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Update on the McDonald Observatory Search for Planets Around White Dwarf Stars:
Dying Stars, Living Planets

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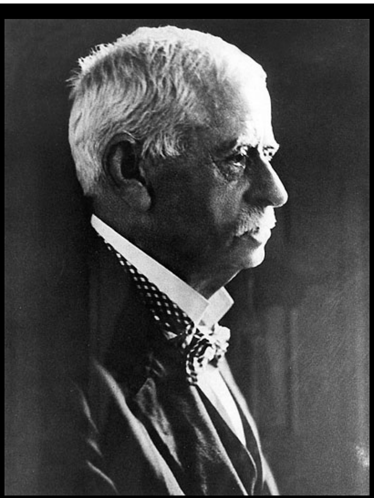
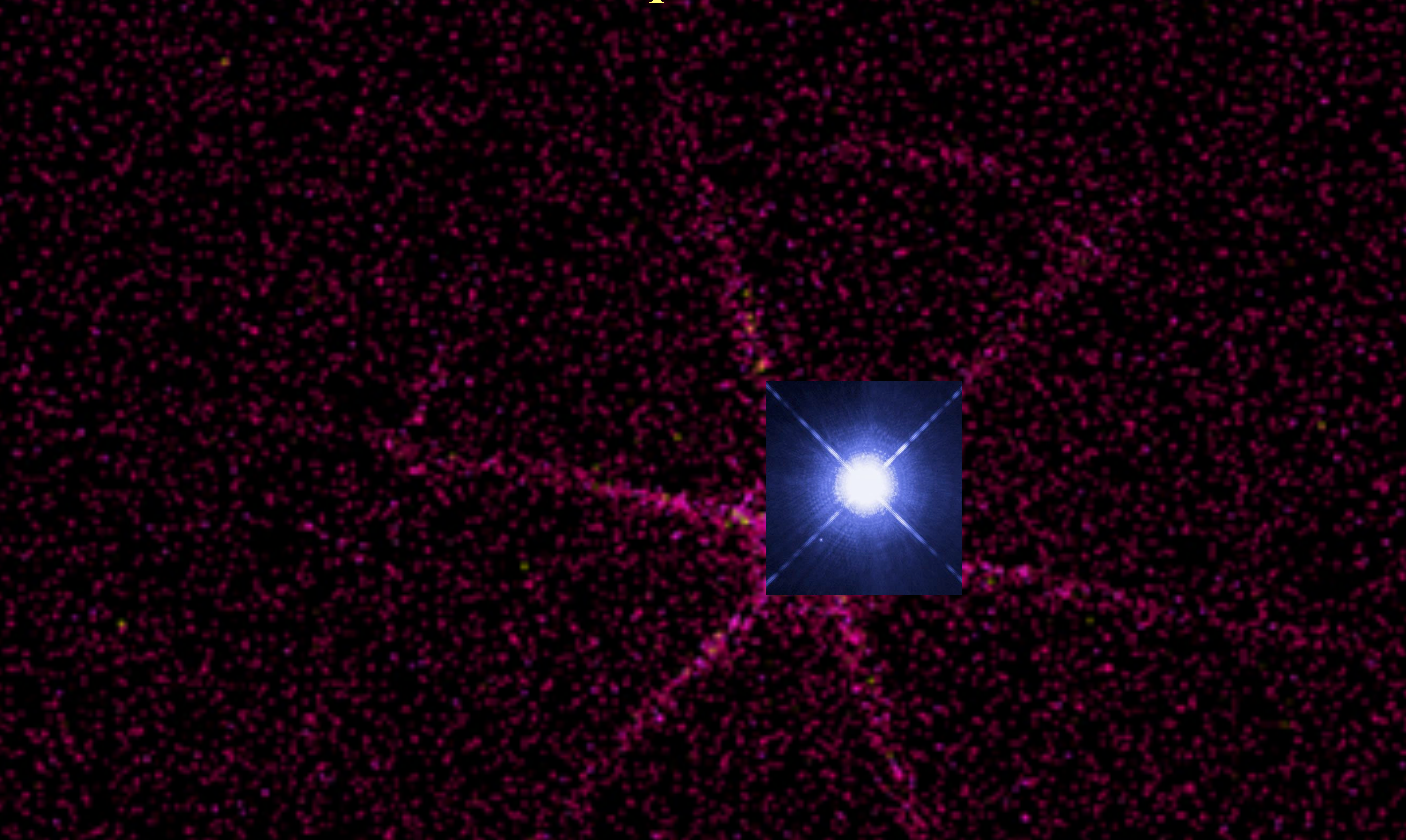


"One of the first tasks to be undertaken by the staff of the McDonald Observatory will be to investigate further the mysteries of the white dwarfs."

-- May 5th, 1939

White Dwarf Stars: Eddington's "*Impossible*" Star



What Are White Dwarf Stars?

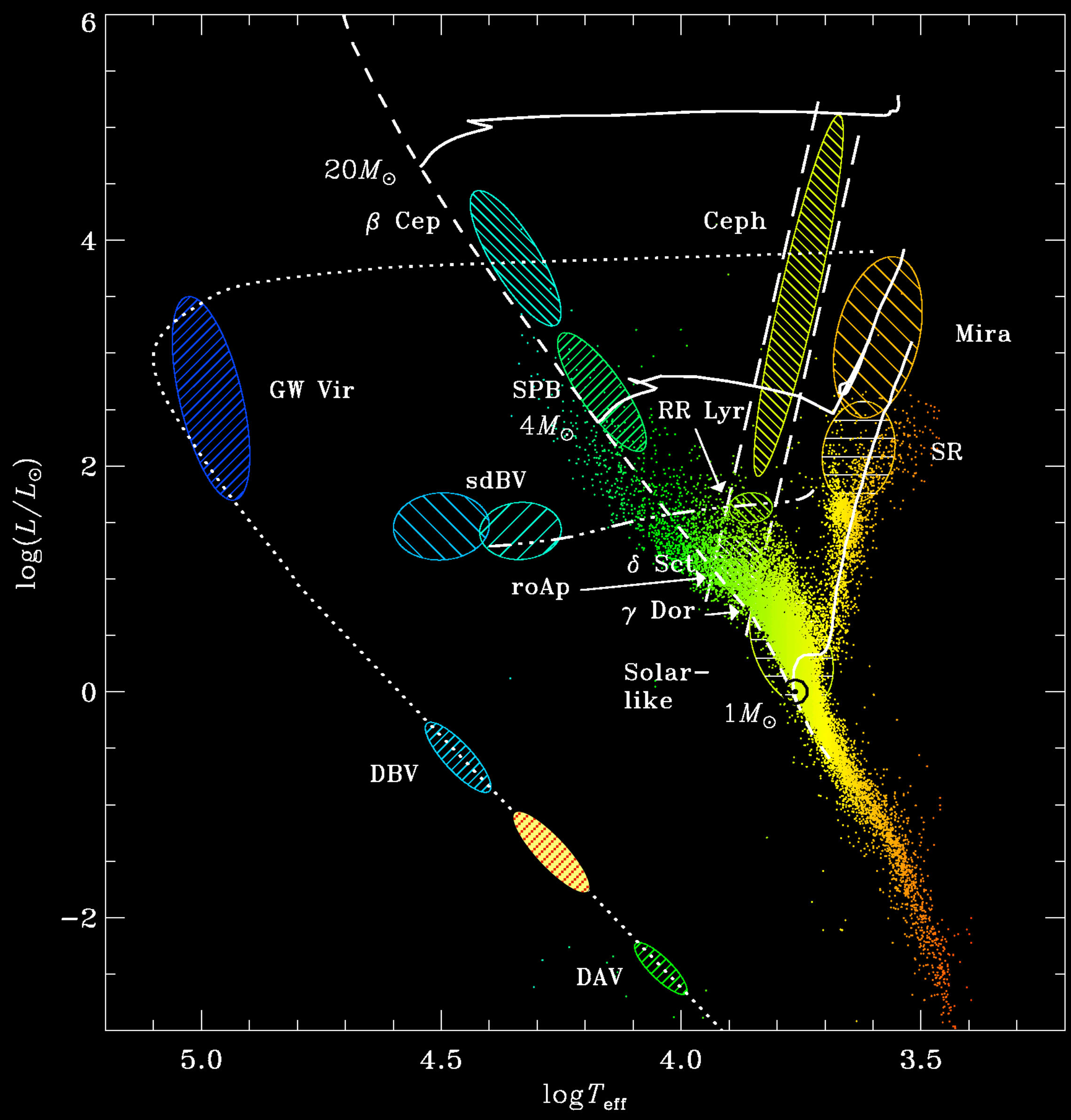
- ***Endpoint*** of evolution for most stars
- ***Homogeneous*** in mass and surface composition
- ***Uncomplicated*** in structure and composition; evolution is just cooling

