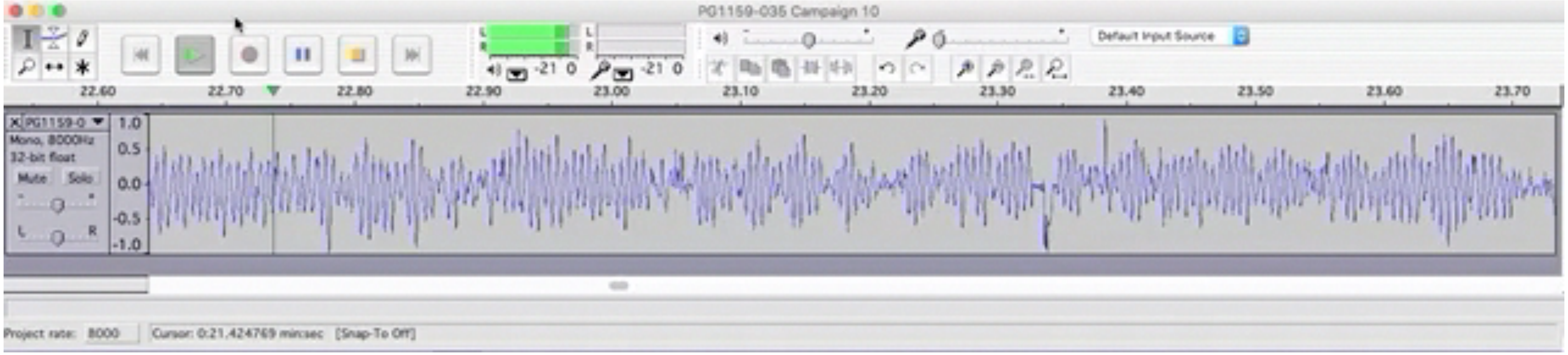
P	P-390	
390	0	
424	34	?
451	61	3 x 20.3
495	105	5 x 21.0
516	126	6 x 21.0
539	149	7 x 21.3
645	255	12 x 21.3
832	442	21 x 21.0

PG1159 through the years



Corsico et al. [WET] 2008

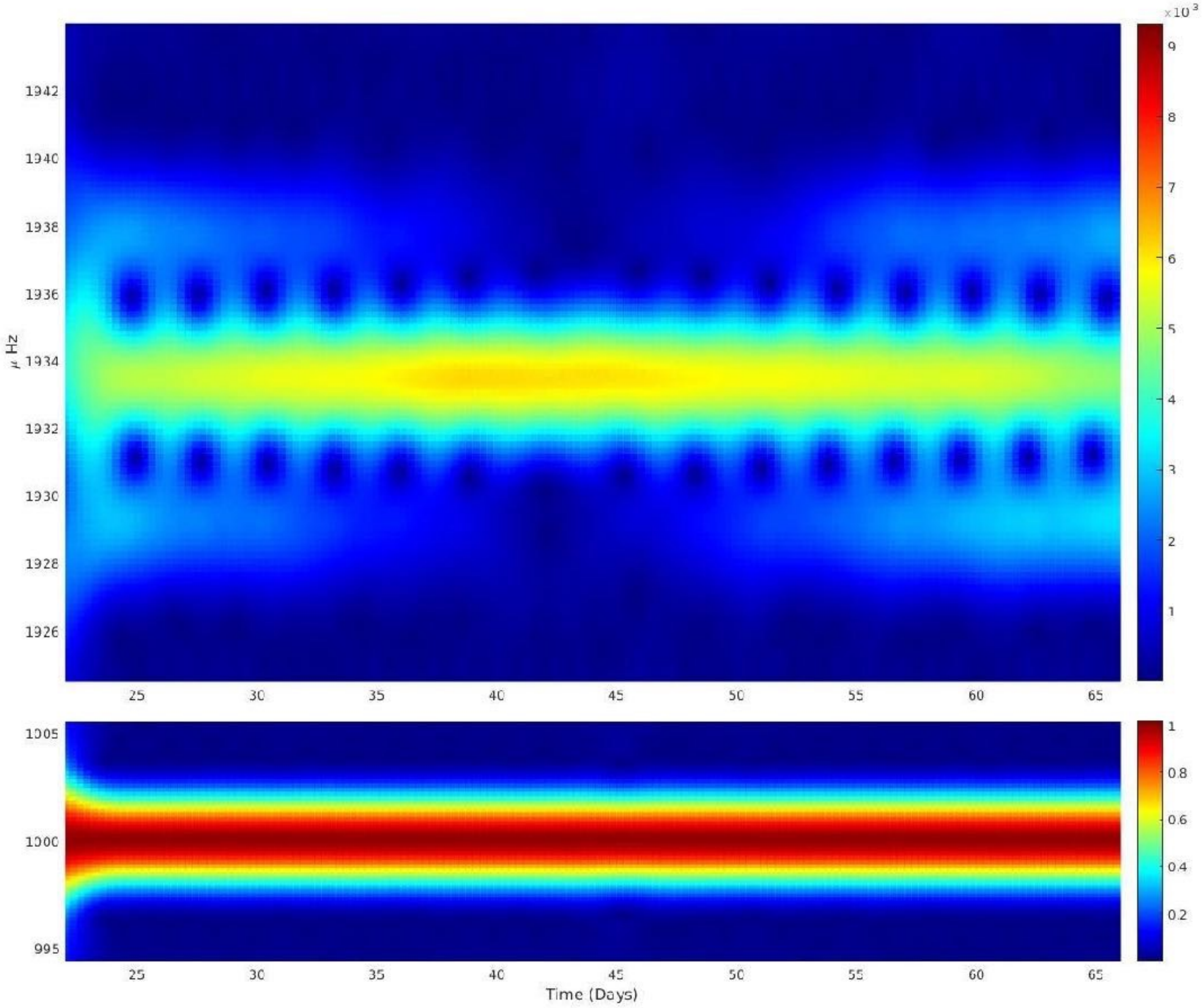
middling time scale variability… at 86,400 x



Mono, 8000Hz
32-bit float

Project rate: 8000

Cursor: 0:21.424769 min:sec [Snap-To Off]

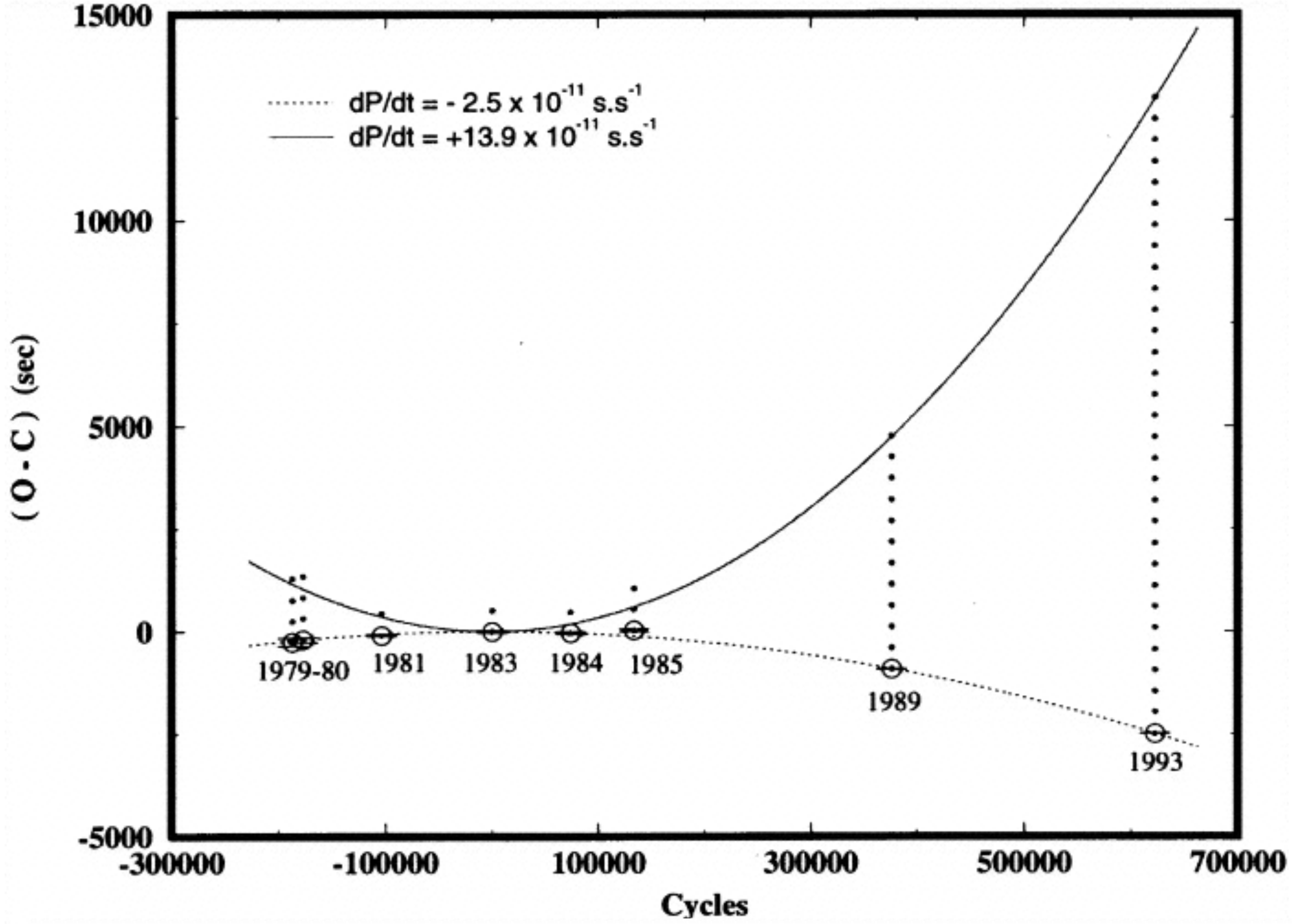


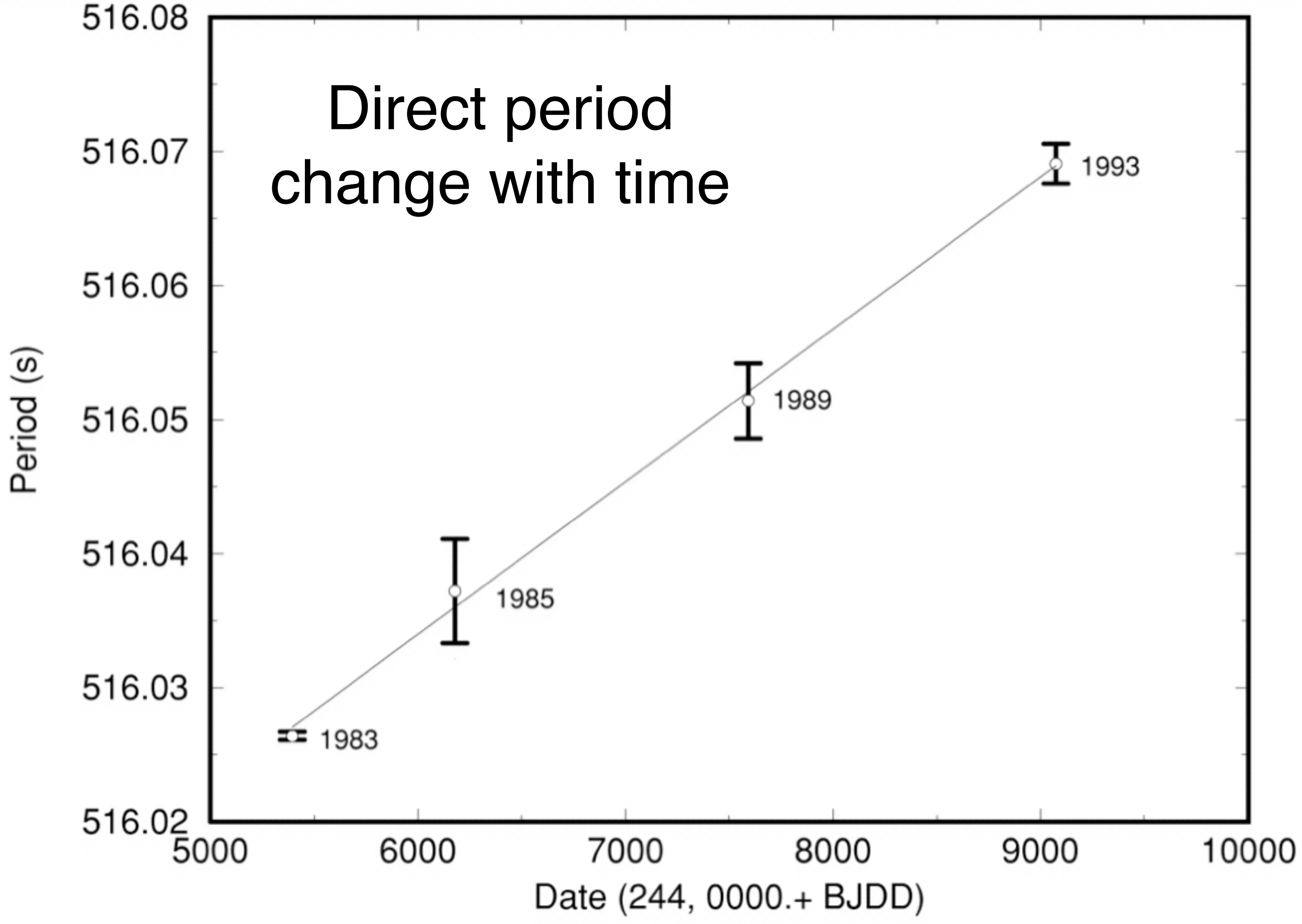
PG 1159
phase stability

(Costa et al. 1999, 2007)

