Finding invisible objects around early-type main-sequence stars from phase modulation of their pulsations

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Chile-Japan Academic Forum 2016
Workshop 01 Astronomy
November 8, 2016, Puerto Natales

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Finding invisible binary companions

- Eclipse : Goodricke J. 1783, Roy. Soc. London, 73, 474
- Astrometry : Bessel F. W. 1844, AN, 22, 145
- Spectroscopy : Vogel H. C. 1889, AN, 121,241

  Pickering E. C. 1890, The Observatory, 13, 80
- Puls timing : Moffett T. J., Barnes T. G., III, Feel F. C., Jr., Jefferys W. H. &

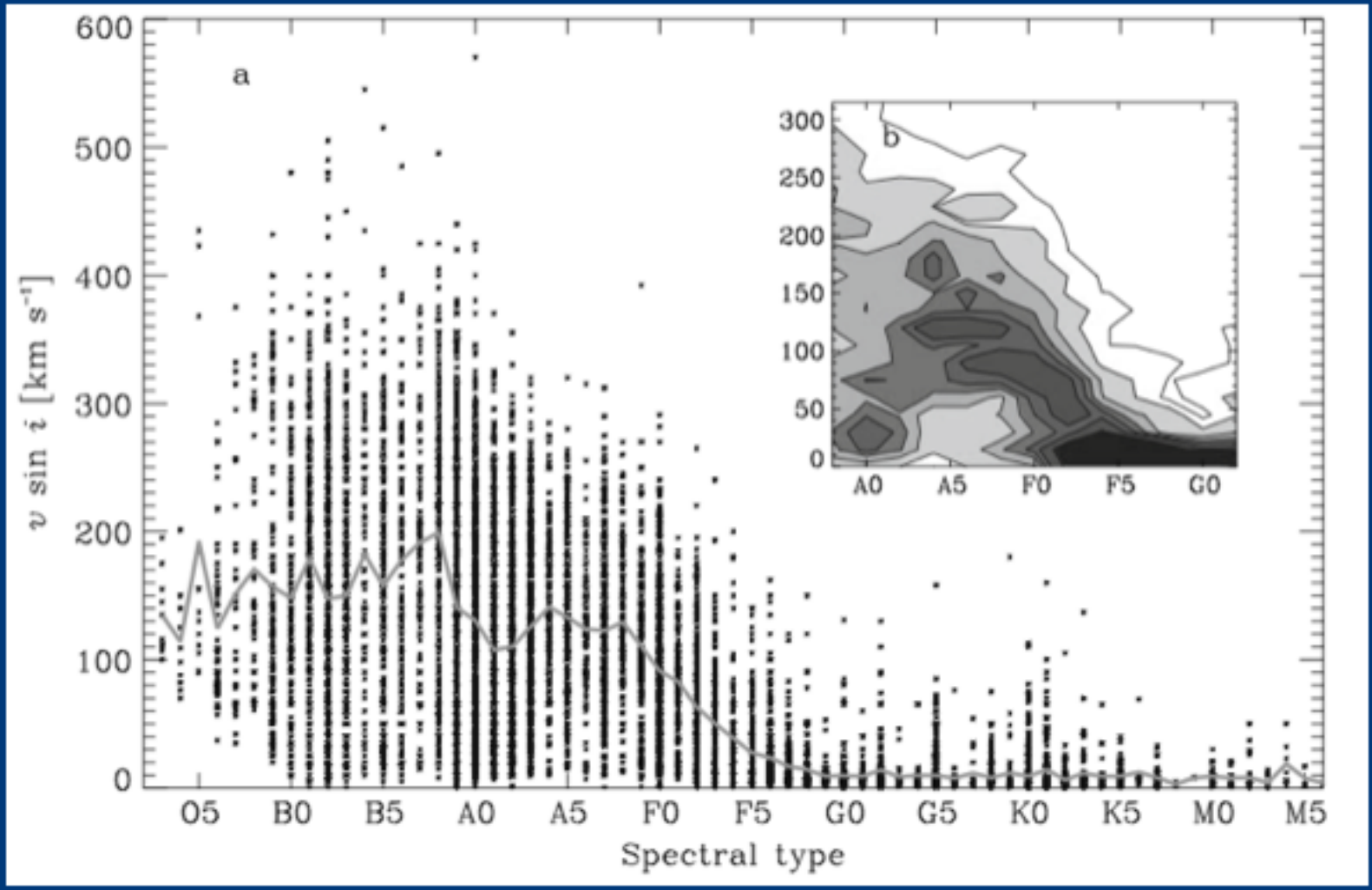
  Achtermann, J. M. 1988, AJ, 95, 1534
- Photometry : Shibahashi H. & Kurtz D. W. 2012, MNRAS, 422, 738

  Murphy S. J., Bedding T. R., Shibahashi H., Kurtz D. W. & Kjeldsen H. 2014, MNRAS, 441, 2515

Finding invisible exoplanets

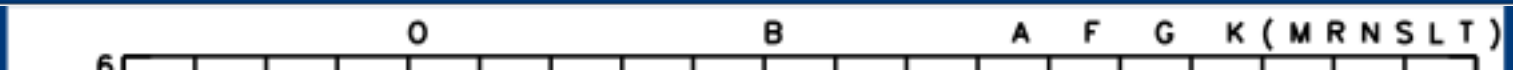
- Transit : Charbonneau D., Brown T. M., Latham D. W. & Mayor M. 2000, ApJ, 529, L45
- Astrometry : not successful yet
- Radial velocity : Mayor M. & Queloz D. 1995, Nature, 378, 355
- Puls timing : Wolszczan A. & Frail D. A. 1992, Nature, 355, 145