They Shed Their Complexity!

… and Why Should I Care?

- **Representative** (and personal)
  - 98% of all stars, including our sun, will become one
  - Archeological history of star formation in our galaxy
- **Extreme physics:** plasmon neutrinos, internal crystallization, and dark matter, calibrate inertial confinement (laser fusion)
- ***Envelopes in same EOS domain as planetary interiors***
- ***Debris disks and accreting rocks/asteroid material – flame testing extrasolar rocks …***
- ***A way to find Solar Systems dynamically like our own***

The first new class of pulsating white dwarf found in the last 25 years!



All four have been discovered at McDonald Observatory!

Surface Brightness Variations 100-1,000 s

$l = 2$ modes

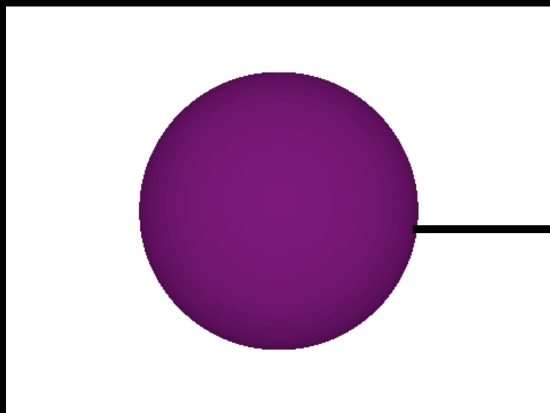
$l = 3$ modes

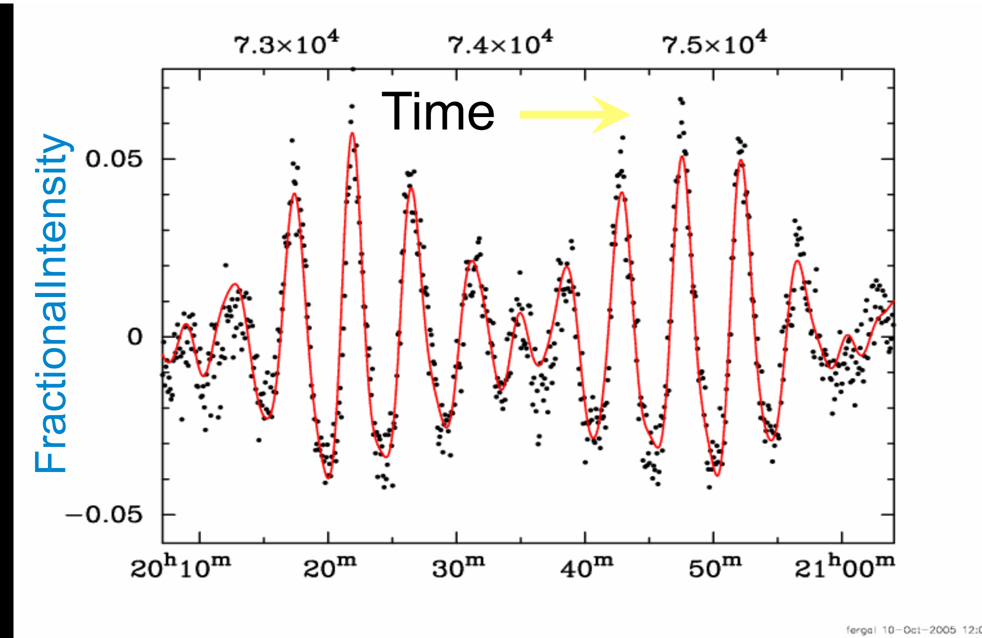
$l = 1$ modes

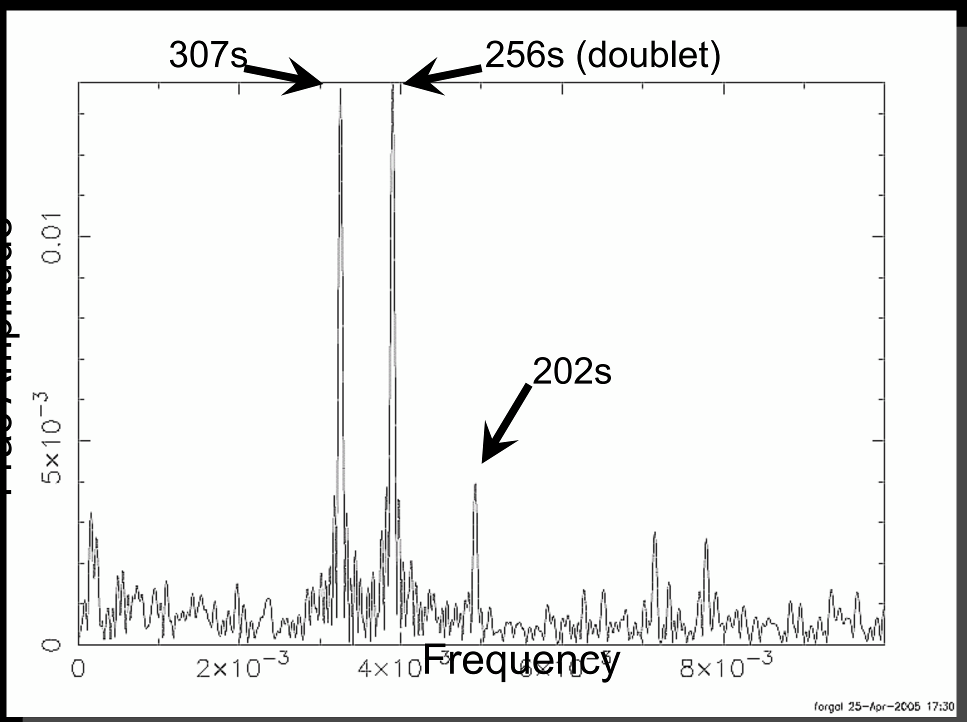
Nonradial Gravity Modes: g-modes

Quantum numbers
l,m,n

Most commonly observed modes are $l = 1$







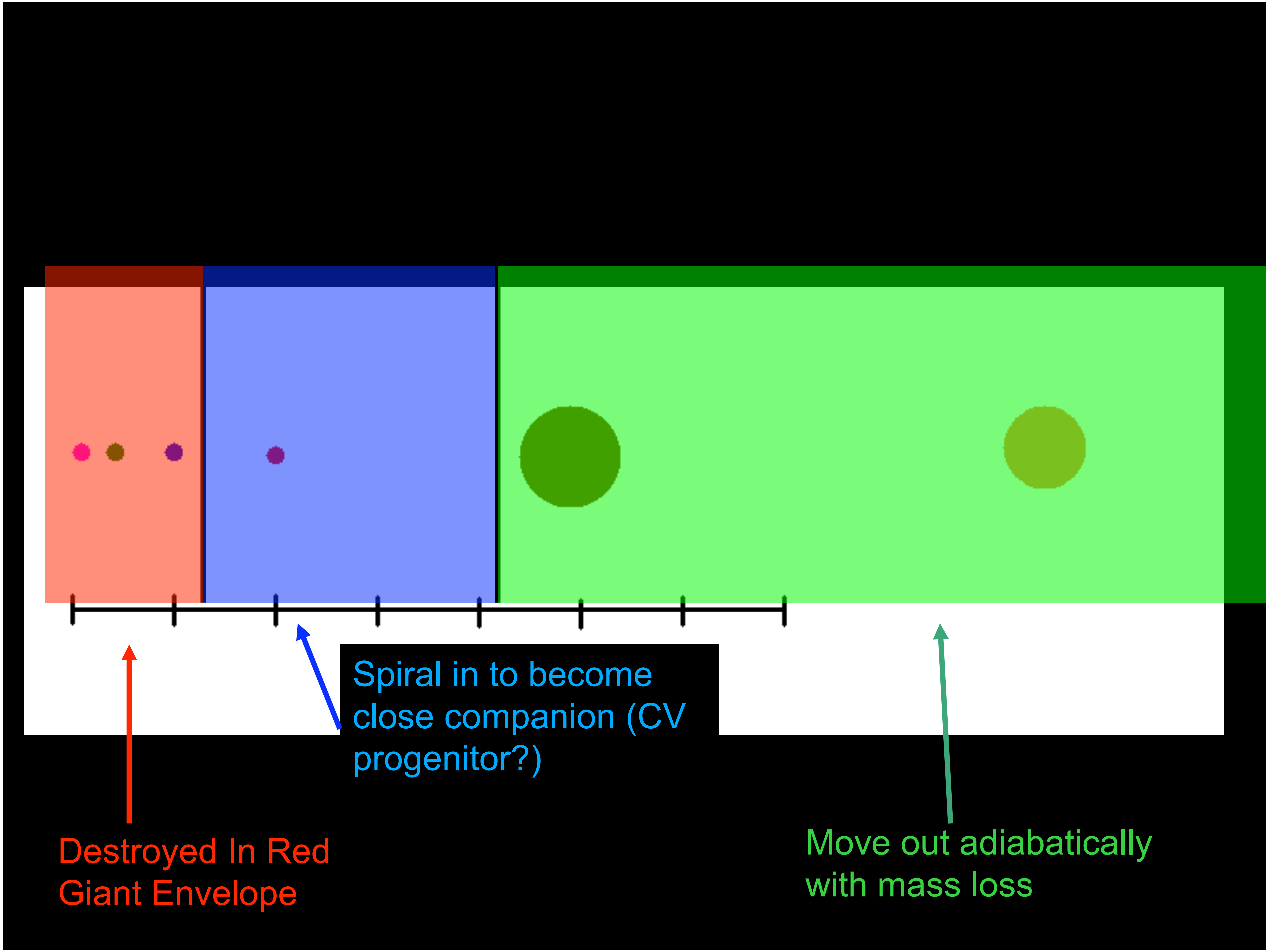
- All (?) DAs become variable at ≈ 12,000K
- Non-radial multi-periodic *g*-mode pulsations
- Periods between 100-1000s, amplitudes ~1%

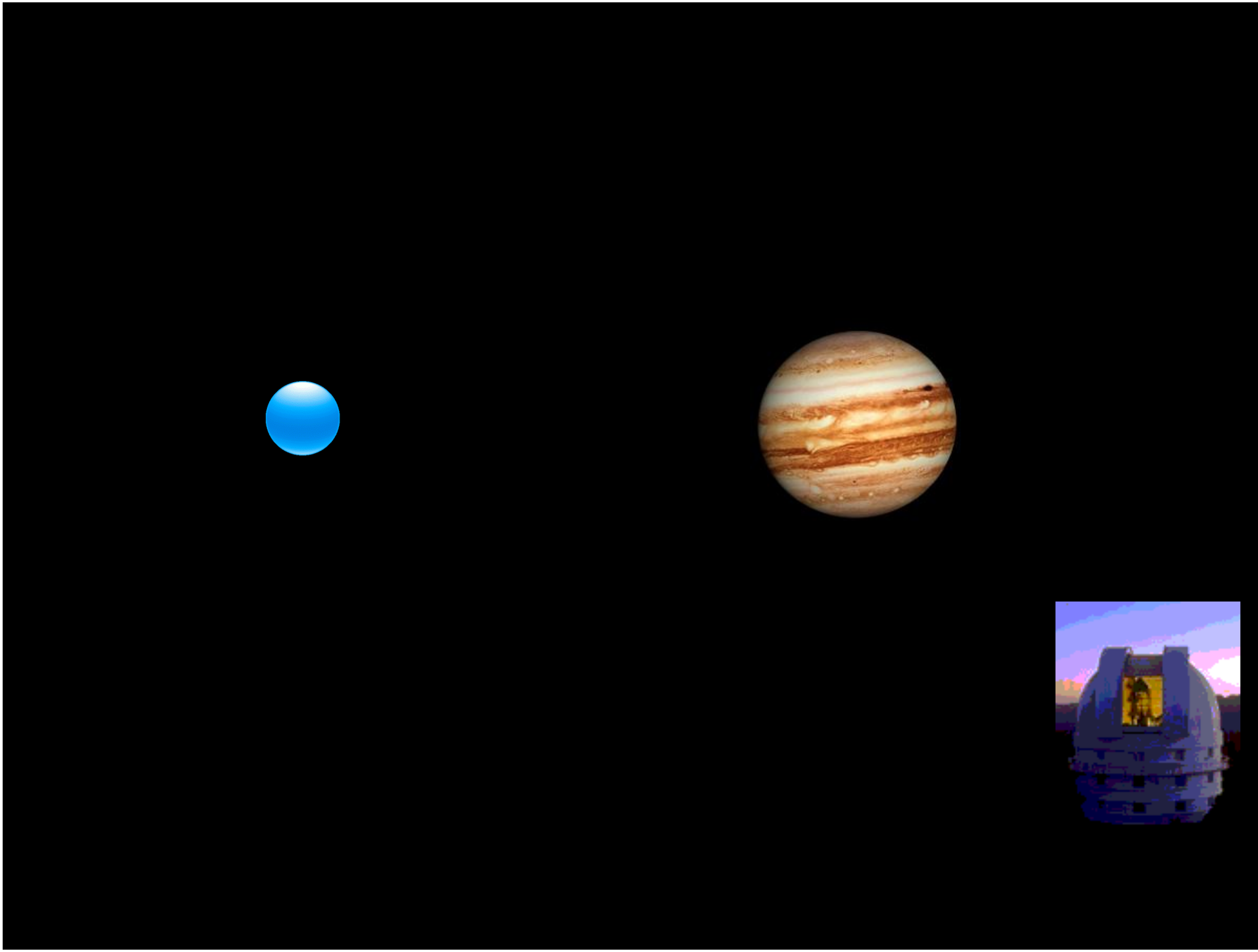
Extreme Stability Pulsators: **DBV** and **HDAV Stars**