$dP/dt = +13 \times 10^{-11}$

theoretical values for dP/dt generally range from +0.05 to +10 $\times 10^{-11}$

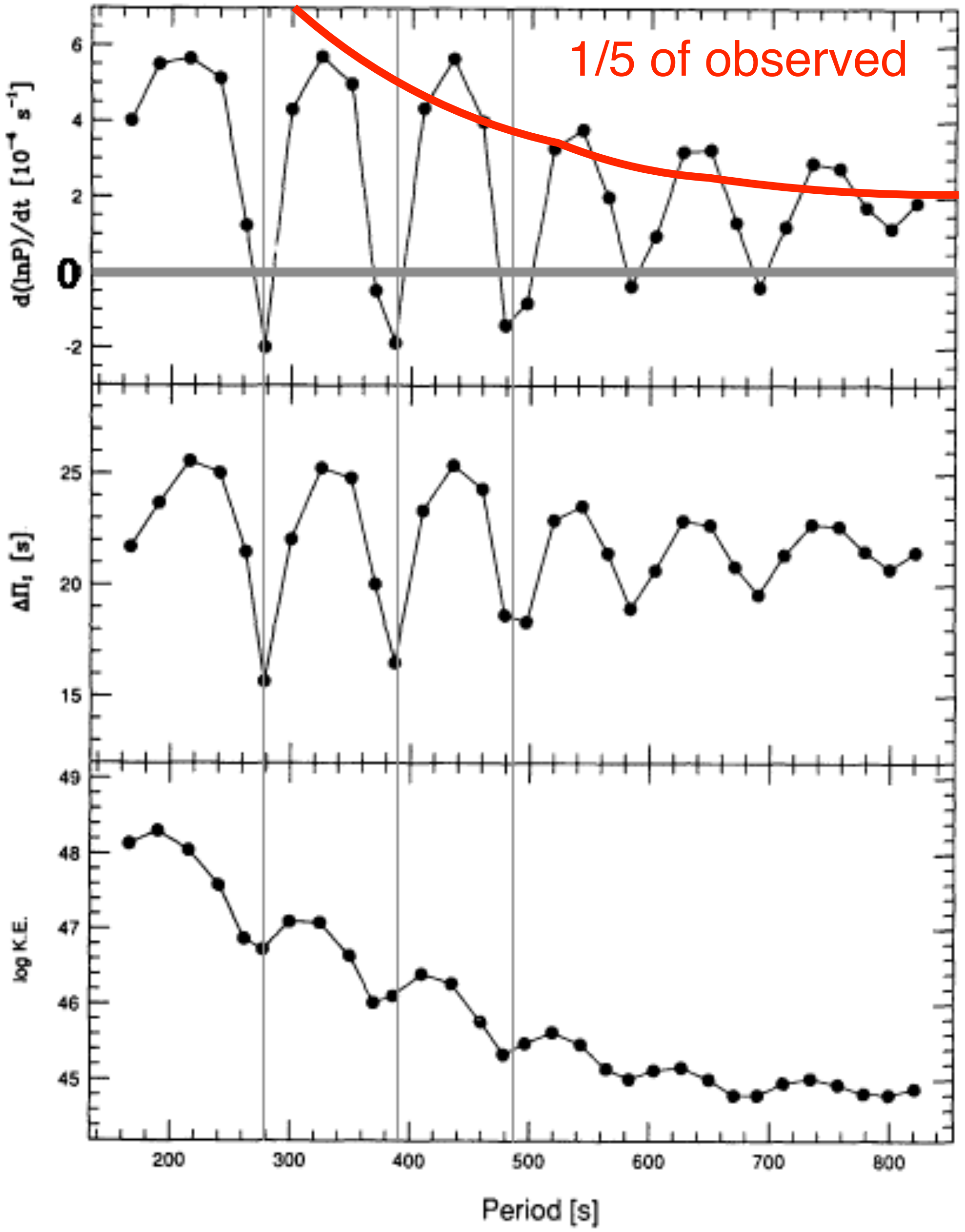


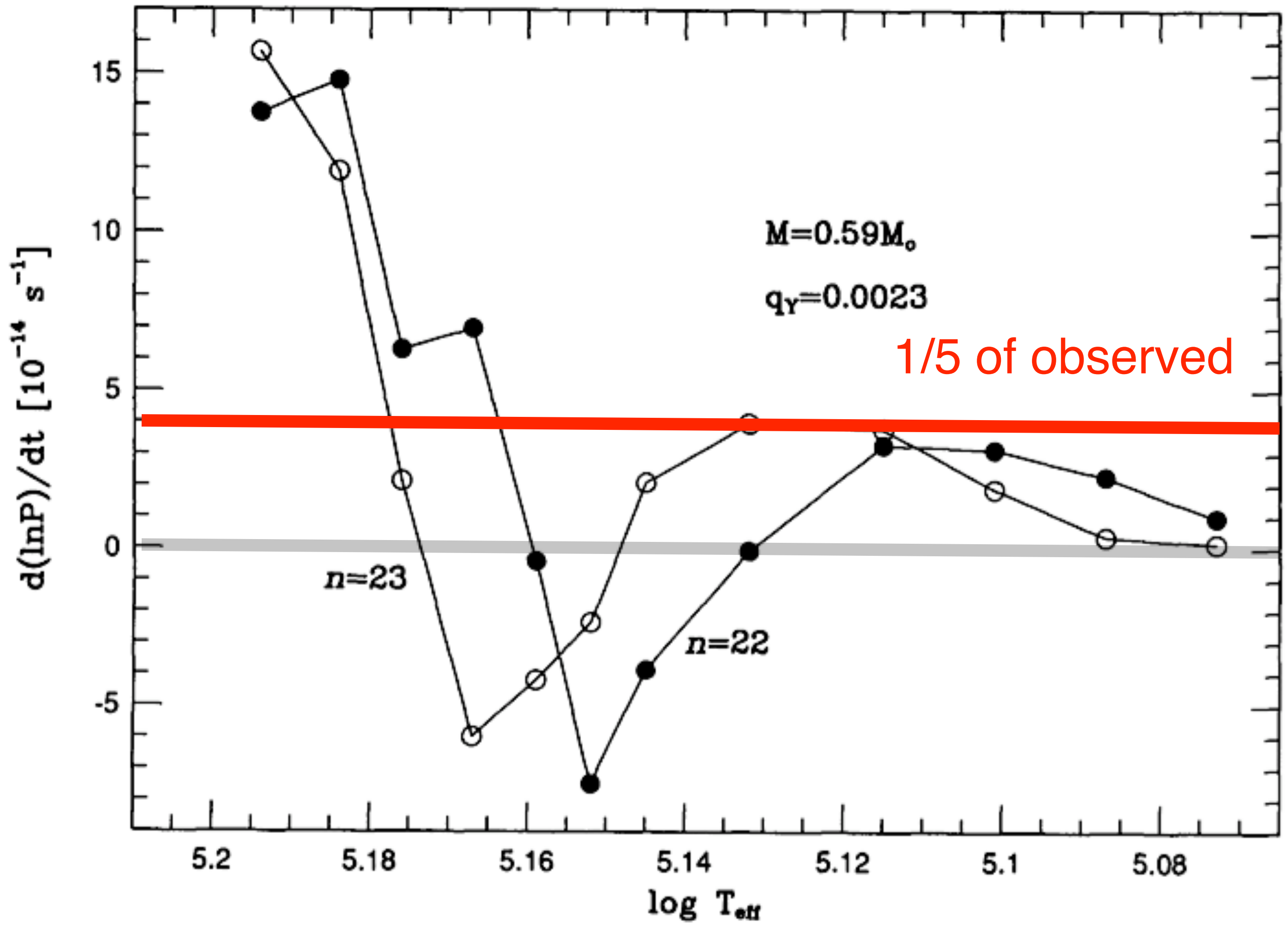


Direct period change with time

Some models of PG 1159

(Kawaler and Bradley 1994)

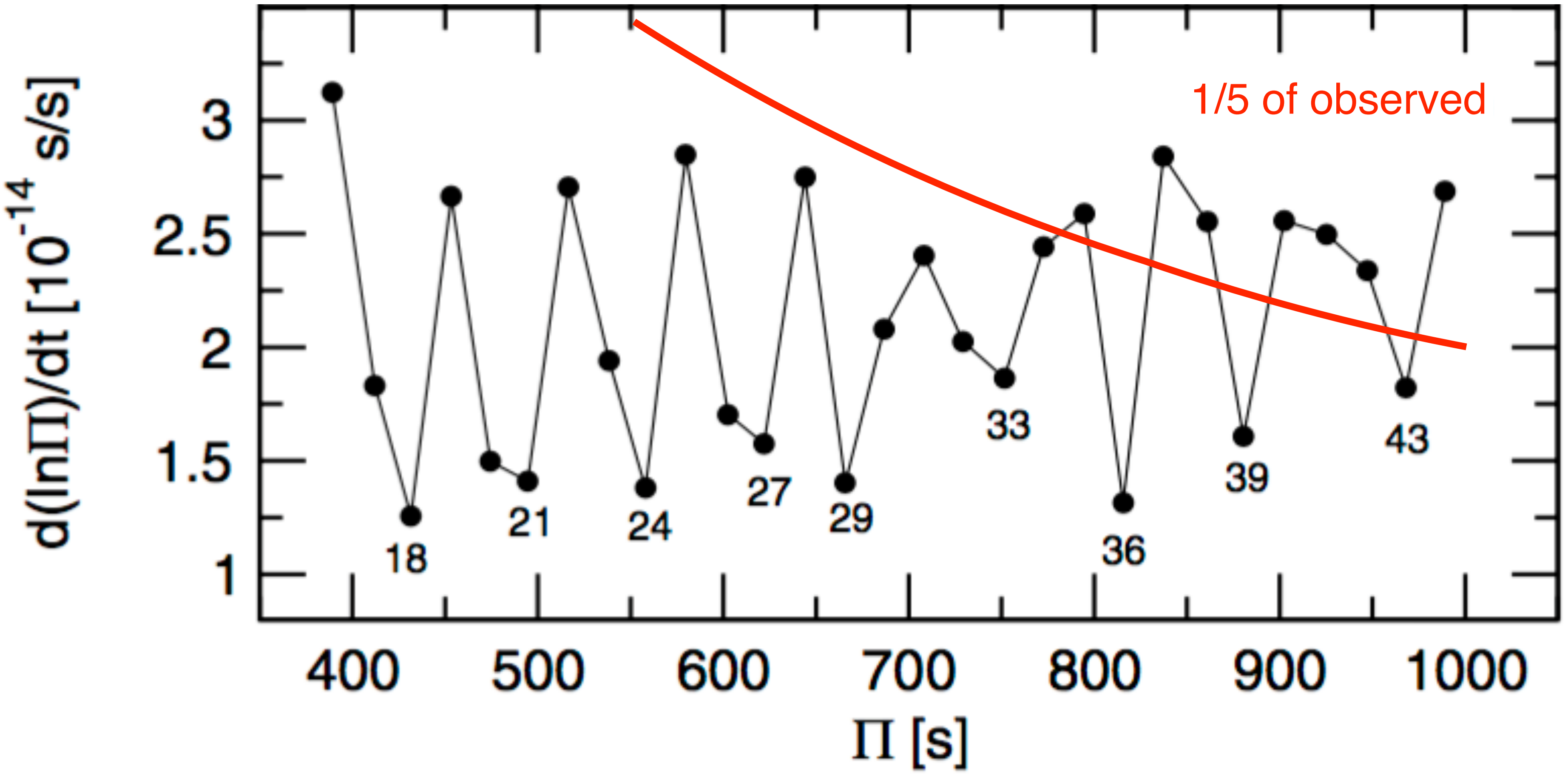




- Model dP/dt is (way) too small compared to observation
  - need to check with dP/dt for other modes
  - theoretical value is always a lower limit to dP/dt

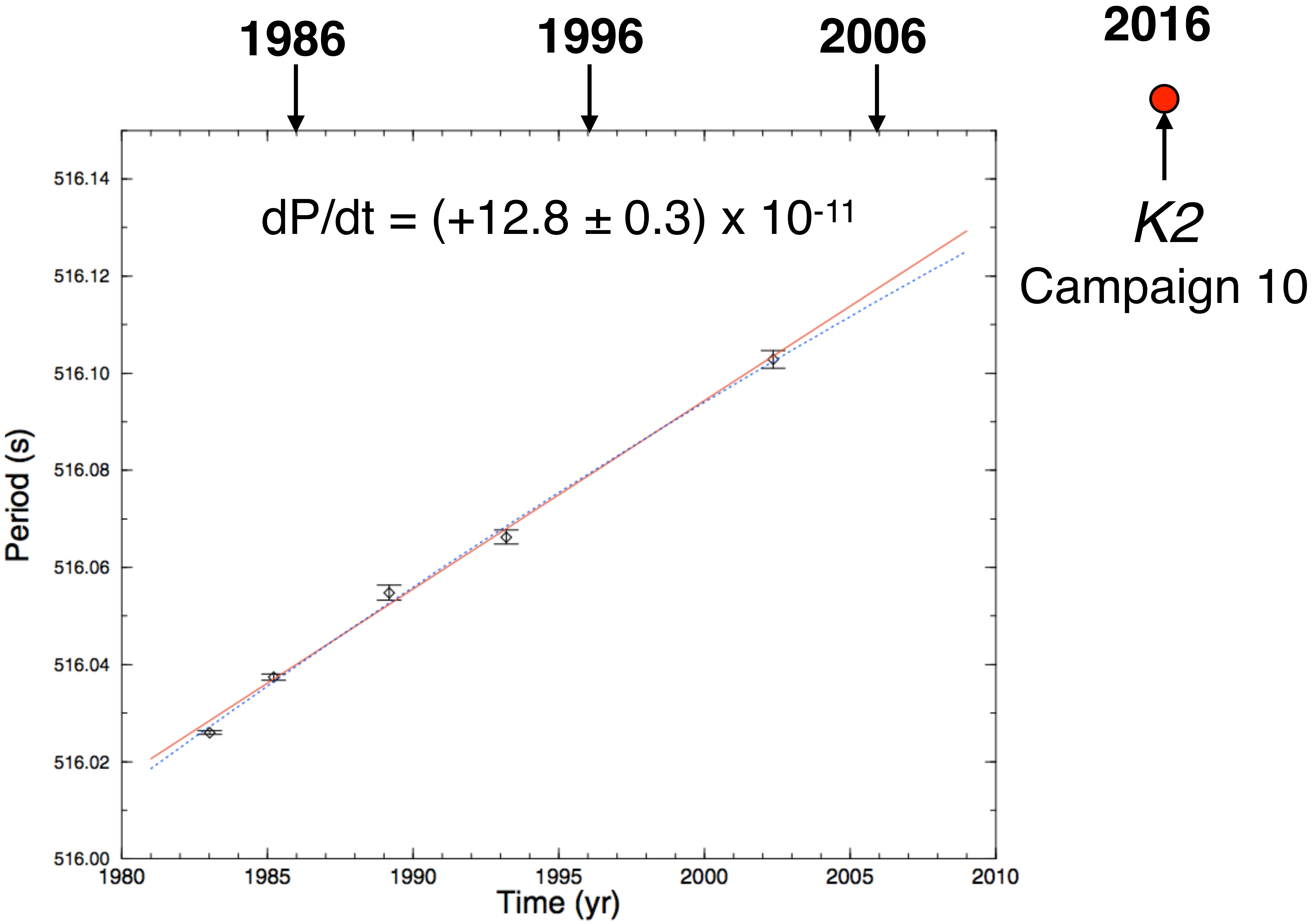
Other models of PG 1159

(Córsico et al. 2008)