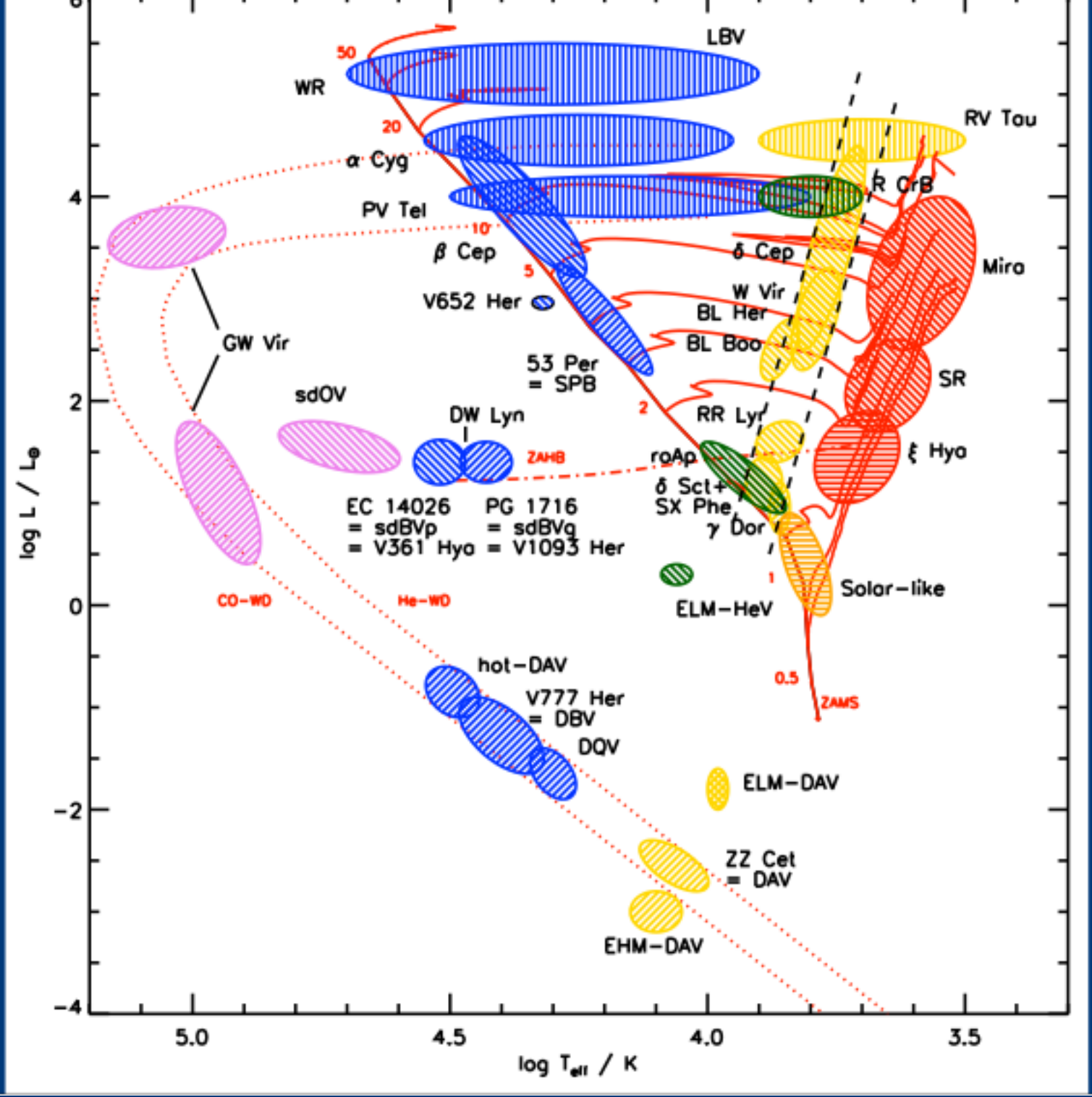
Doppler shift vs $\mathcal{V}_{\mathrm{rot}}$



Doppler shift vs v_{rot}

- RV method: Limited to late-type stars (G, K, M)
- A-type stars: Only Retired A stars (subgiants)
- Early-type main-sequence stars: ???




LBV
WR
50
20
α Cyg
RV Tau
R CrB
PV Tel
10
β Cep
5
δ Cep
Mira
V652 Her
W Vir
BL Her
BL Boo
GW Vir
53 Per
= SPB
SR
sdOV
2
RR Lyr
DW Lyn
ZAHB
roAp
ξ Hya
δ Sct+
SX Phe
γ Dor
EC 14026
= sdBVp
= V361 Hya
PG 1716
= sdBVq
= V1093 Her
1
Solar-like
CO-WD
He-WD
ELM-HeV
hot-DAV
0.5
ZAMS
V777 Her
= DBV
DQV
ELM-DAV
ZZ Cet
= DAV
EHM-DAV
log L / L⊙
log T_eff / K
6
4
2
0
−2
−4
5.0
4.5
4.0
3.5

Strategy

Use stellar pulsation as a clock :

$$\cos\left[\omega_0\left(t-\frac{1}{c}\int_0^t v_{\mathrm{rad}}(t')\,dt'\right)\right]$$

time delay

Measurement of *Phase Modulation* (PM)

$$\Phi(t) := \frac{\omega_0}{c}\int_0^t v_{\mathrm{rad}}(t')\,dt'$$

Doppler shift

radial velocity / light speed

Phase shift

light travel-time across the orbit / pulsation period

Preferable conditions:

- long-lived coherent pulsation
- stable amplitude
- short pulsation period & large orbit size
- continuous observations
- precise photometry
- no transit