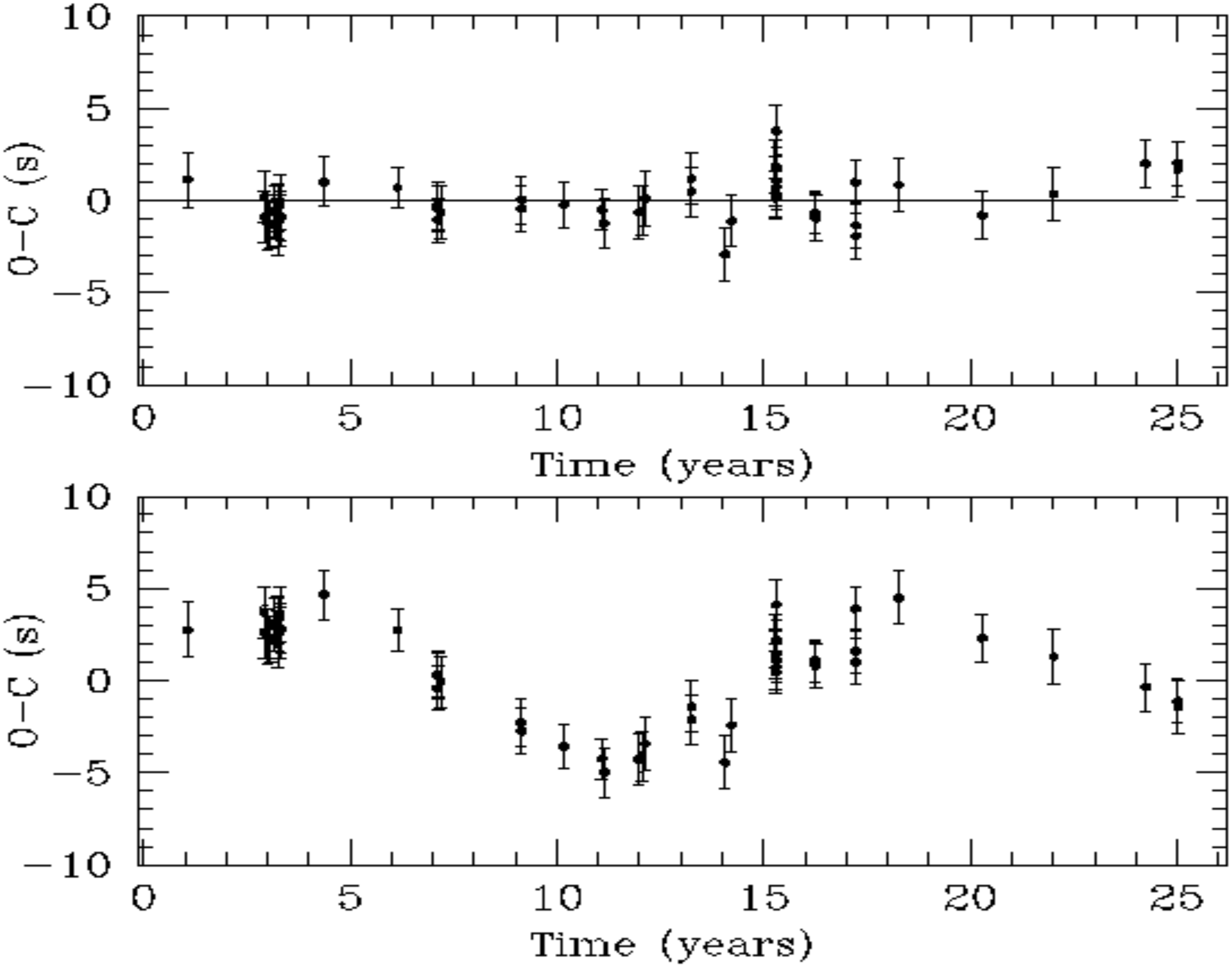
- Stellar evolution becomes a spectator sport!
- Extreme Physics: Plasmons and axions
- The most stable optical clocks—only a few millisecond pulsars are more stable (or are they …?)

Motivation: Why Look for Planets Around White Dwarf Stars?

- Clocks in orbit => information on companions. Watch for change in light travel time due to reflex orbital motion.
- Planet search samples a unique range of planet masses and separations, similar to our own Solar System
- ~10^{-3} fainter than progenitor, makes follow up by direct observation possible (Mullally et al. 2007)
- They come with age estimates …

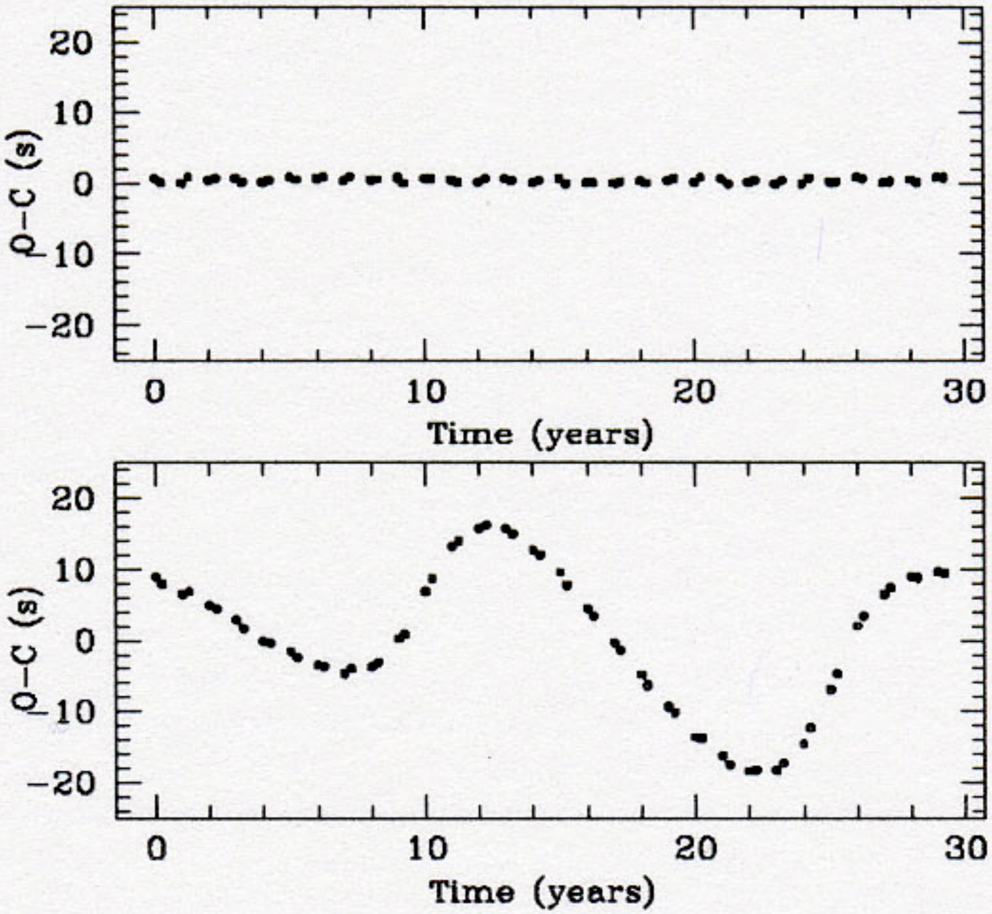

Spiral in to become close companion (CV progenitor?)
Destroyed In Red Giant Envelope
Move out adiabatically with mass loss