- Model dP/dt is ***still*** too small compared to observation
  - need to check with dP/dt for other modes
  - theoretical value is always a lower limit to dP/dt

P vs. *t* for the 516s mode **w/ new result from *K2***



1986

1996

2006

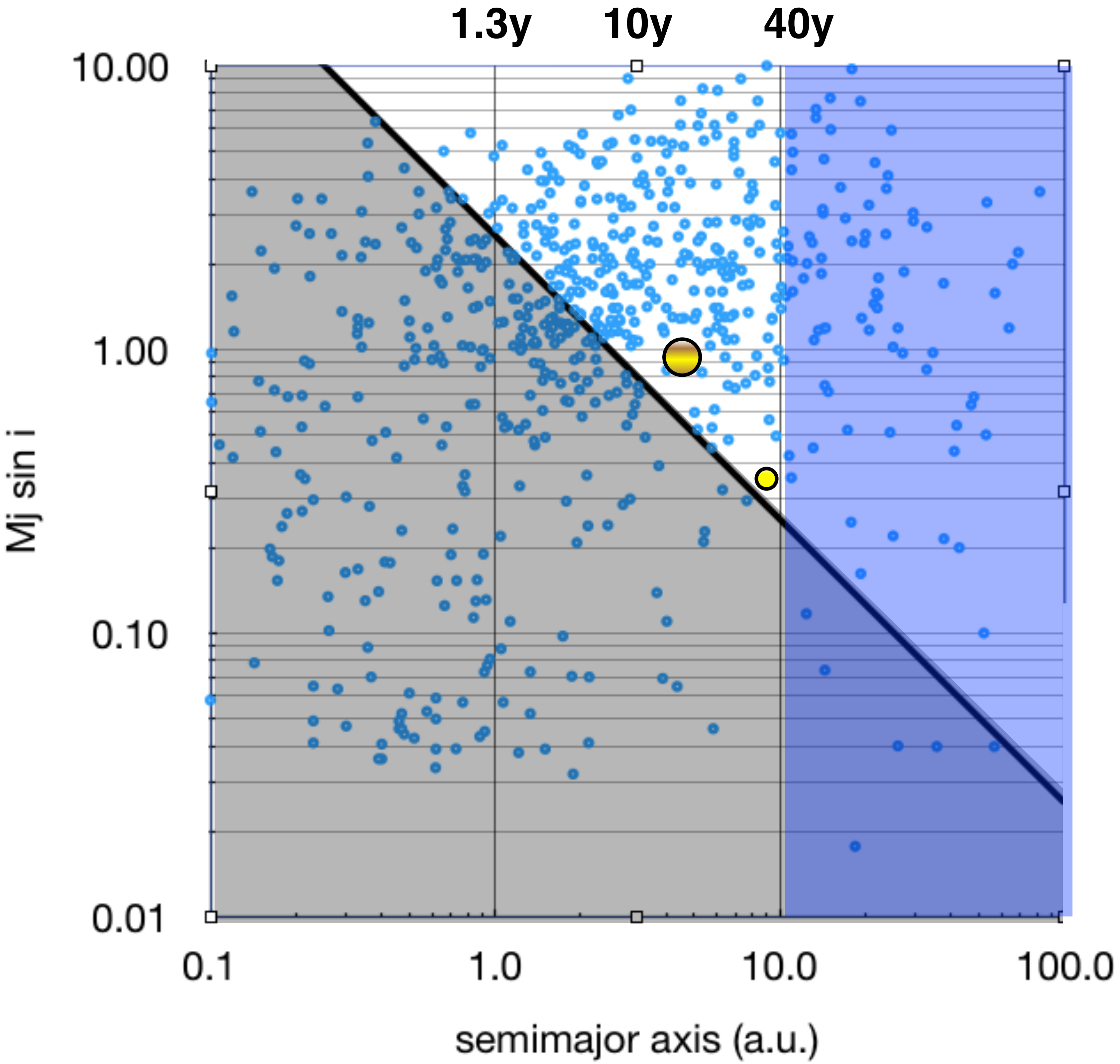
2016

K2

Campaign 10

$dP/dt = (+12.8 \pm 0.3) \times 10^{-11}$

PG 1159 - planet limits

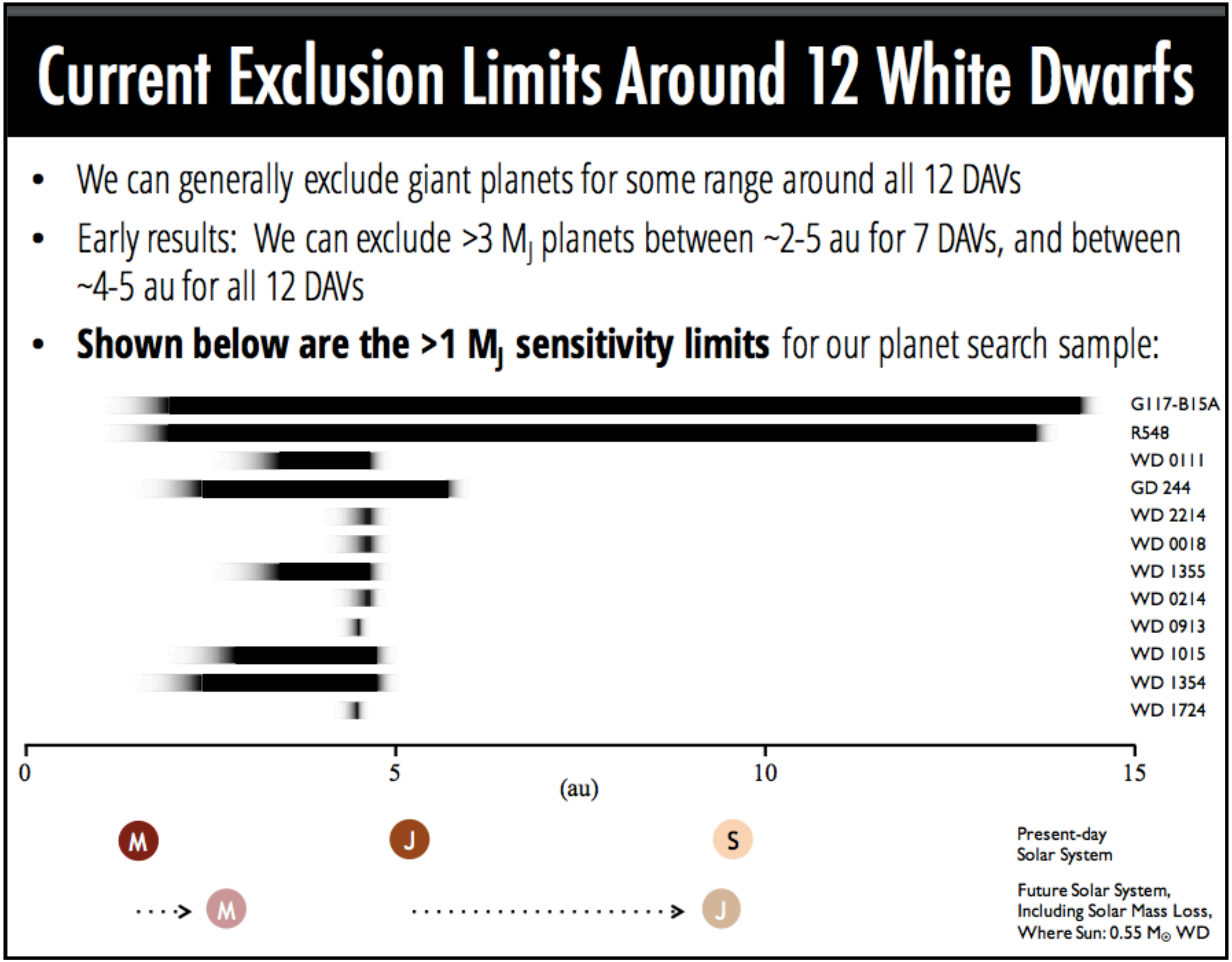


0.6M$_{\odot}$ primary

2 s (O-C) timing

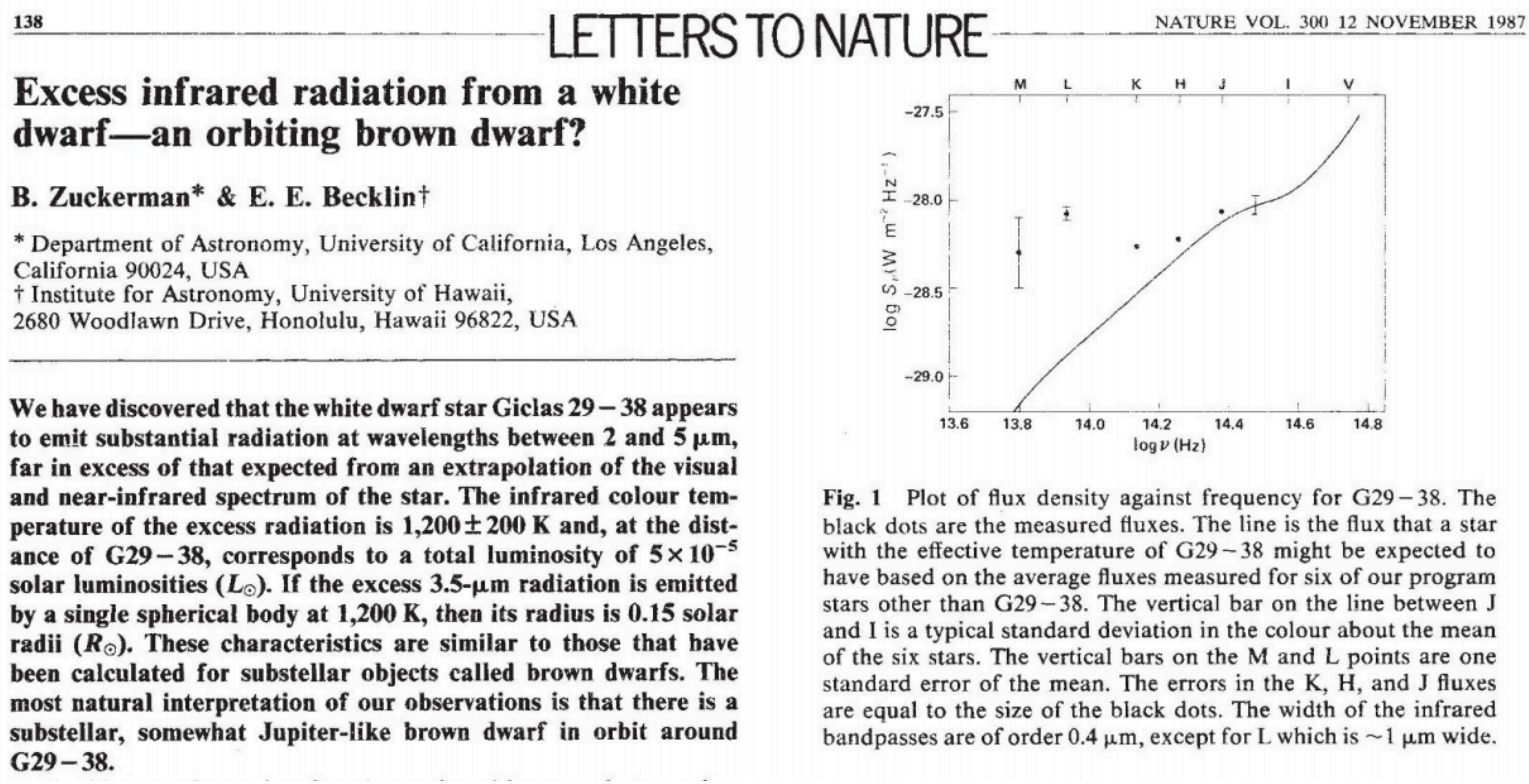
40 year span

from JJ Hermes:



Current Exclusion Limits Around 12 White Dwarfs

- We can generally exclude giant planets for some range around all 12 DAVs
- Early results: We can exclude >3 M_J planets between ~2-5 au for 7 DAVs, and between ~4-5 au for all 12 DAVs
- **Shown below are the >1 M_J sensitivity limits** for our planet search sample:



Excess infrared radiation from a white dwarf—an orbiting brown dwarf?