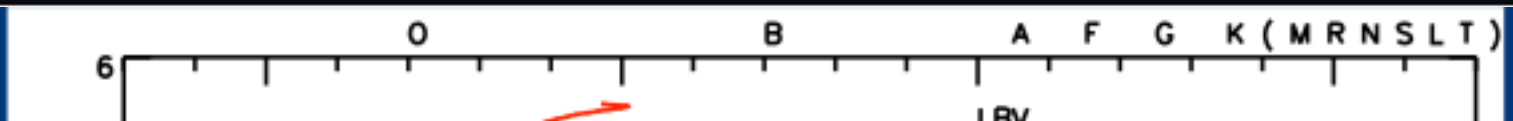
Long-term ground-based observations

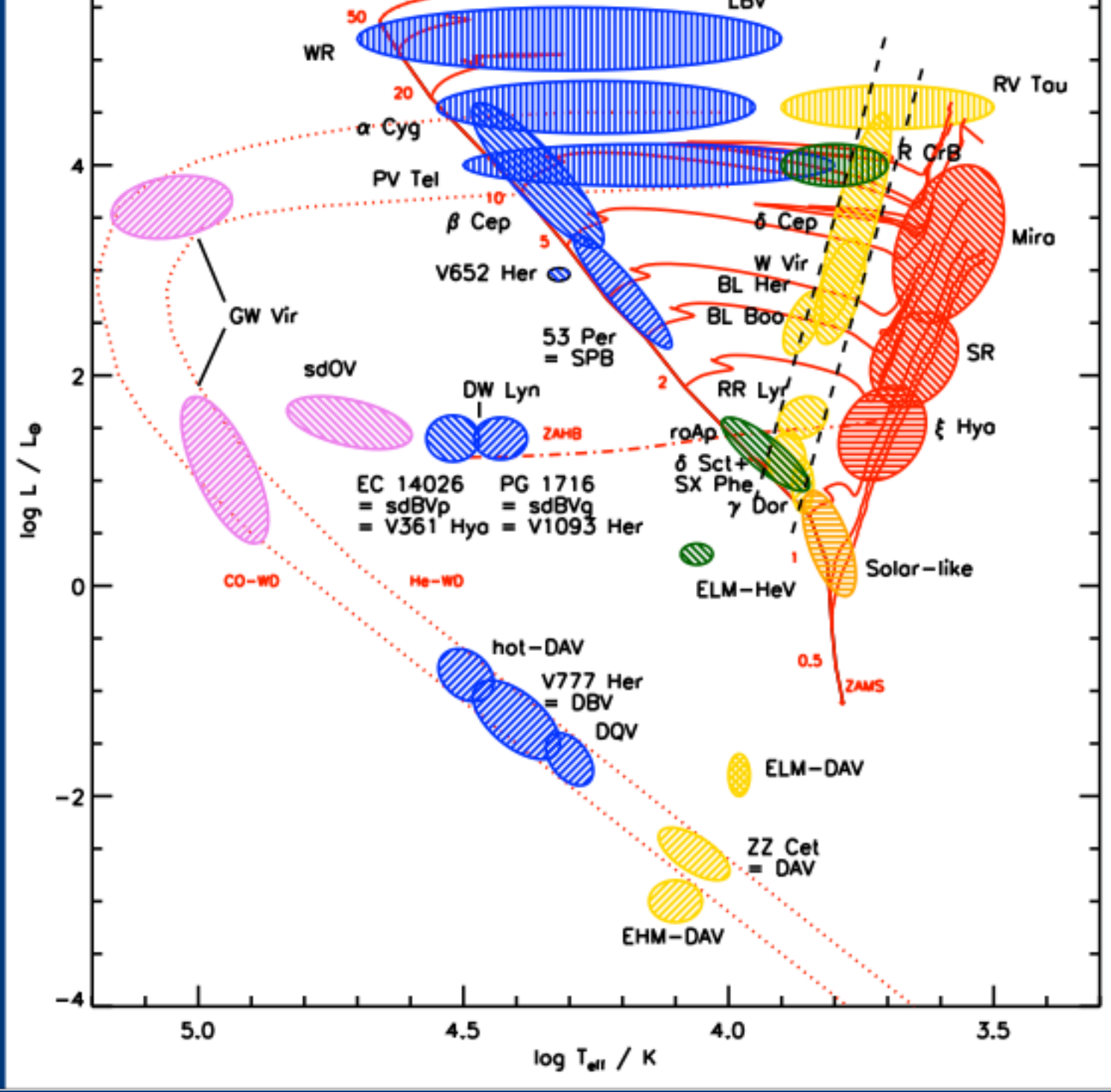
OGLE

WASP

etc

Kepler Space Telescope





Delta Scuti stars

main-sequence stars on the Cepheid instability strip
the most numerous pulsating variables
A-type stars: $M \sim 1.6$ - 2.0 $M_\odot$, $T_{\rm eff} \sim 7000$ - 8000 K
$(GM/R^3)^{-1/2} \sim 1.5$ - 2 h

Kepler Space Telescope

4-yr uninterrupted photometry from space
sampling : every 30 minutes
190,000 stars in the Cygnus-Lyrae field
A stars ~ 10,000