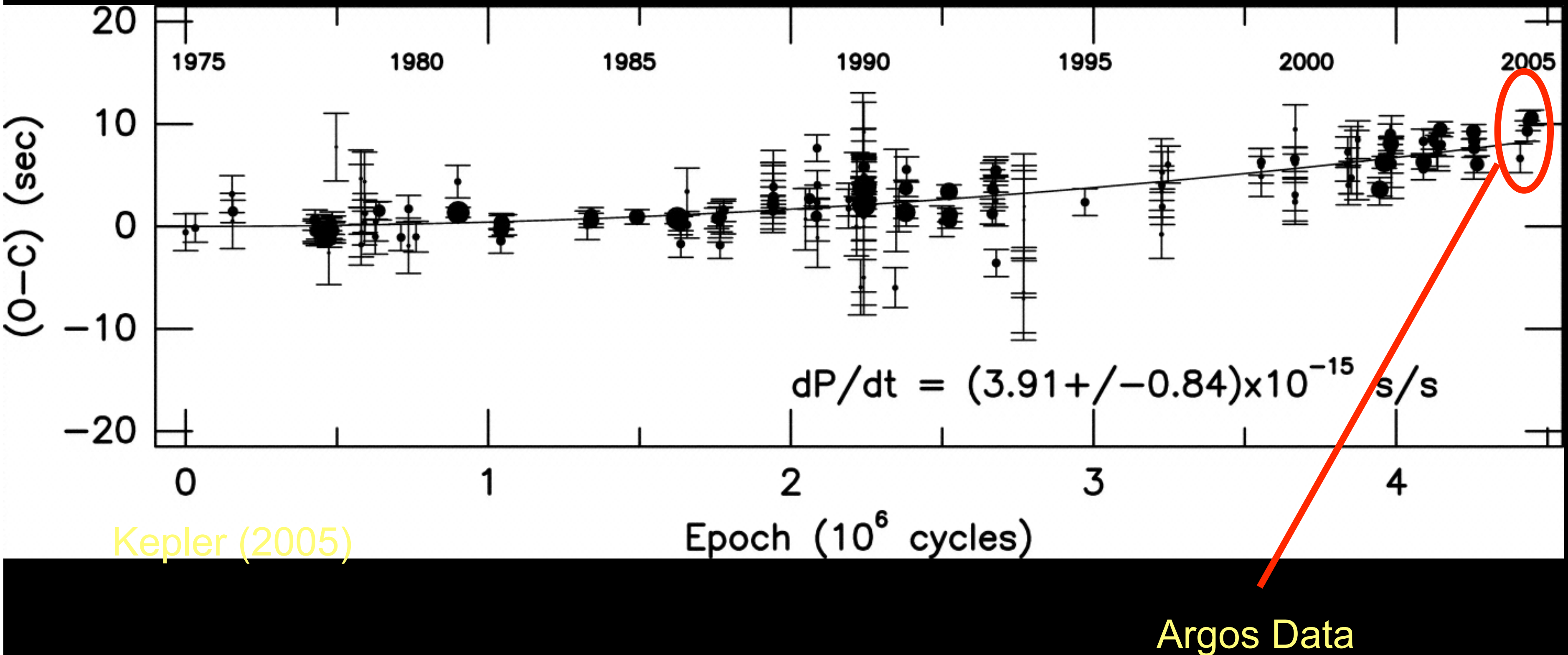


10
5
0
−5
−10
O−C (s)
0
5
10
15
20
25
Time (years)
10
5
0
−5
−10
O−C (s)
0
5
10
15
20
25
Time (years)