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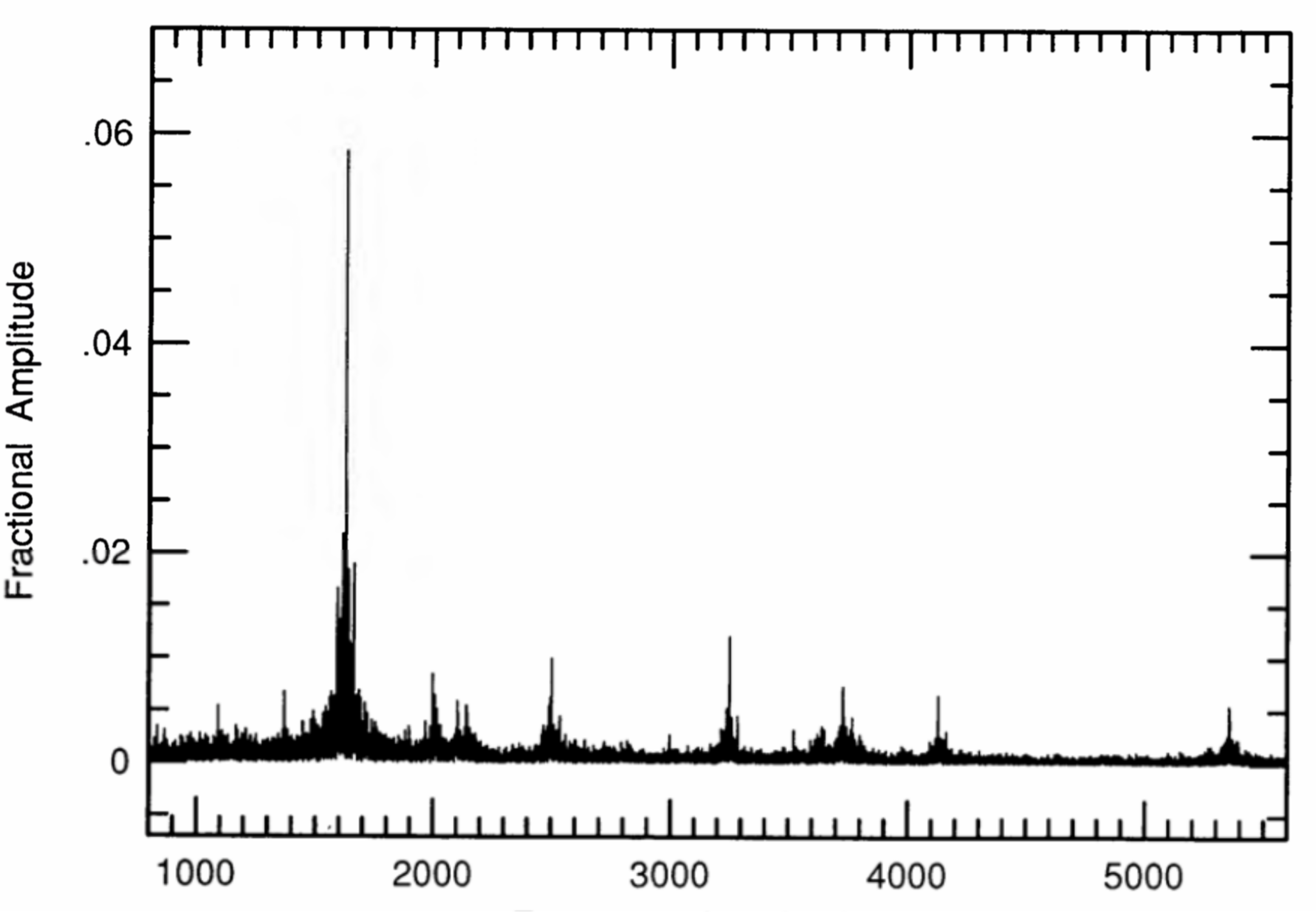
* Department of Astronomy, University of California, Los Angeles,
California 90024, USA
† Institute for Astronomy, University of Hawaii,
2680 Woodlawn Drive, Honolulu, Hawaii 96822, USA

We have discovered that the white dwarf star Giclas 29 − 38 appears to emit substantial radiation at wavelengths between 2 and 5 μm, far in excess of that expected from an extrapolation of the visual and near-infrared spectrum of the star. The infrared colour temperature of the excess radiation is 1,200 ± 200 K and, at the distance of G29 − 38, corresponds to a total luminosity of 5×10^{-5} solar luminosities ($L_\odot$). If the excess 3.5-μm radiation is emitted by a single spherical body at 1,200 K, then its radius is 0.15 solar radii ($R_\odot$). These characteristics are similar to those that have been calculated for substellar objects called brown dwarfs. The most natural interpretation of our observations is that there is a substellar, somewhat Jupiter-like brown dwarf in orbit around G29 − 38.

Fig. 1 Plot of flux density against frequency for G29 − 38. The black dots are the measured fluxes. The line is the flux that a star with the effective temperature of G29 − 38 might be expected to have based on the average fluxes measured for six of our program stars other than G29 − 38. The vertical bar on the line between J and I is a typical standard deviation in the colour about the mean of the six stars. The vertical bars on the M and L points are one standard error of the mean. The errors in the K, H, and J fluxes are equal to the size of the black dots. The width of the infrared bandpasses are of order 0.4 μm, except for L which is ~1 μm wide.

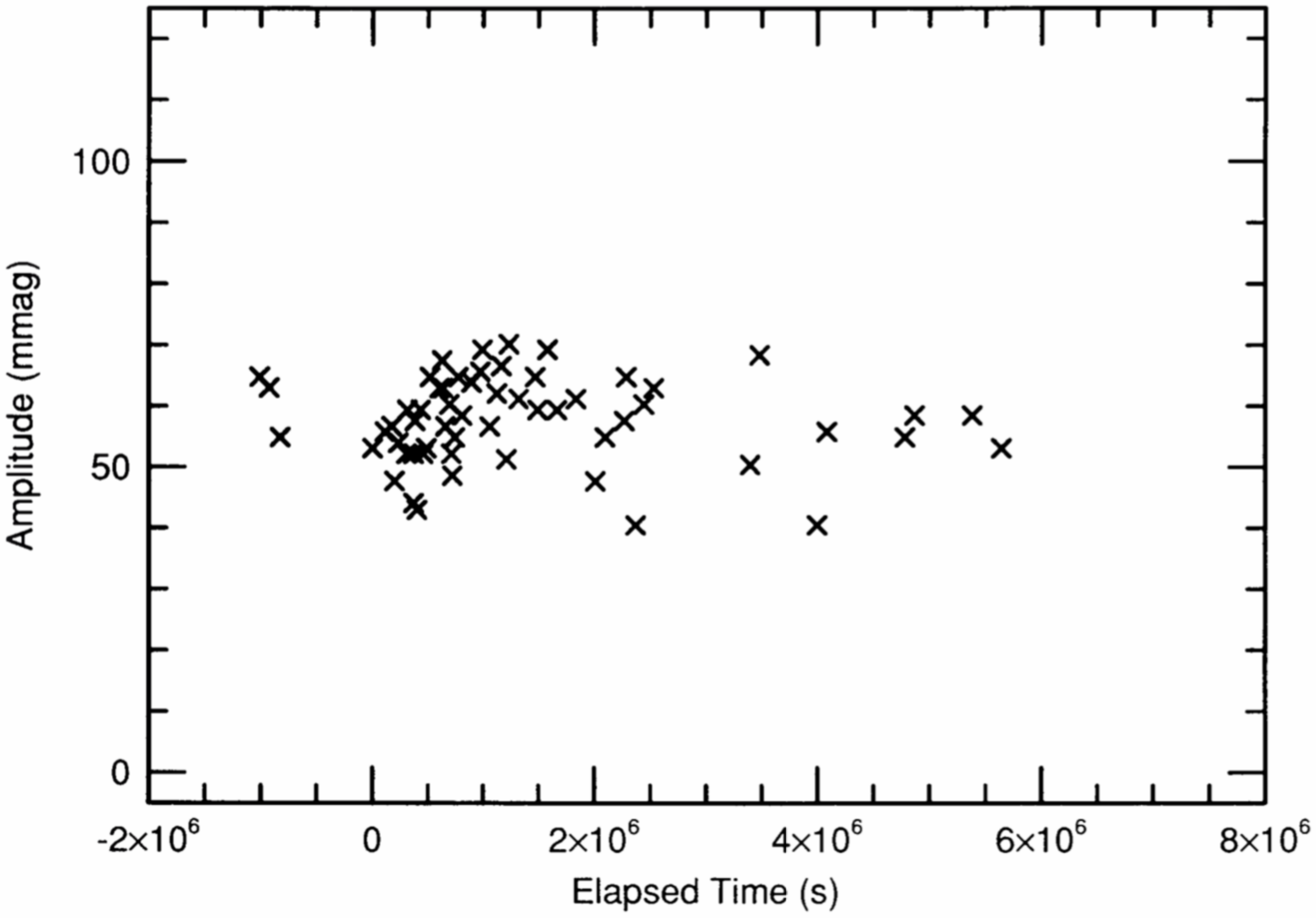
G 29-38

Winget et al. (1990)



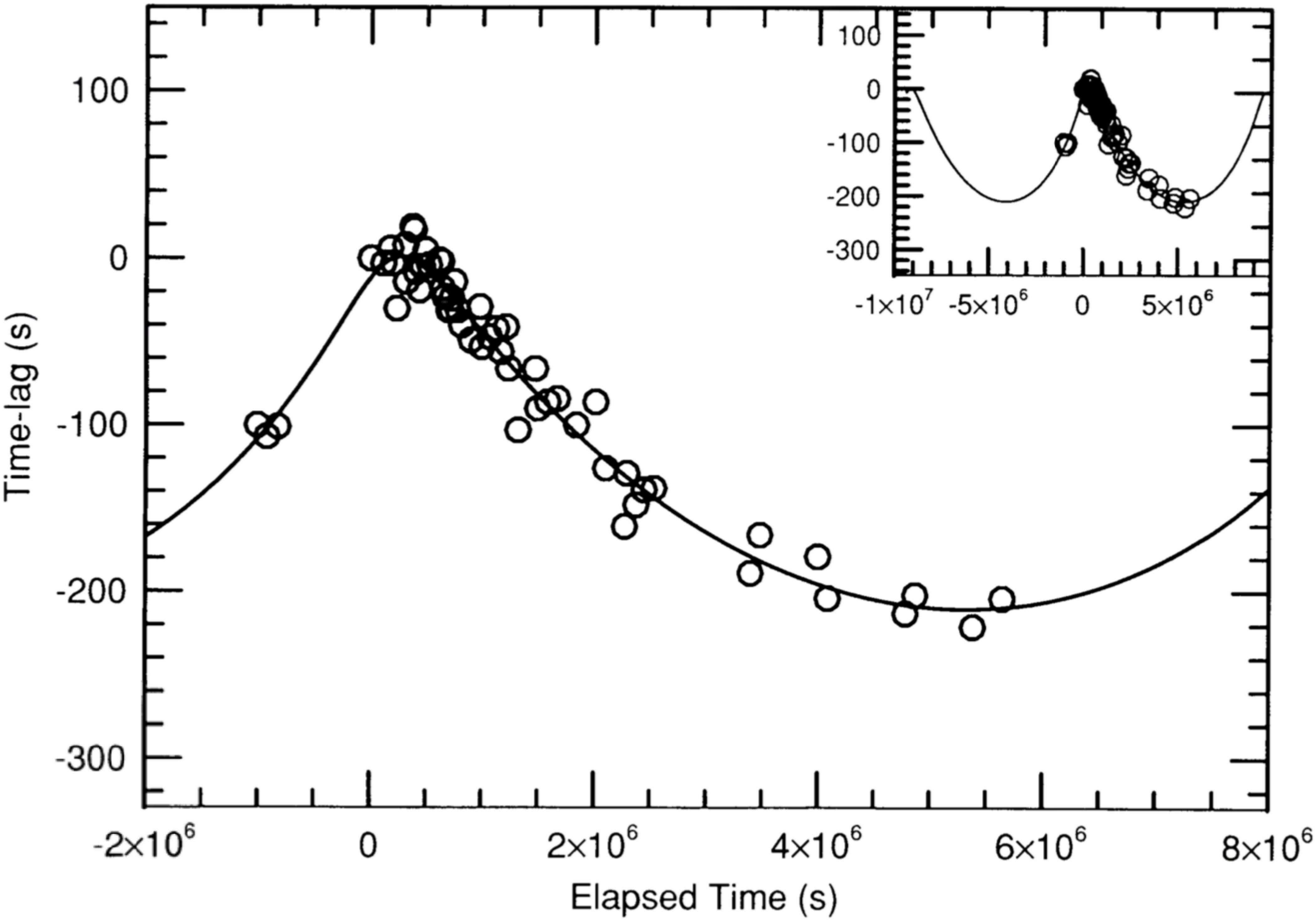
G 29-38

Winget et al. (1990)