Light curve of KIC 7917485 observed by *Kepler*

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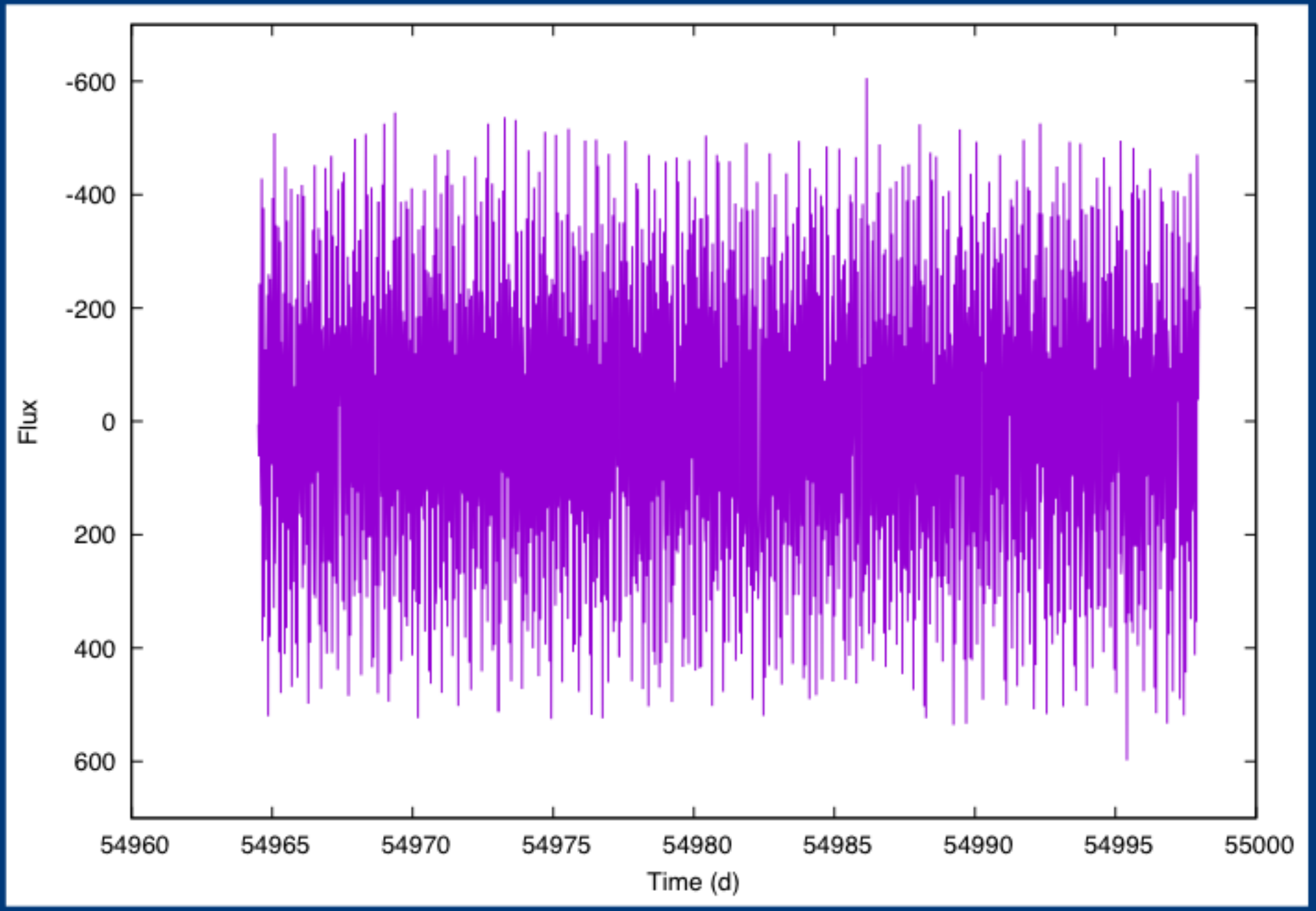