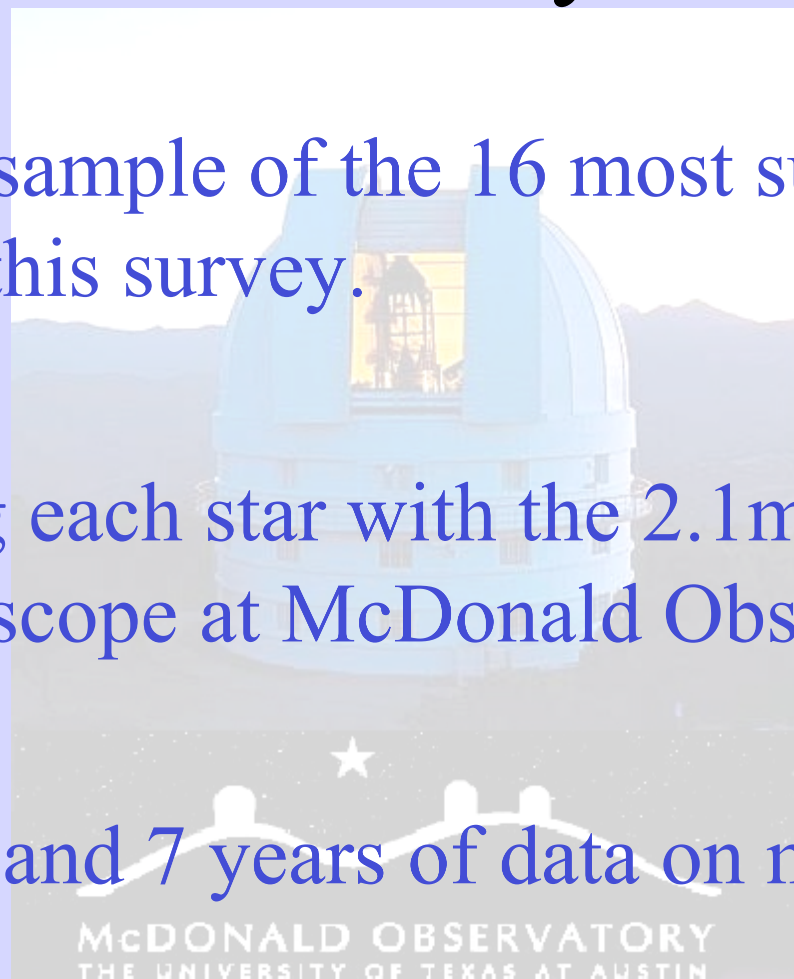
Multiple Planets



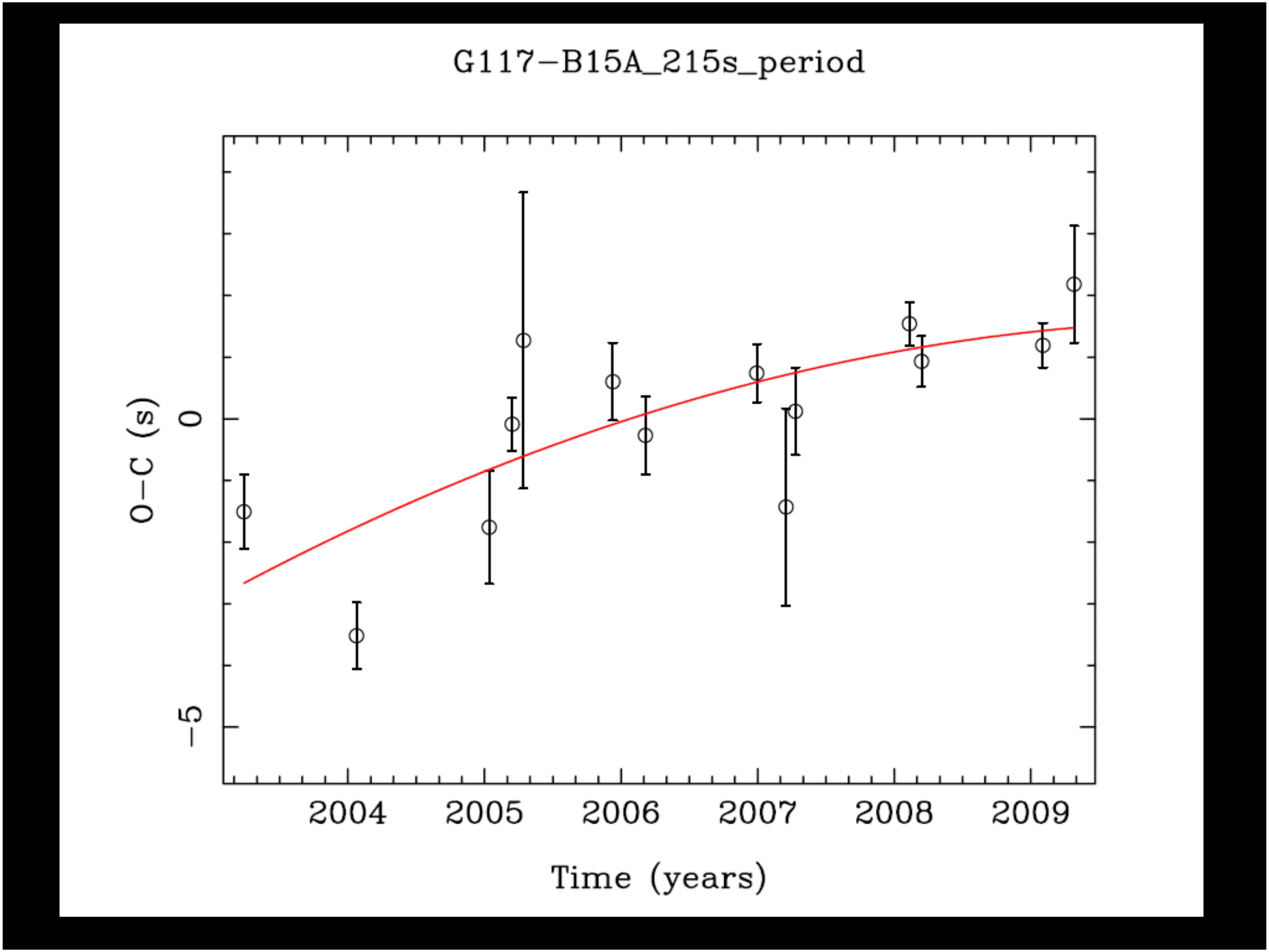
DAV pulsations are **very** stable



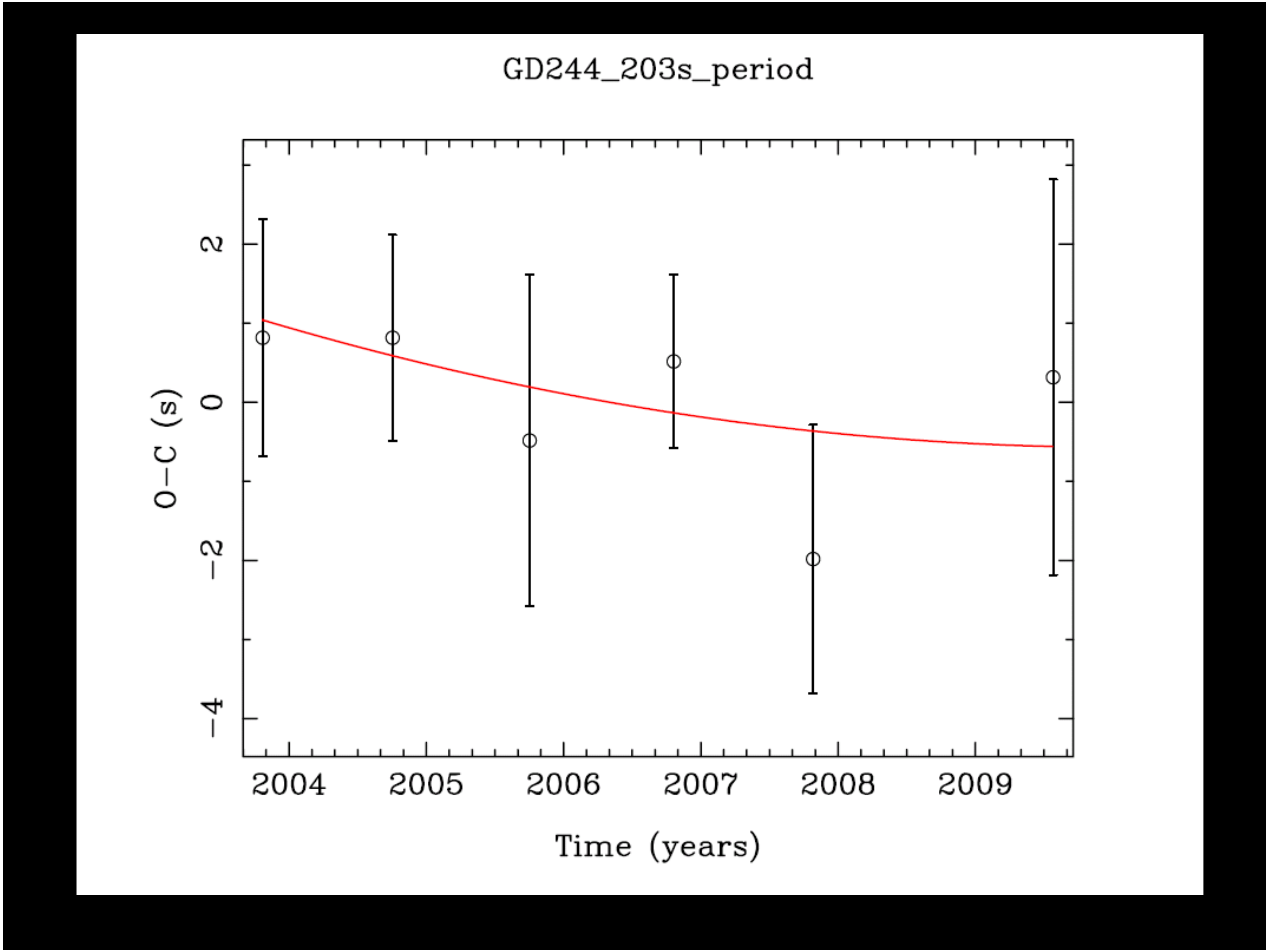
Our Survey



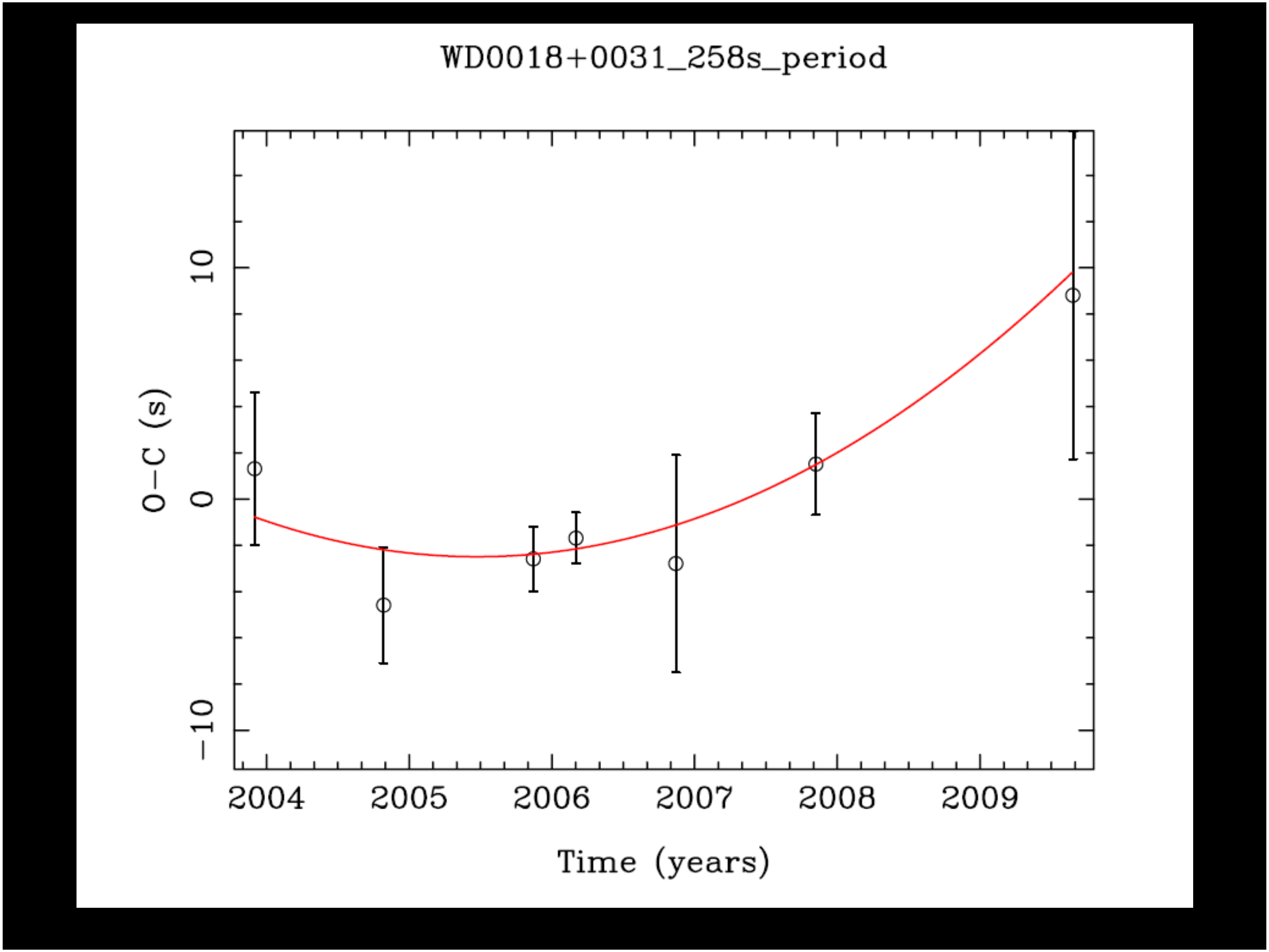
- Selected a sample of the 16 most suitable DAVs for this survey.