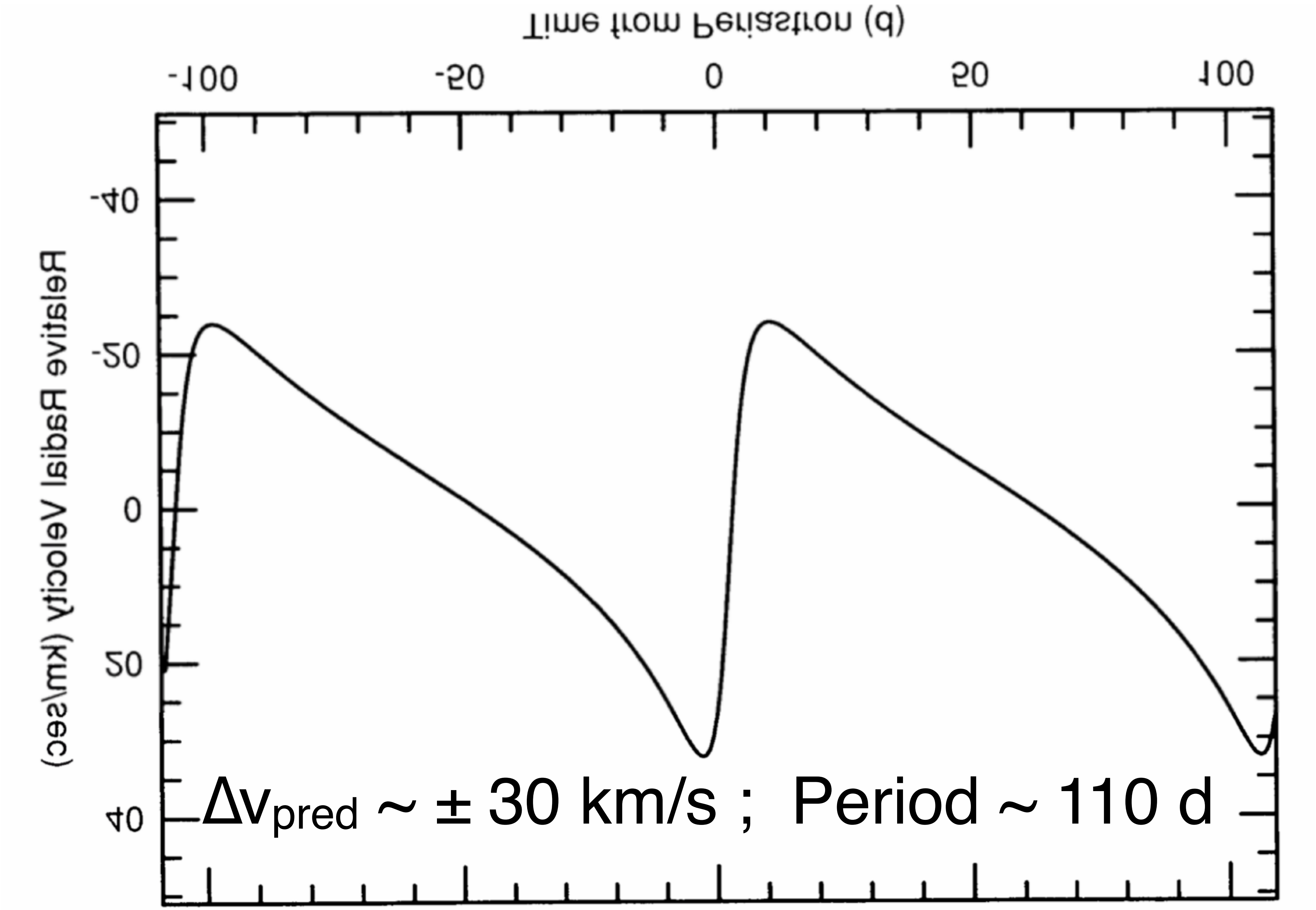
G 29-38

Winget et al. (1990)



G 29-38

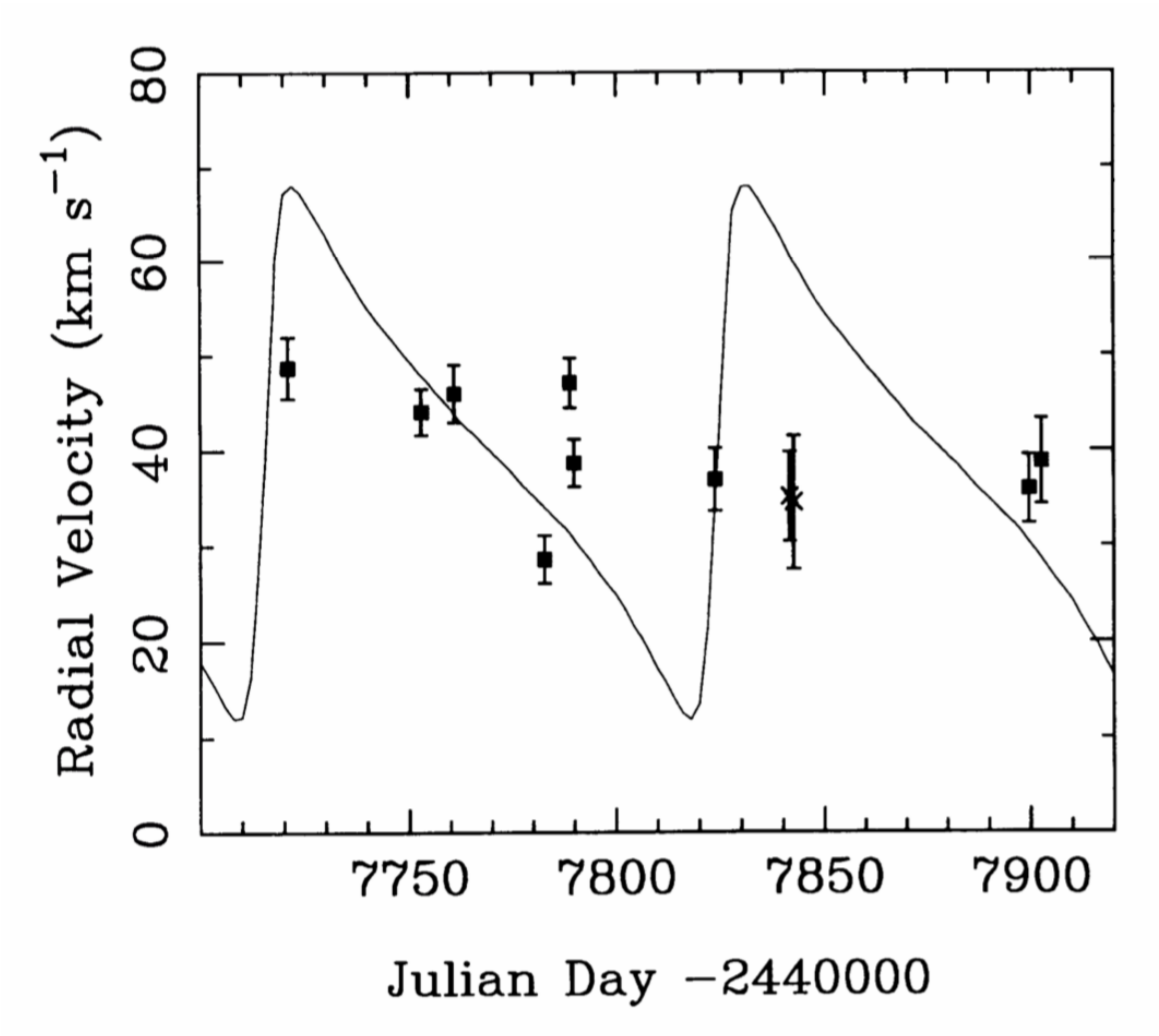
Winget et al. (1990)



$\Delta v_{\rm pred} \sim \pm$ 30 km/s ; Period ~ 110 d

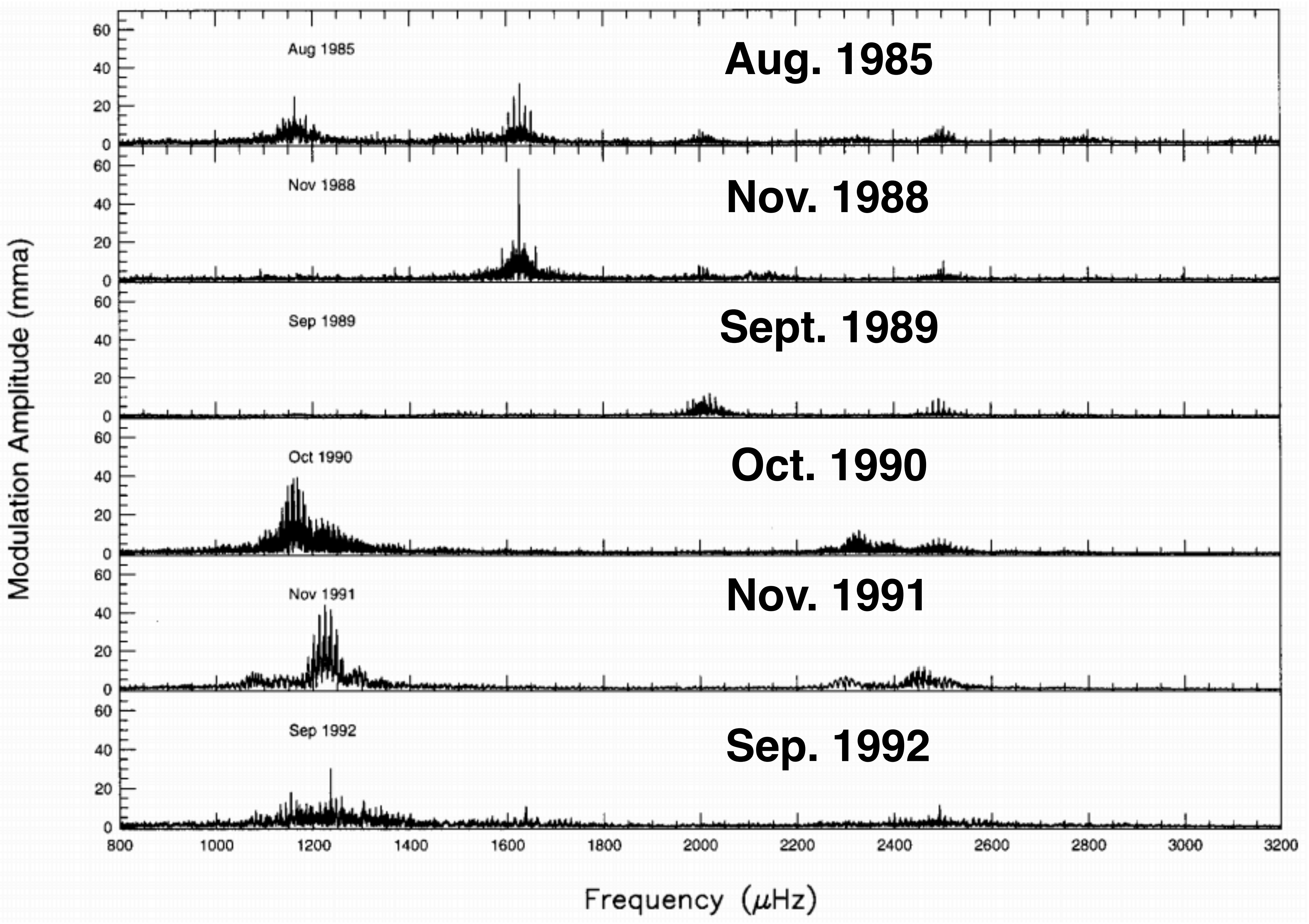
G 29-38

Graham et al. (1990)



G 29-38

Kleinman et al. (1998)



Aug. 1985

Nov. 1988

Sept. 1989

Oct. 1990

Nov. 1991

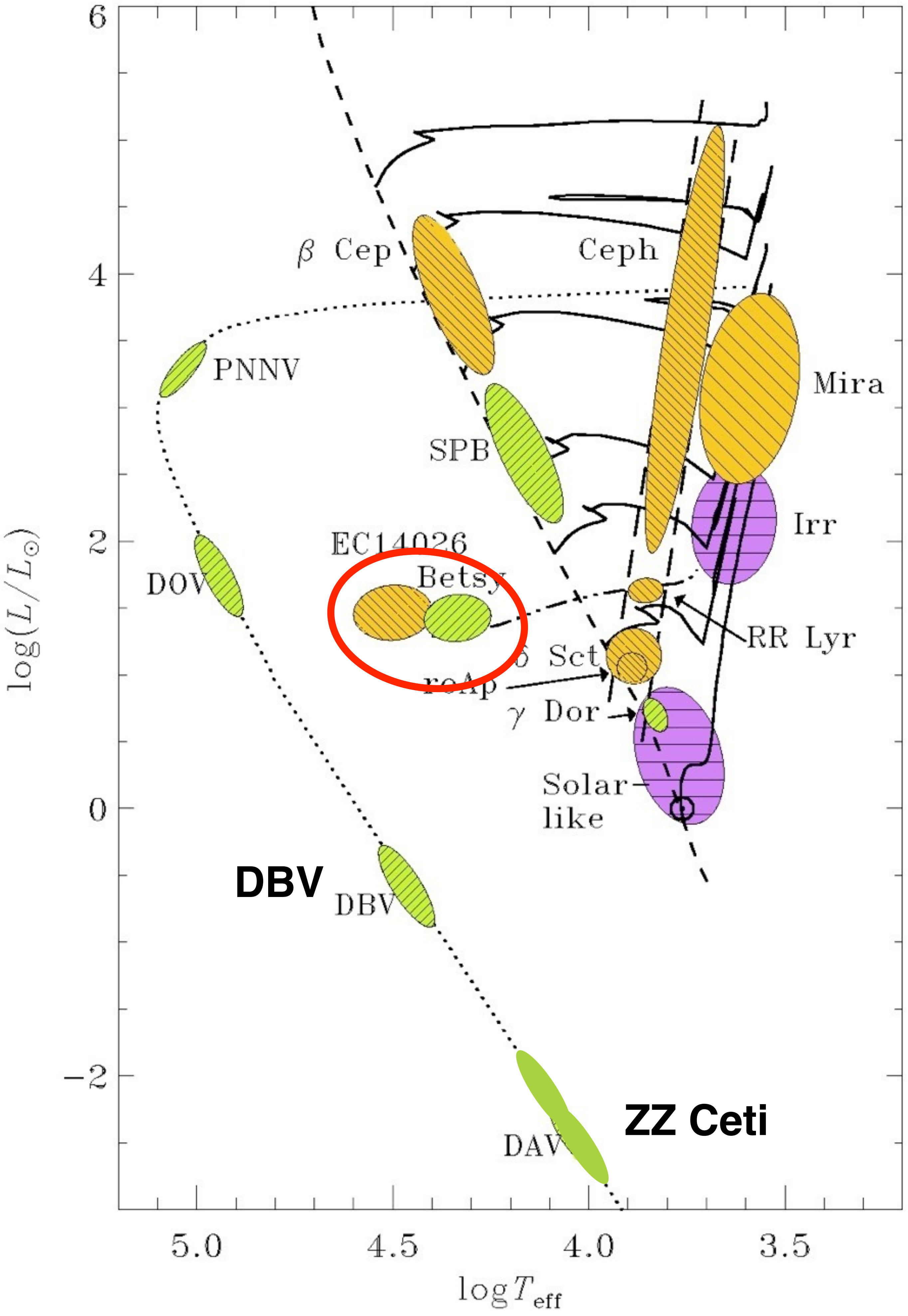
Sep. 1992

A Giant Planet Orbiting a Hot, Evolved Star

Silvotti et al.