Lesson 1: easy case KIC9651065

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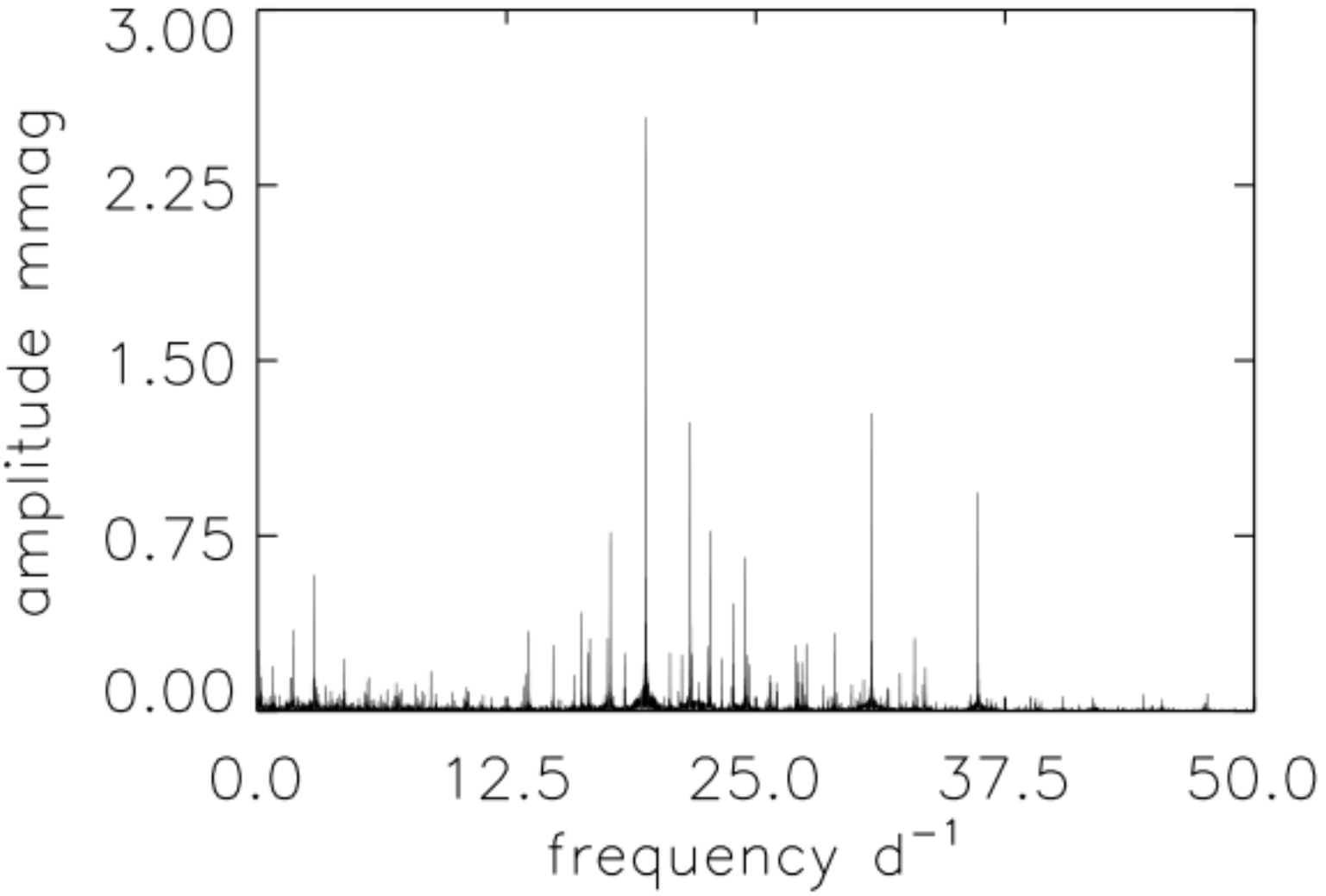
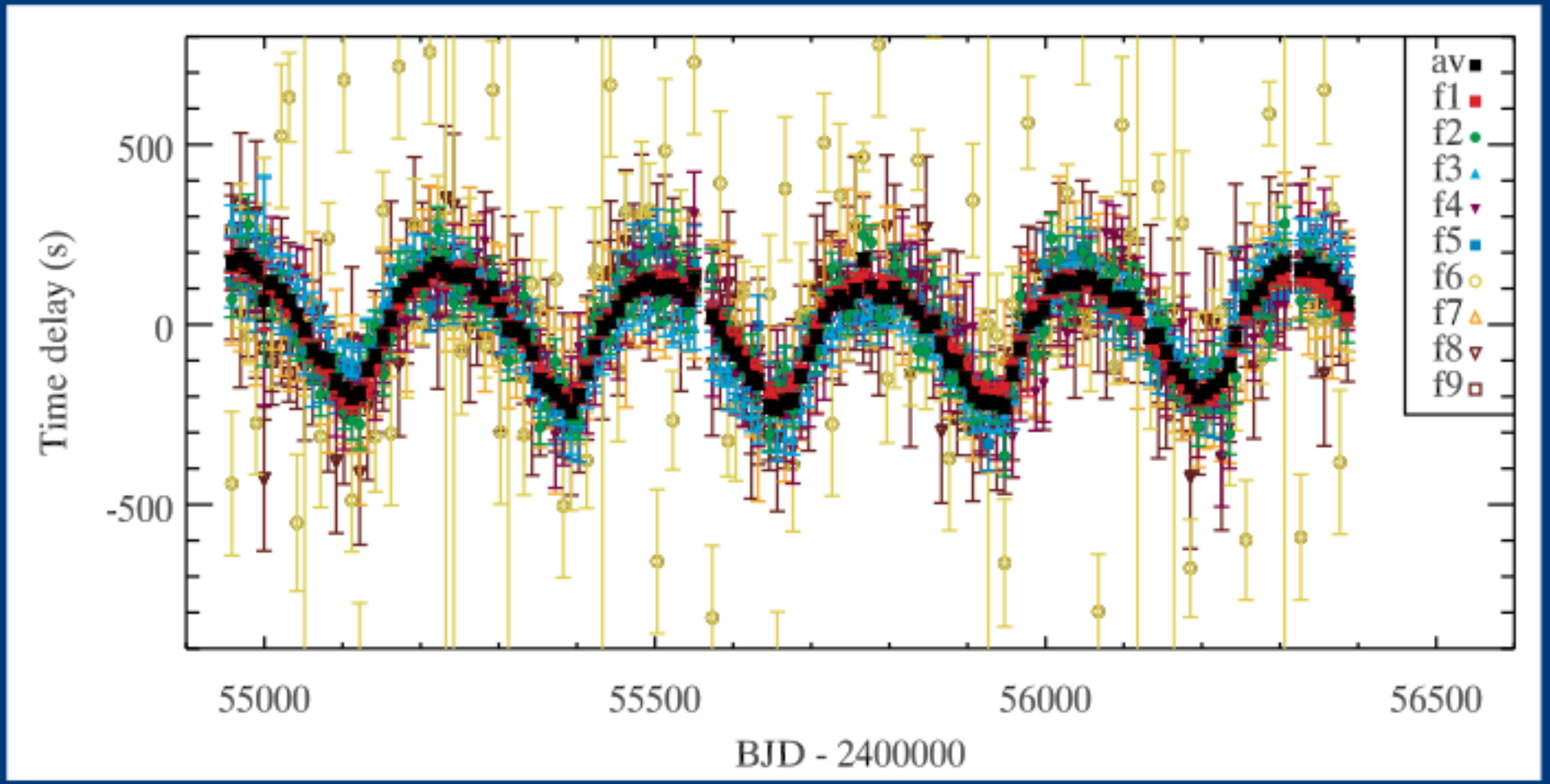
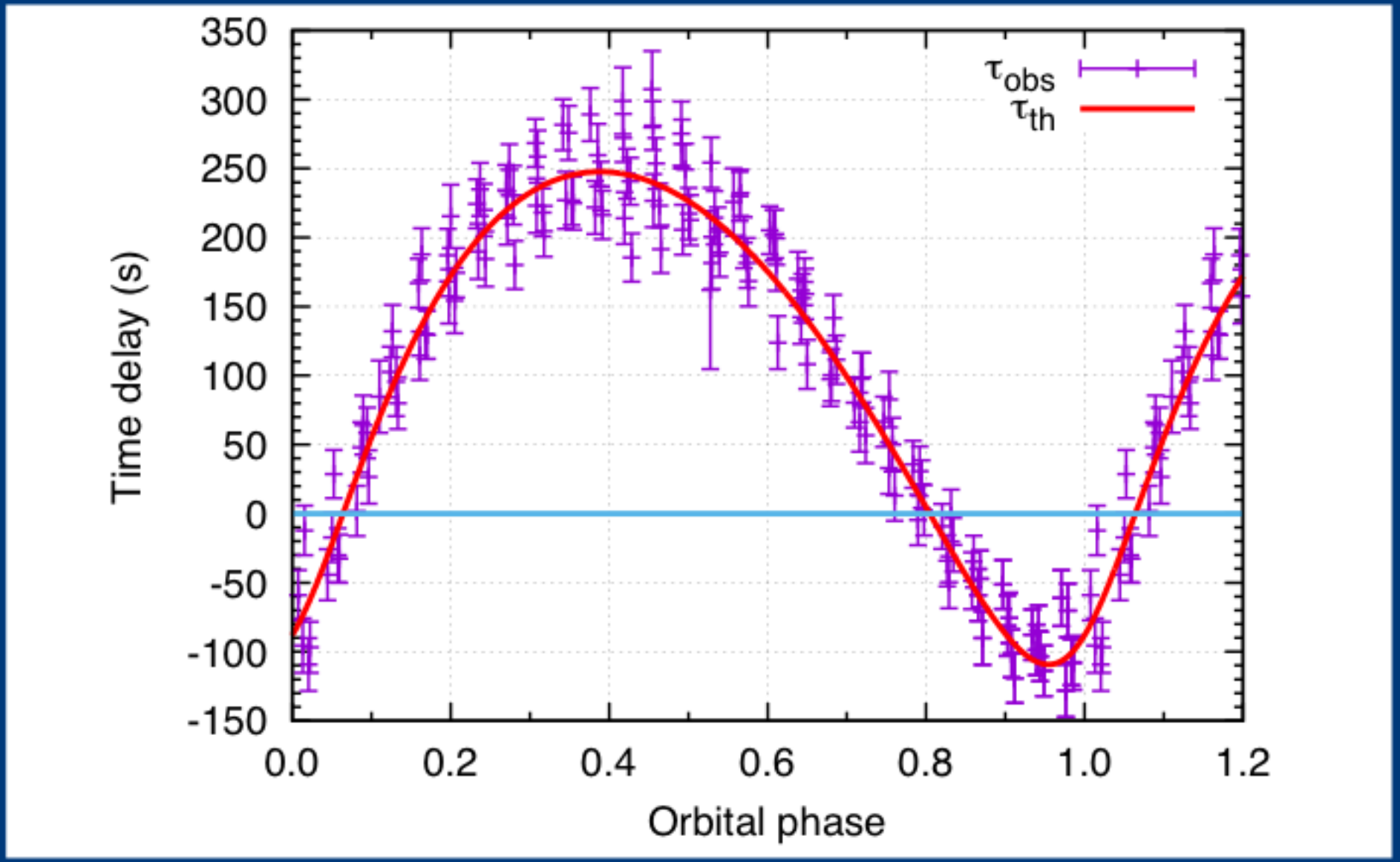