- Monitoring each star with the 2.1m Otto Struve telescope at McDonald Observatory
- Between 5 and 7 years of data on most stars.



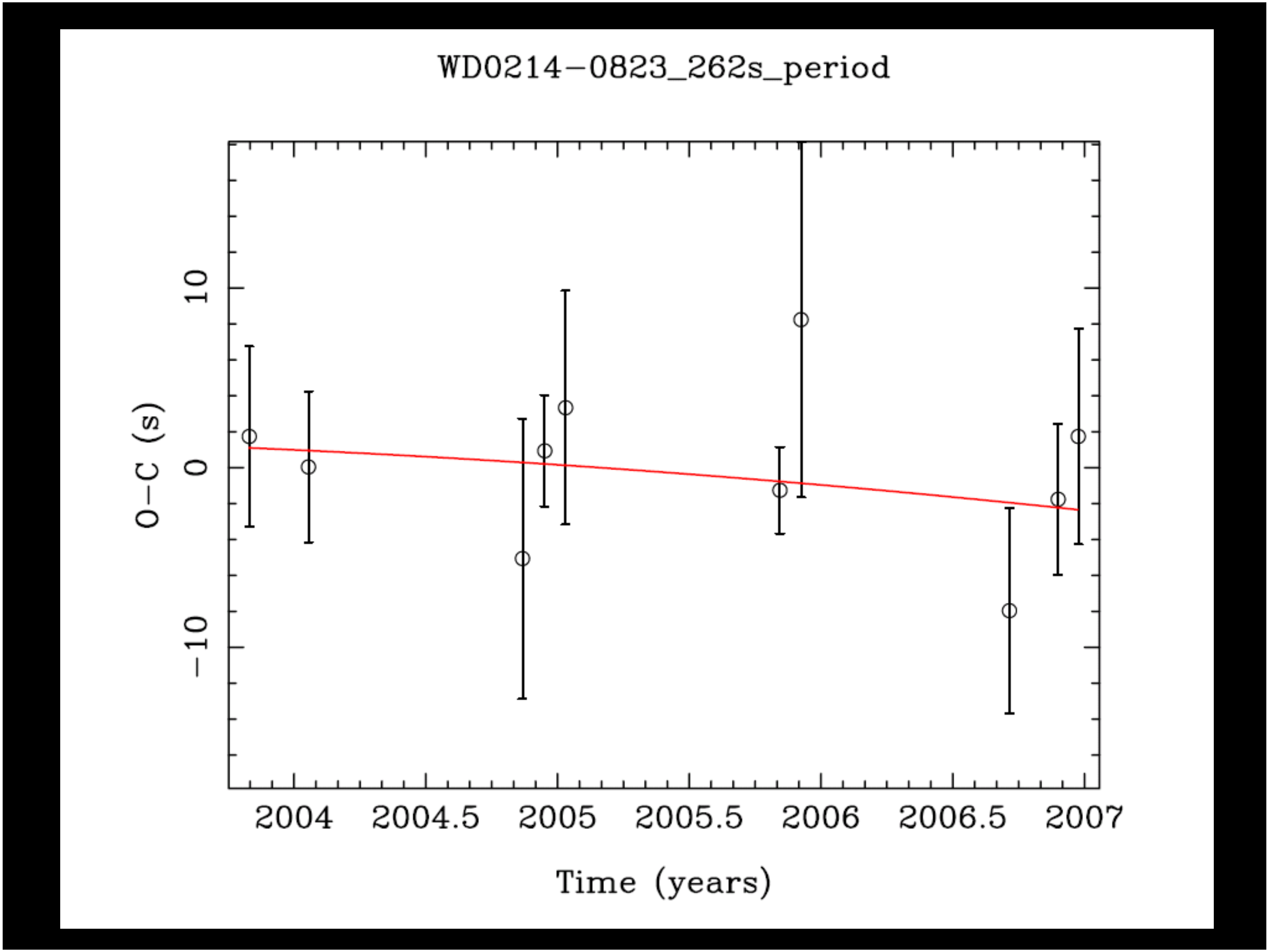
G117−B15A_215s_period
O−C (s)
0
−5
2004
2005
2006
2007
2008
2009
Time (years)