Nature, September 13, 2007

Pulsating stars in the HR diagram



▨ p modes heat engine

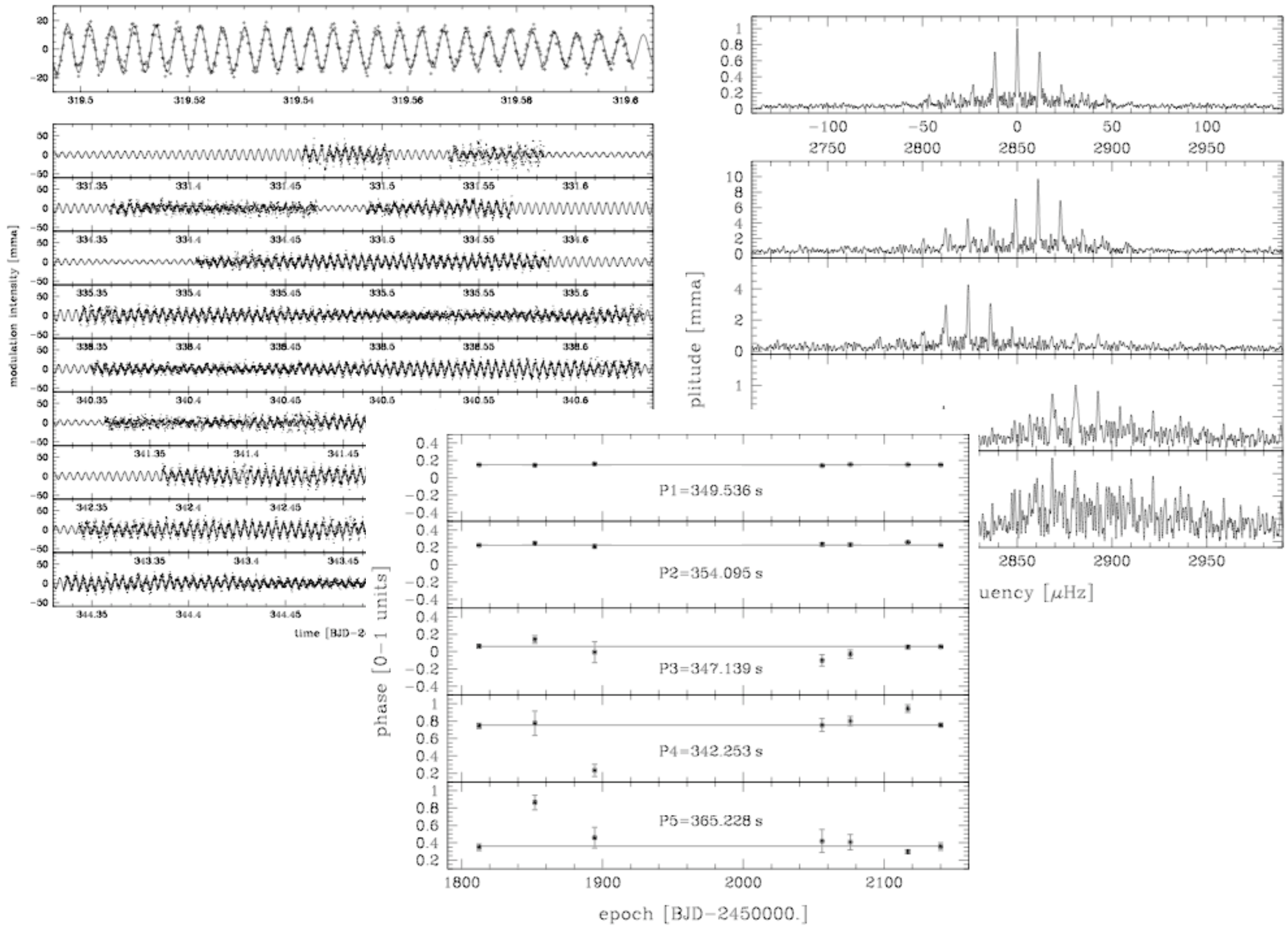
▨ g modes heat engine

▤ solarlike oscillations

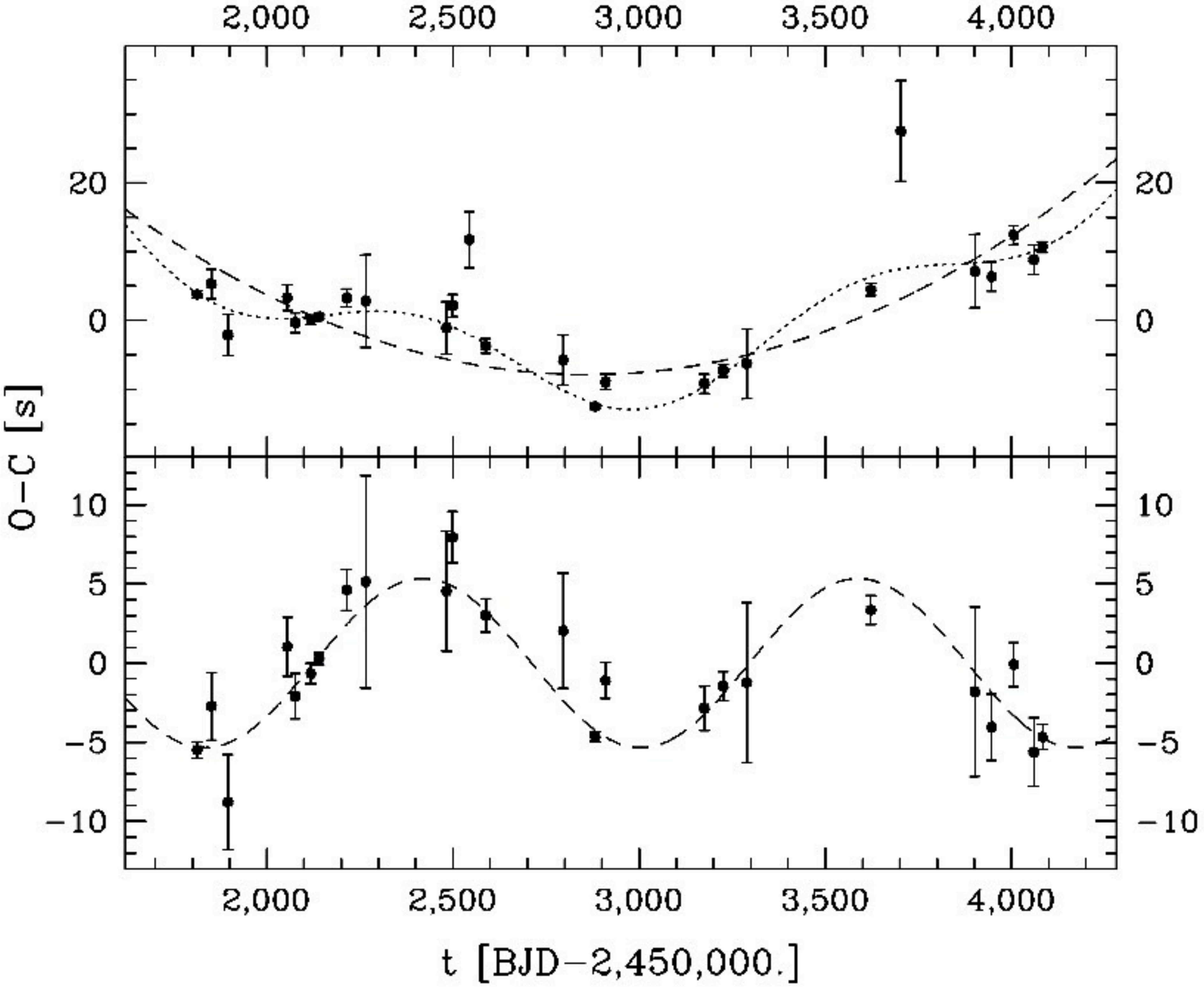
from J. Christensen-Dalsgaard

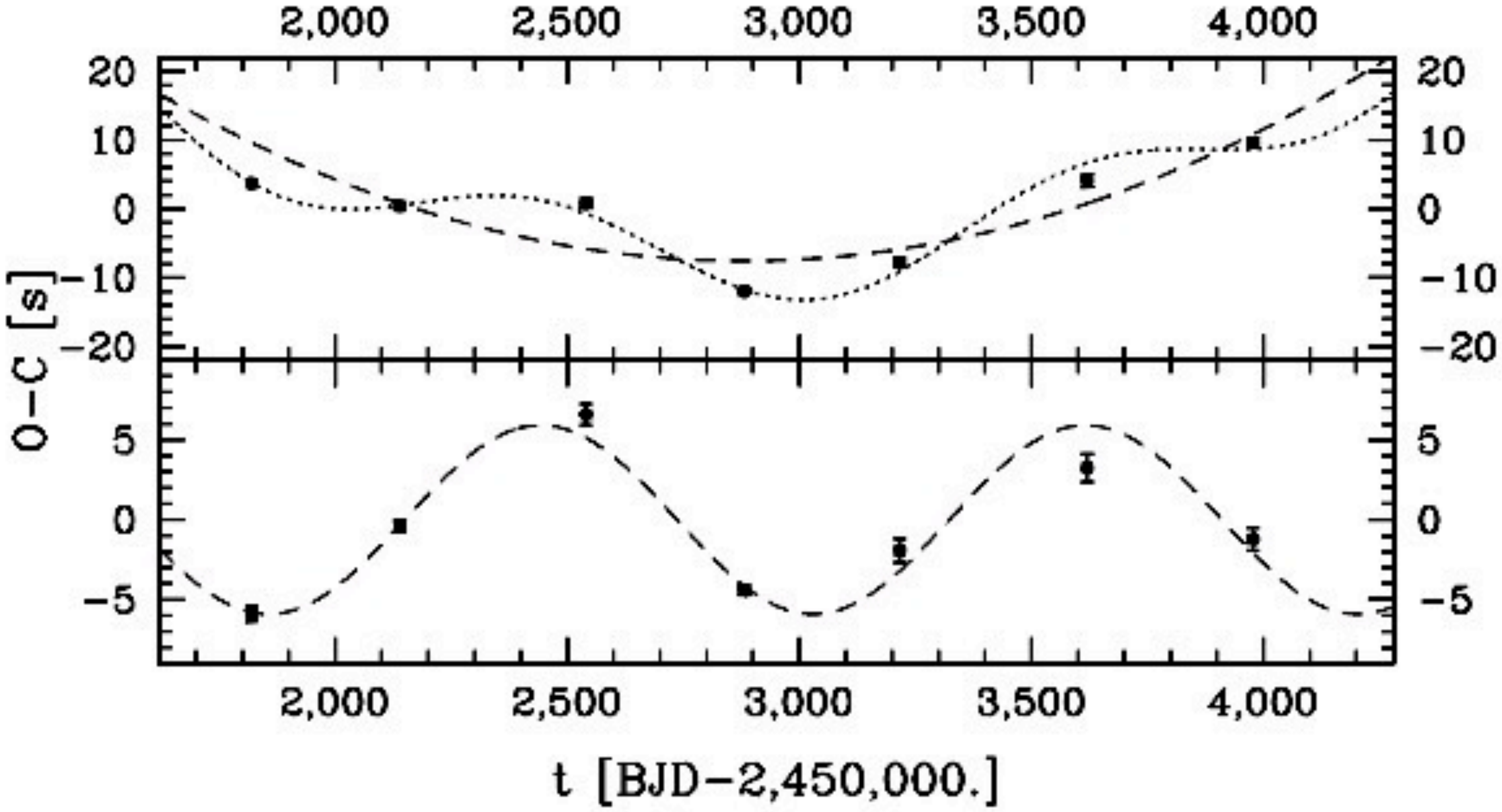
2001-2002

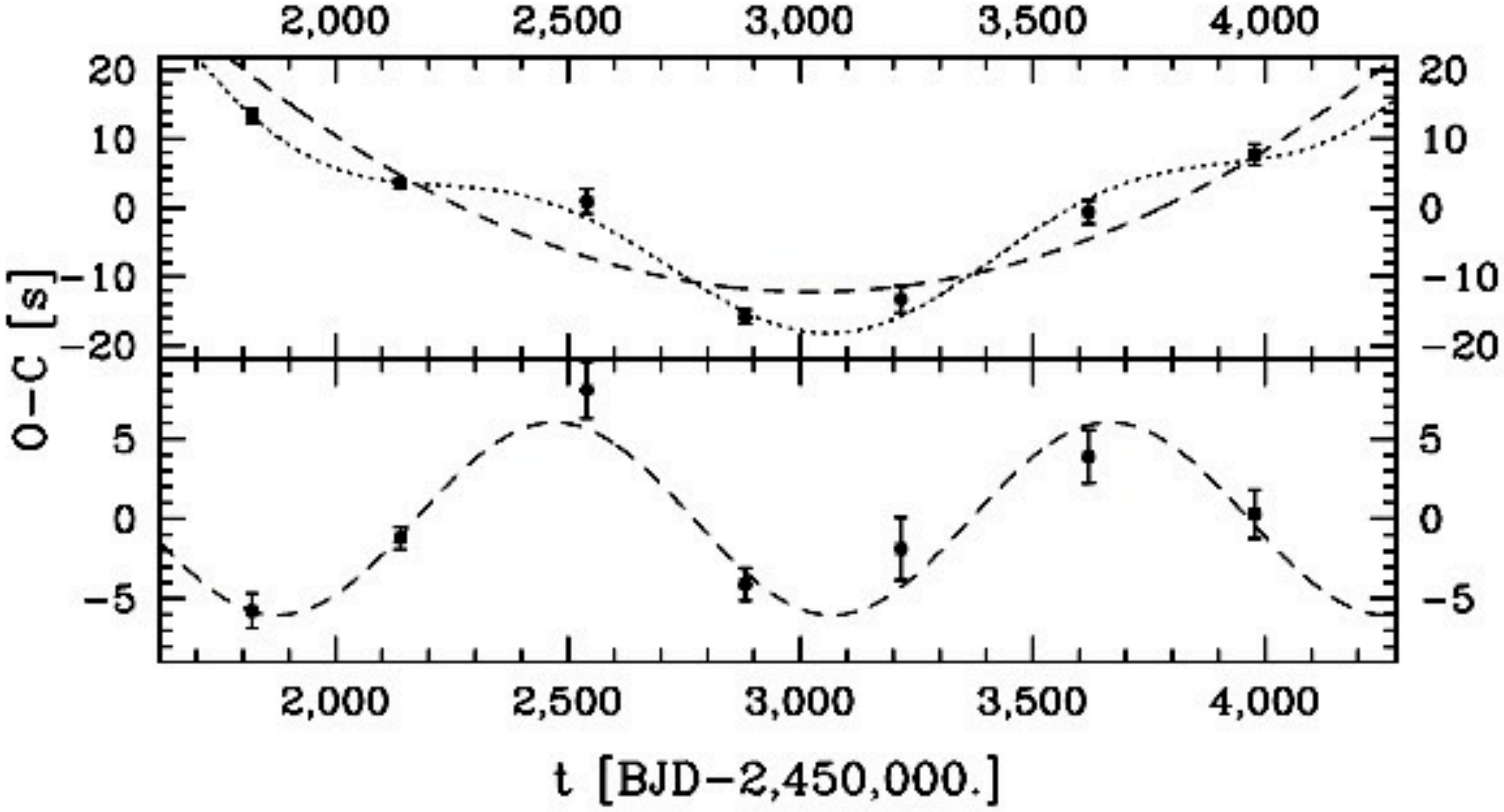
R. Silvotti et al.: The temporal spectrum of the sdBV star HS 2201+2610 at 2 ms resolution



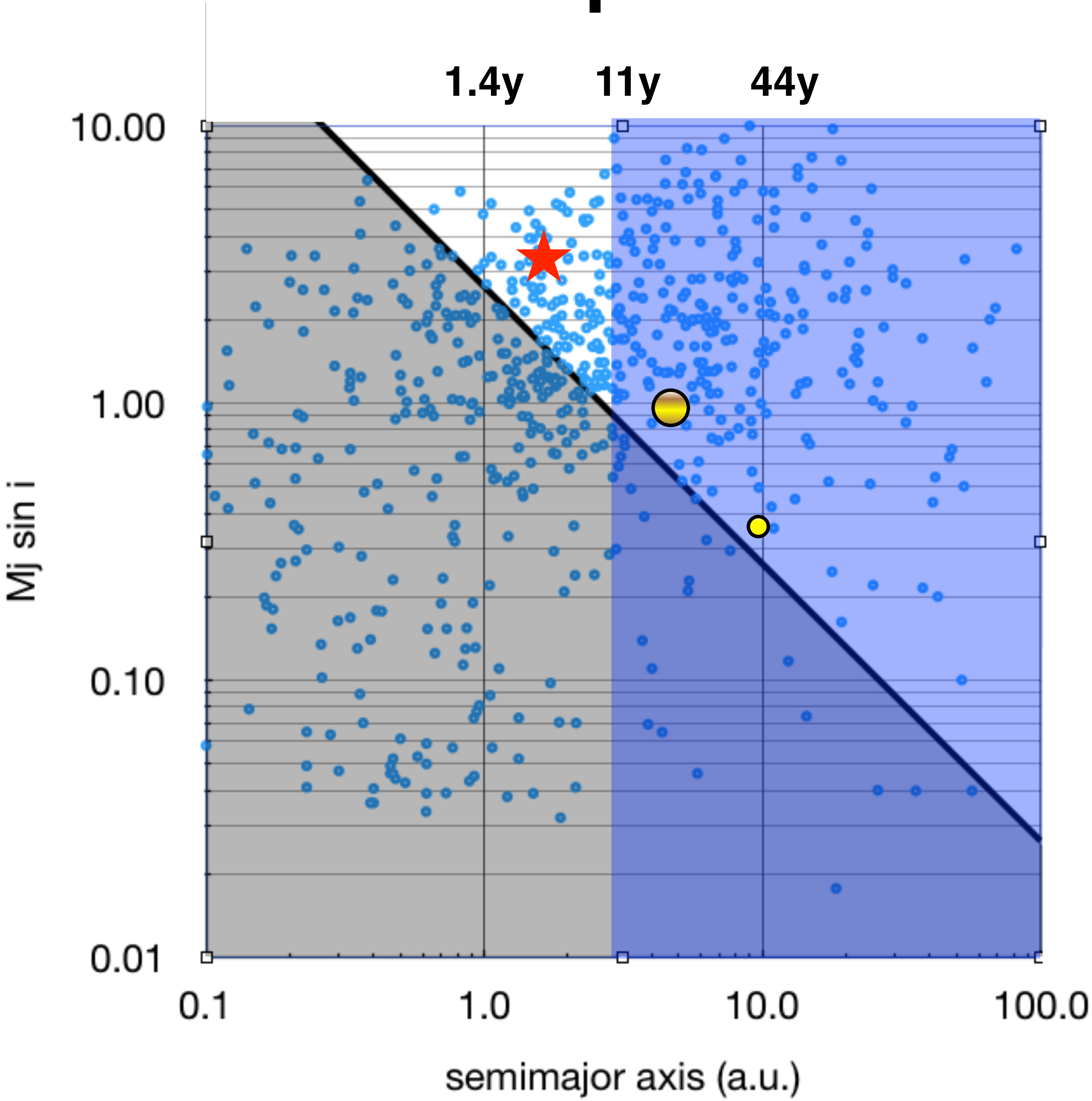
2006




2,000
2,500
3,000
3,500
4,000
20
10
0
−10
−20
5
0
−5
O−C [s]
t [BJD−2,450,000.]


2,000
2,500
3,000
3,500
4,000
20
10