Lesson 1: easy case KIC9651065

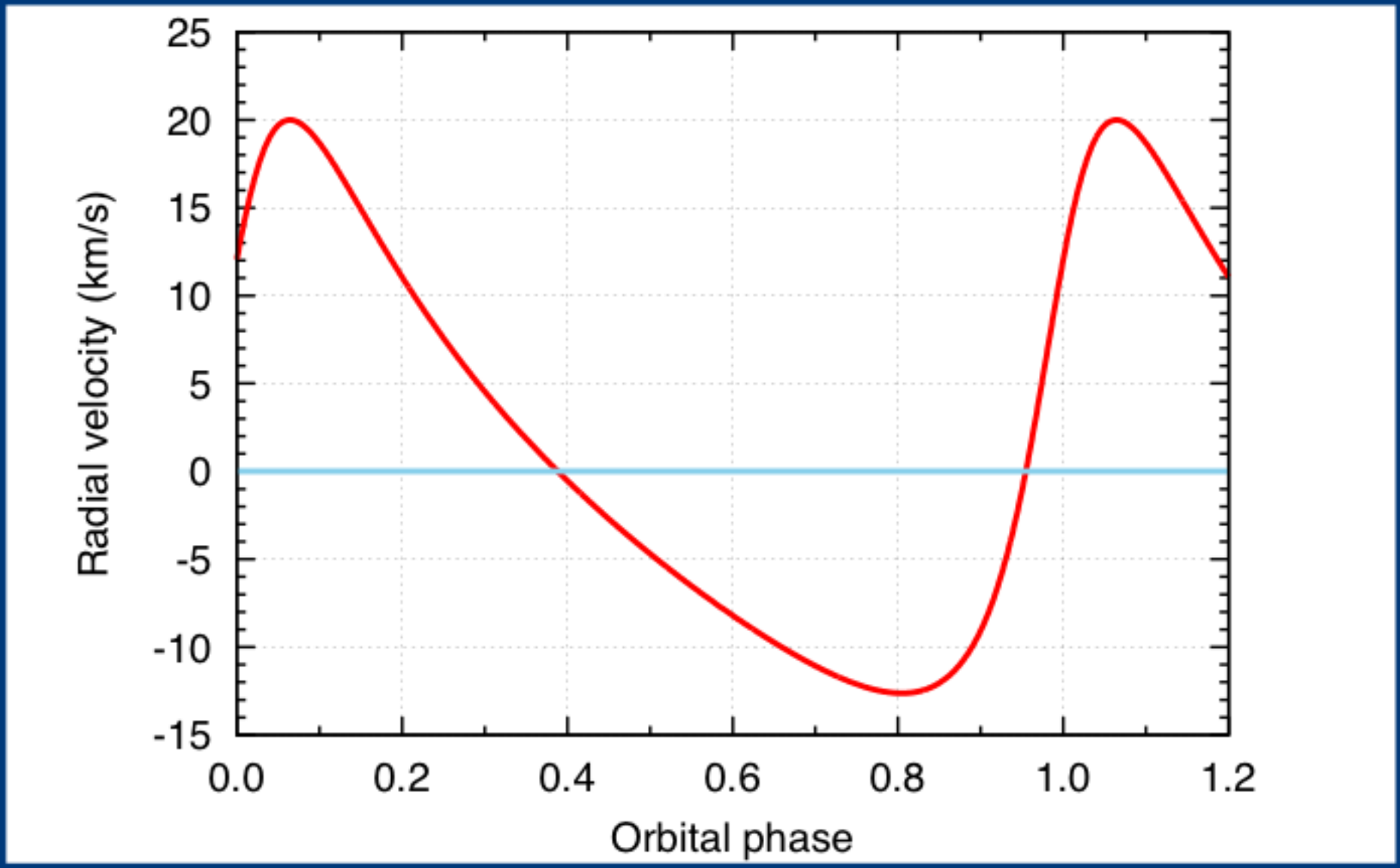


Murphy S. J. & Shibahashi H. 2015, MNRAS, 450, 4475



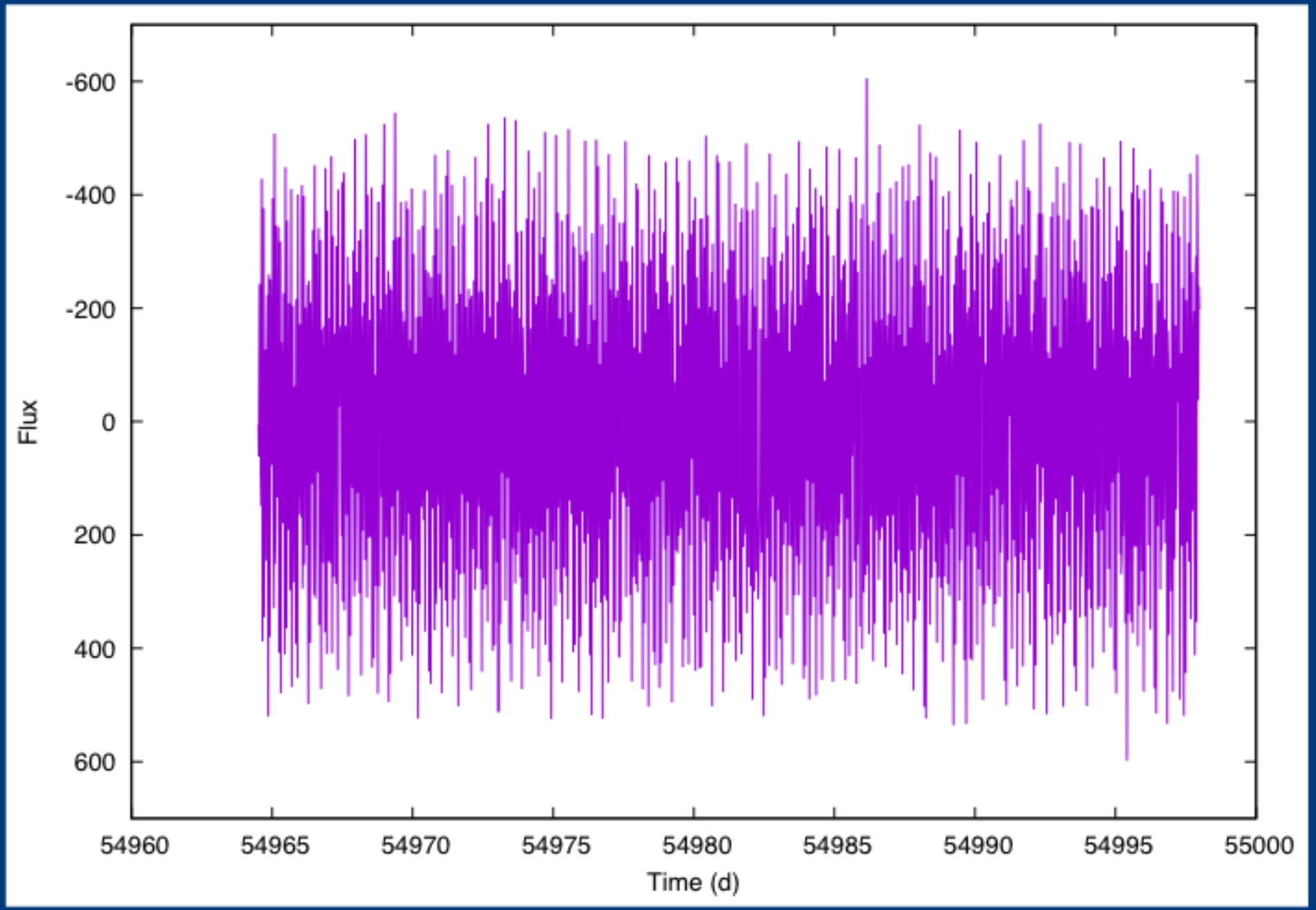
Murphy S. J. & Shibahashi H. 2015, MNRAS, 450, 4475