0
−10
−20
5
0
−5
O−C [s]
t [BJD−2,450,000.]

HS 2201 - planet limits



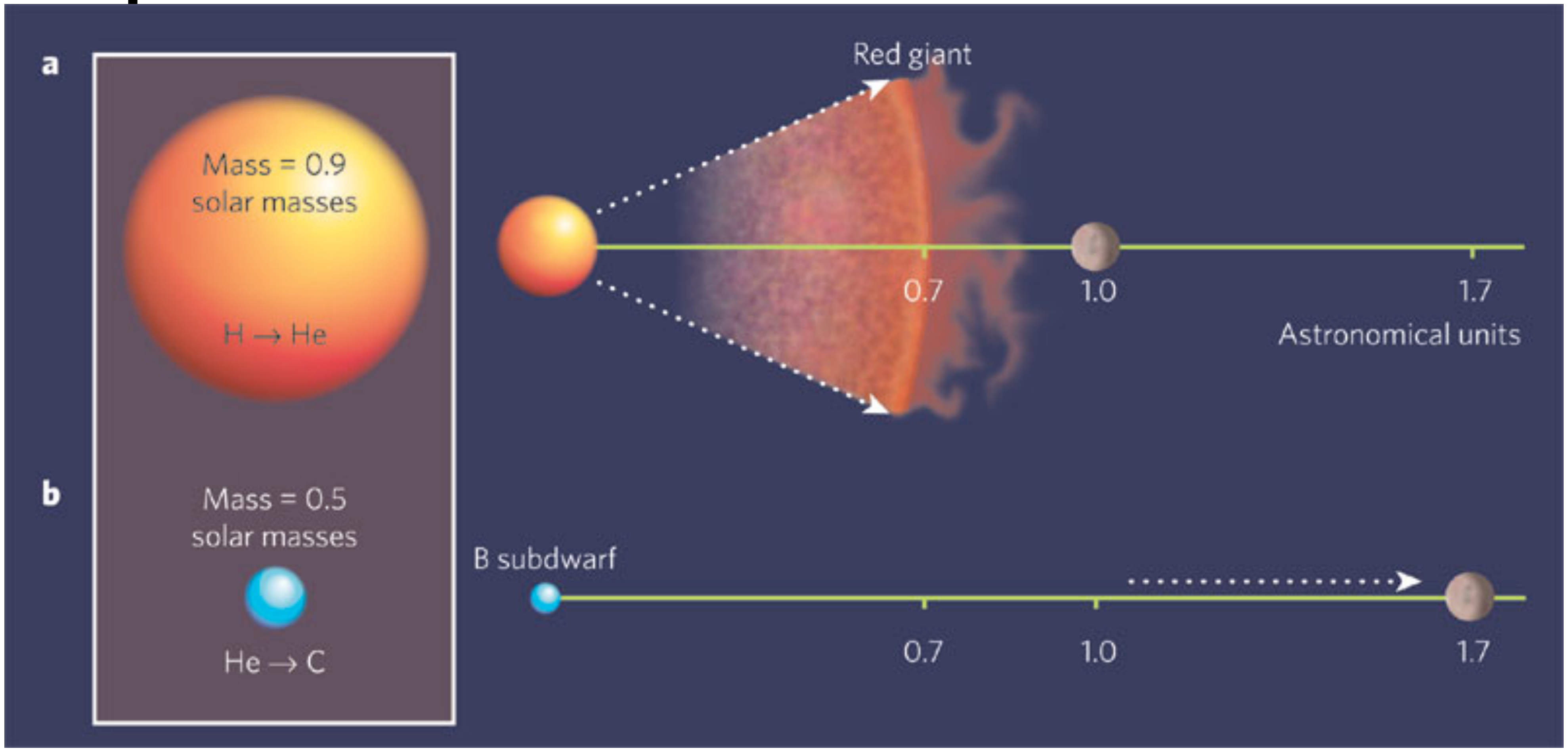
0.5 M_o primary

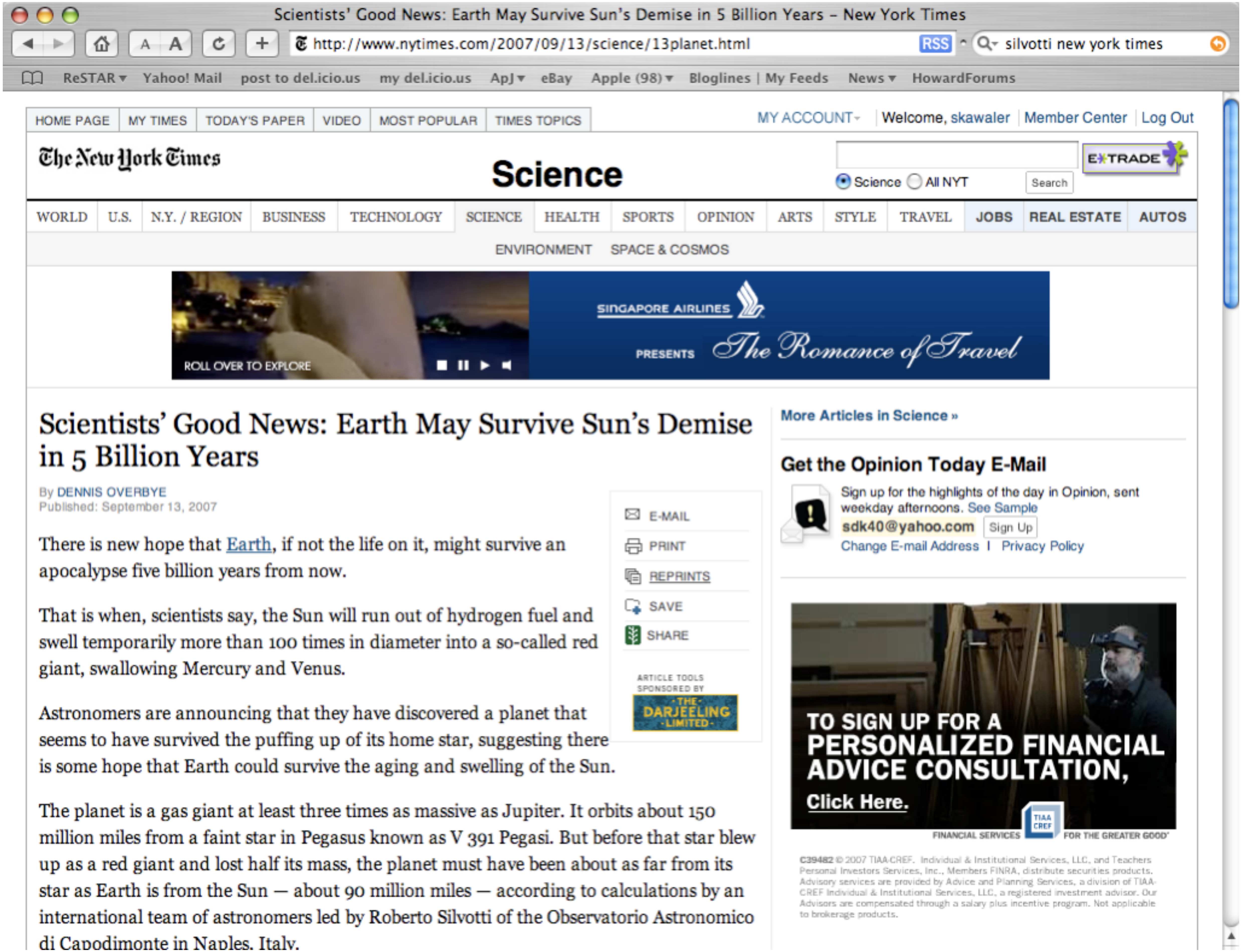
2.5 s (O-C) timing

10 years

Results

- secular variation
  - time scale of 10^7 years
  - expected rate for this evolutionary stage
  - sign indicates late stage of post-EHB
- a giant planet





Scientists' Good News: Earth May Survive Sun's Demise in 5 Billion Years

By DENNIS OVERBYE
Published: September 13, 2007

There is new hope that Earth, if not the life on it, might survive an apocalypse five billion years from now.

That is when, scientists say, the Sun will run out of hydrogen fuel and swell temporarily more than 100 times in diameter into a so-called red giant, swallowing Mercury and Venus.

Astronomers are announcing that they have discovered a planet that seems to have survived the puffing up of its home star, suggesting there is some hope that Earth could survive the aging and swelling of the Sun.

The planet is a gas giant at least three times as massive as Jupiter. It orbits about 150 million miles from a faint star in Pegasus known as V 391 Pegasi. But before that star blew up as a red giant and lost half its mass, the planet must have been about as far from its star as Earth is from the Sun — about 90 million miles — according to calculations by an international team of astronomers led by Roberto Silvotti of the Observatorio Astronomico di Capodimonte in Naples, Italy.

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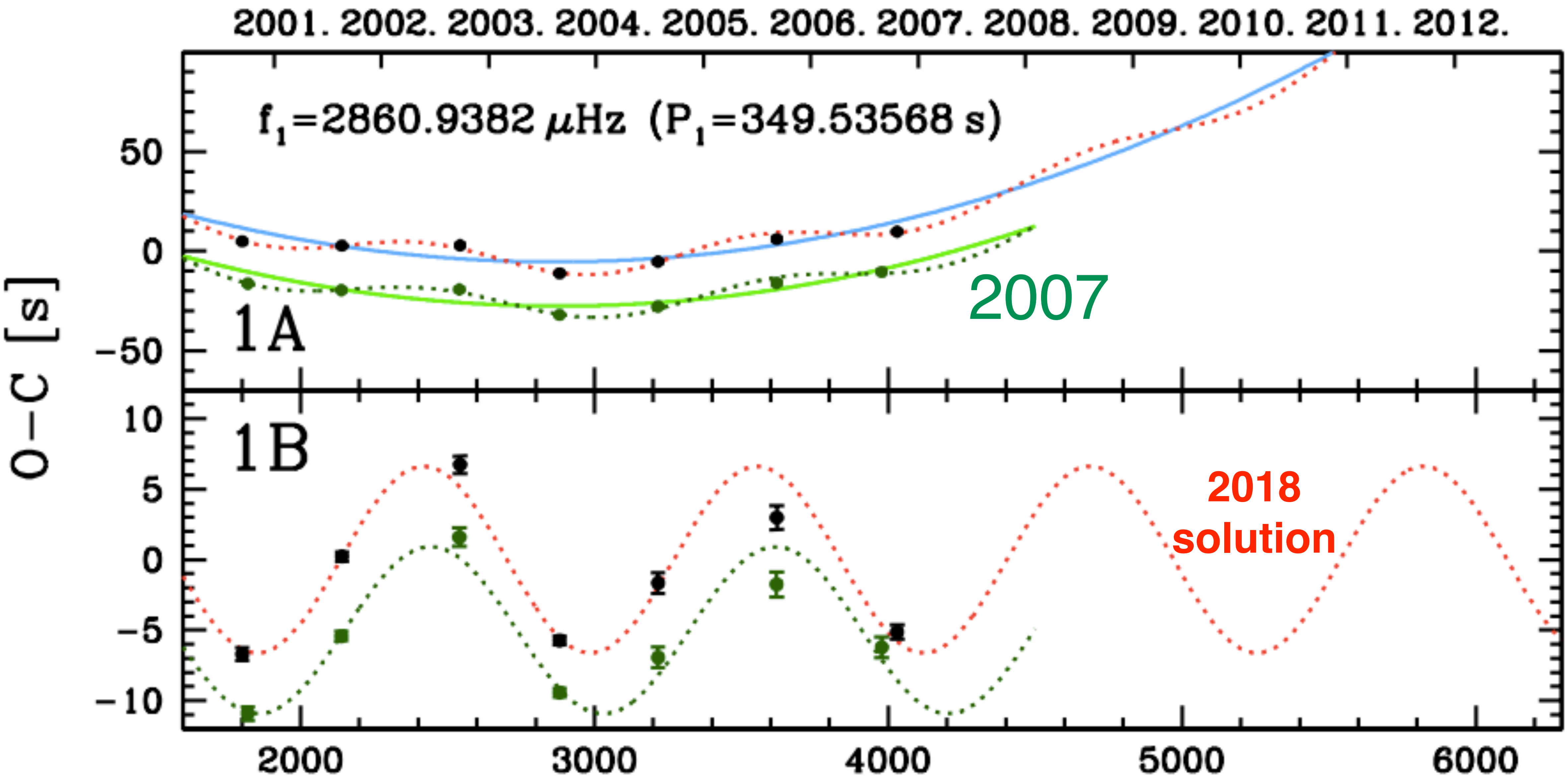
10 years later… an update

(Silvotti et al., 2018)

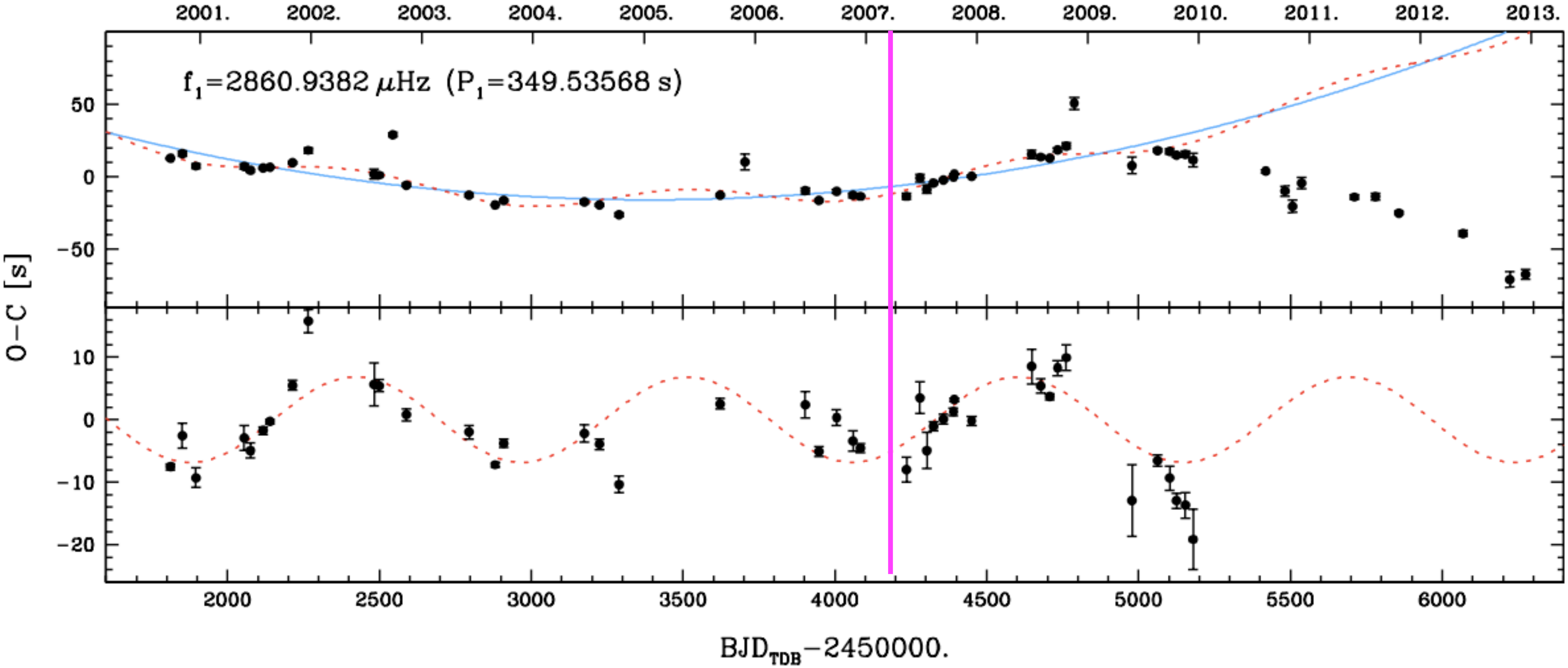
10 years later… an update

(Silvotti et al., 2018)



10 years later… an update

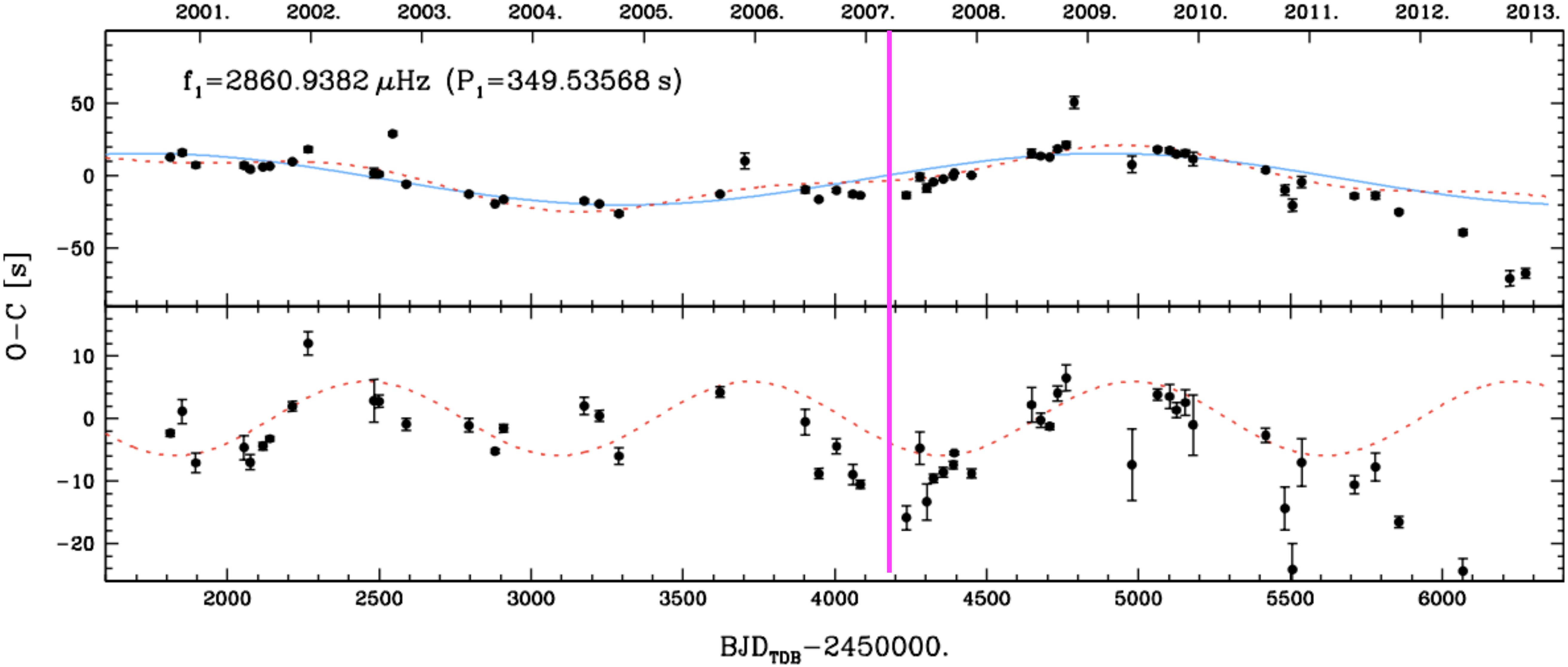
(Silvotti et al., 2018)



parabola + sin fit
only through 2009

10 years later… an update

(Silvotti et al., 2018)



2 sin fit
all data

what’s wrong with the ticker?

- interaction with base of surface convection zone? (Mike Montgomery et al.)
- nonlinear mode coupling / energy exchange?
- sub-detection magnetic fields / dynamo cycles (probably too short a time scale)
- large-scale engineering by dying civilizations to call for help?

conclusions

- WD pulsations are tantalizingly stable
- Secular period changes in some cases are at the theoretical minimum
- Phase (amplitude) (in)stability usually frustrates companion searches
- Prospects remain promising but are observationally intensive
- candidates need independent verification before contacting the New York Times

for more info, ask an expert (not me!)

- Fergal Mullally (SETI Institute)
  - white dwarf limits on giant planets (2007 thesis)
- a Simon J. Murphy (Sydney)
  - main sequence classical pulsators
  - Kepler / K2 results
- Sonja Schuh (MPI, Göttingen), Roberto Silvotti (INAF)
  - sdB pulsators, global telescope networks
- JJ Hermes (Boston University)
- S. O. Kepler (UFRGS Brazil)
  - long term phase stability in WDs
- James Dalessio (Scala Inc.)