Photometrically obtained radial velocity

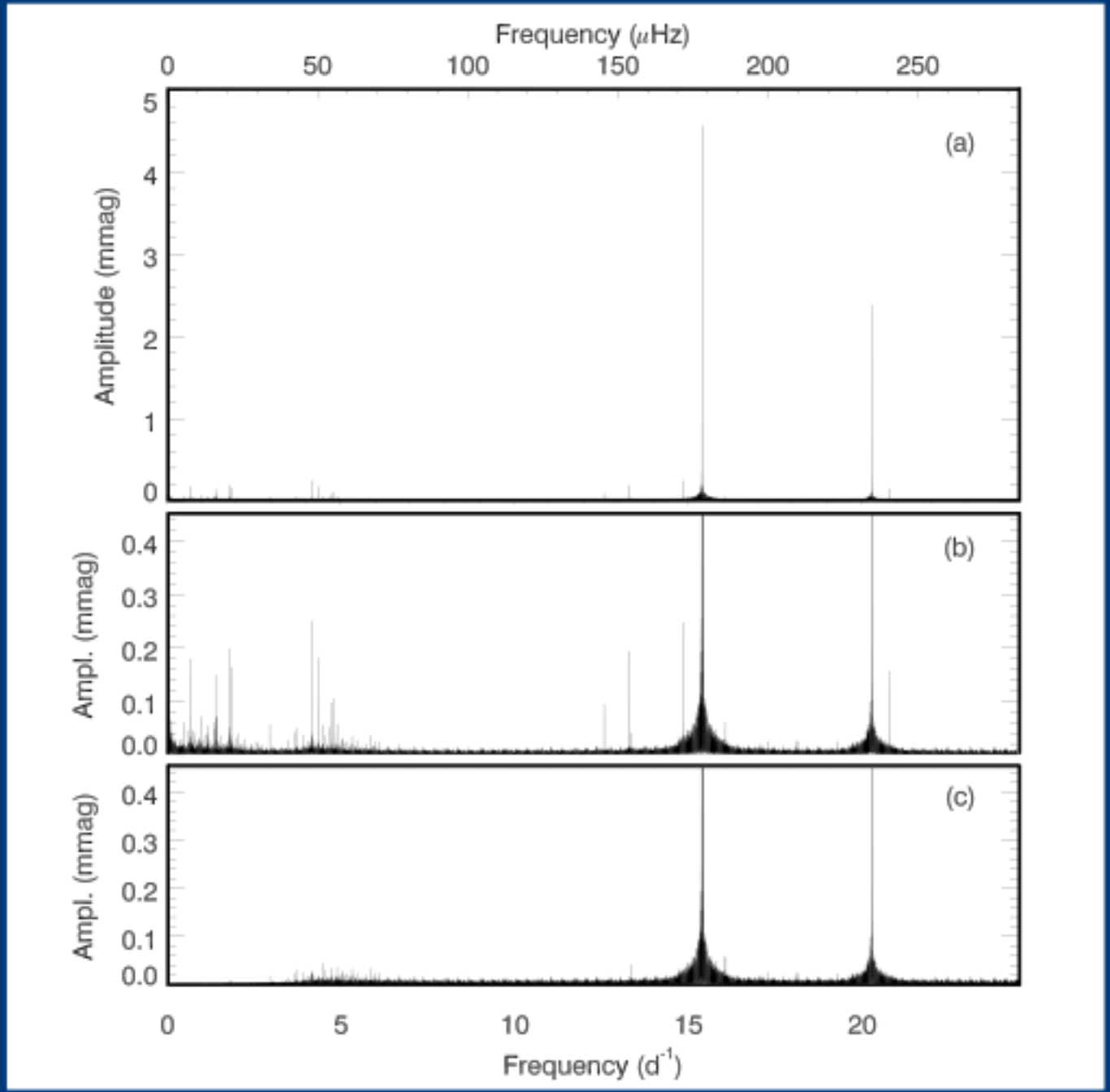


Murphy S. J. & Shibahashi H. 2015, MNRAS, 450, 4475

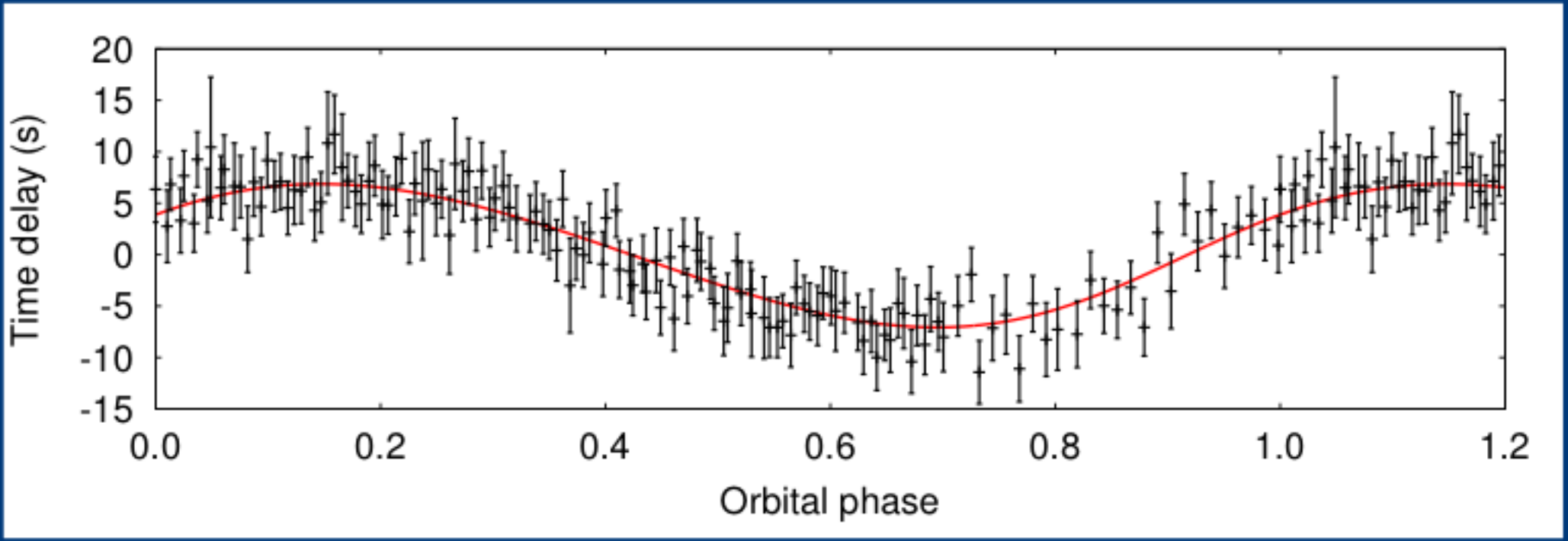
Lesson 2 : a challenging case



Fourier spectrum of LC of KIC 7917485


Frequency (μHz)
0
50
100
150
200
250
Amplitude (mmag)
0
1
2
3
4
5
(a)
Ampl. (mmag)
0.0
0.1
0.2
0.3
0.4
(b)
Ampl. (mmag)
0.0
0.1
0.2
0.3
0.4
(c)
0
5
10
15
20
Frequency (d^{-1})

Time Delay curve of KIC 7917485



Murphy S., Bedding T. R. & Shibahashi H. 2016, ApJ, 827, L17

KIC 7917485

The first (and the only one yet) planet found with PM method

P_{orb}	840 ± 20	d
e	0.15 ± 0.10	
$a_1 \sin i / c$	7.1 ± 0.5	s
$K_1 \sin i$	131 ± 5	m s^{-1}
$f(m_1, m_2, \sin i)$	(5.3 ± 1.0) × 10^{-7}	$M_\odot$
M_1	1.63 ± 0.13	$M_\odot$
$M_2 \sin i$	11.8 ± 0.7	M_{Jup}
$a_2 \sin i$	2.03 ± 0.25	au

Other interesting subjects:

- Binary statistics
- Search for brown dwarfs
- Finding massive compact objects
  - subdwarf B stars
  - white dwarfs
  - neutron stars
  - black holes