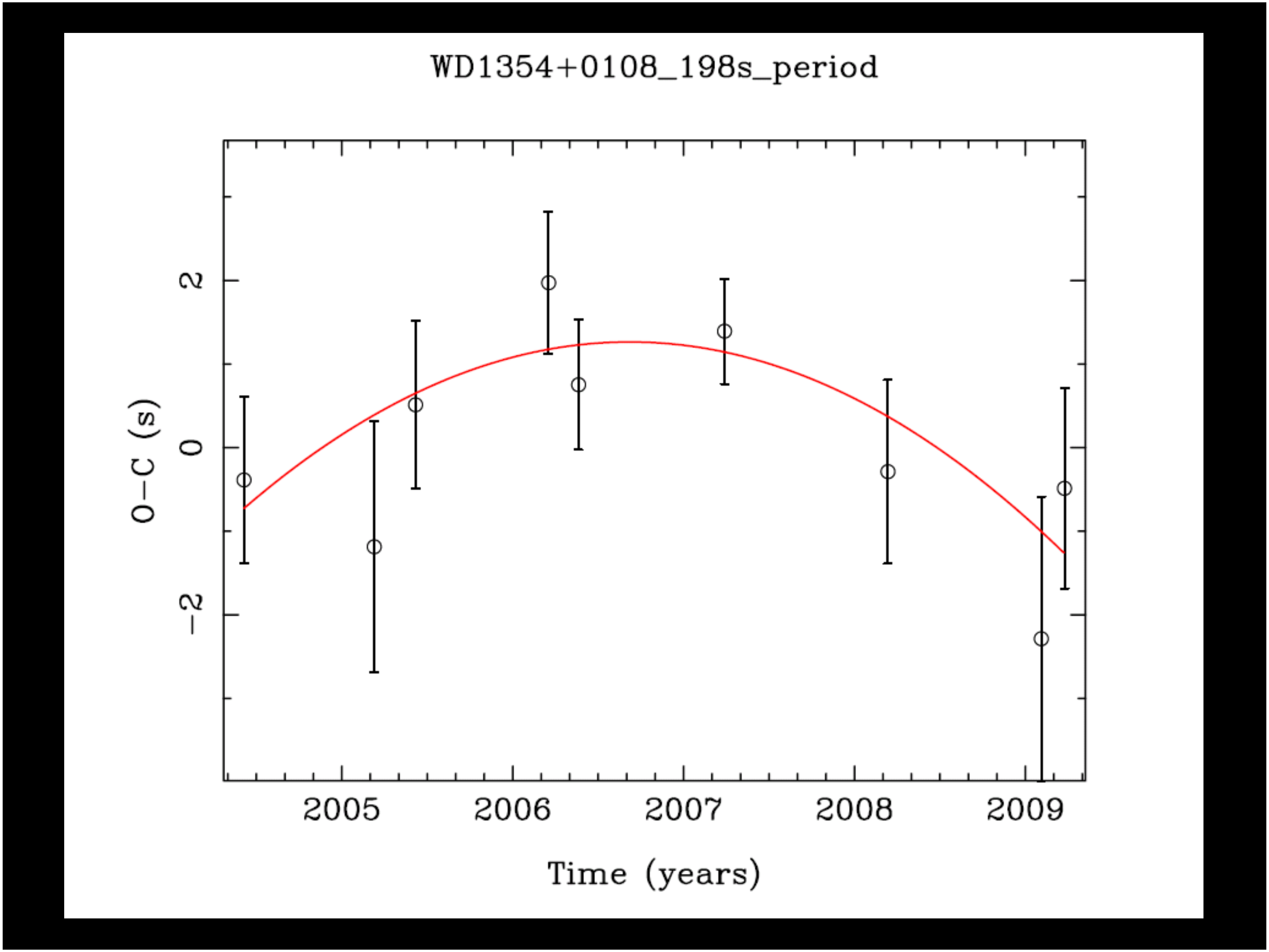
GD244_203s_period
O−C (s)
2
0
−2
−4
2004
2005
2006
2007
2008
2009
Time (years)



WD0018+0031_258s_period
O−C (s)
10
0
−10
2004
2005
2006
2007
2008
2009
Time (years)

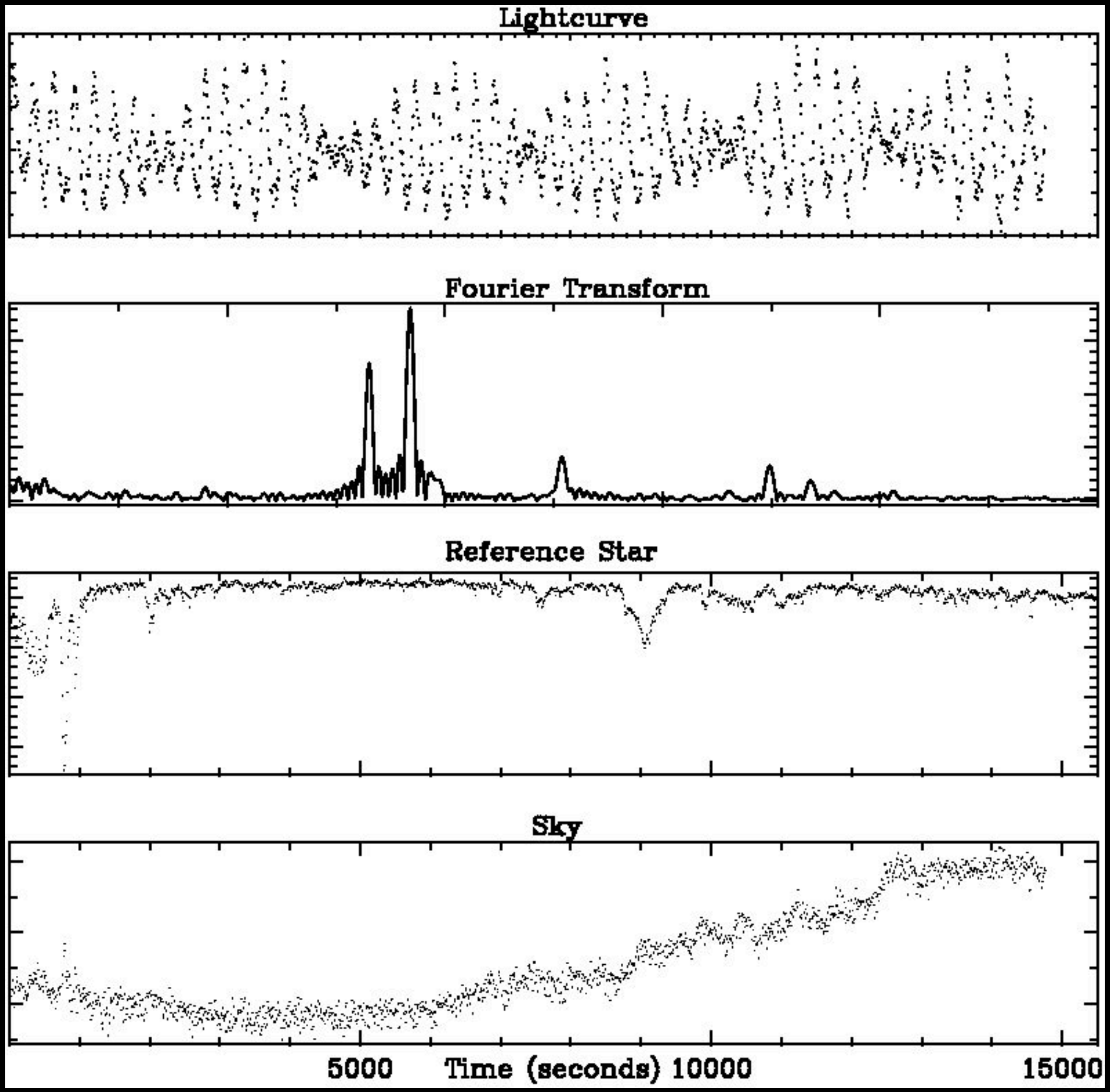


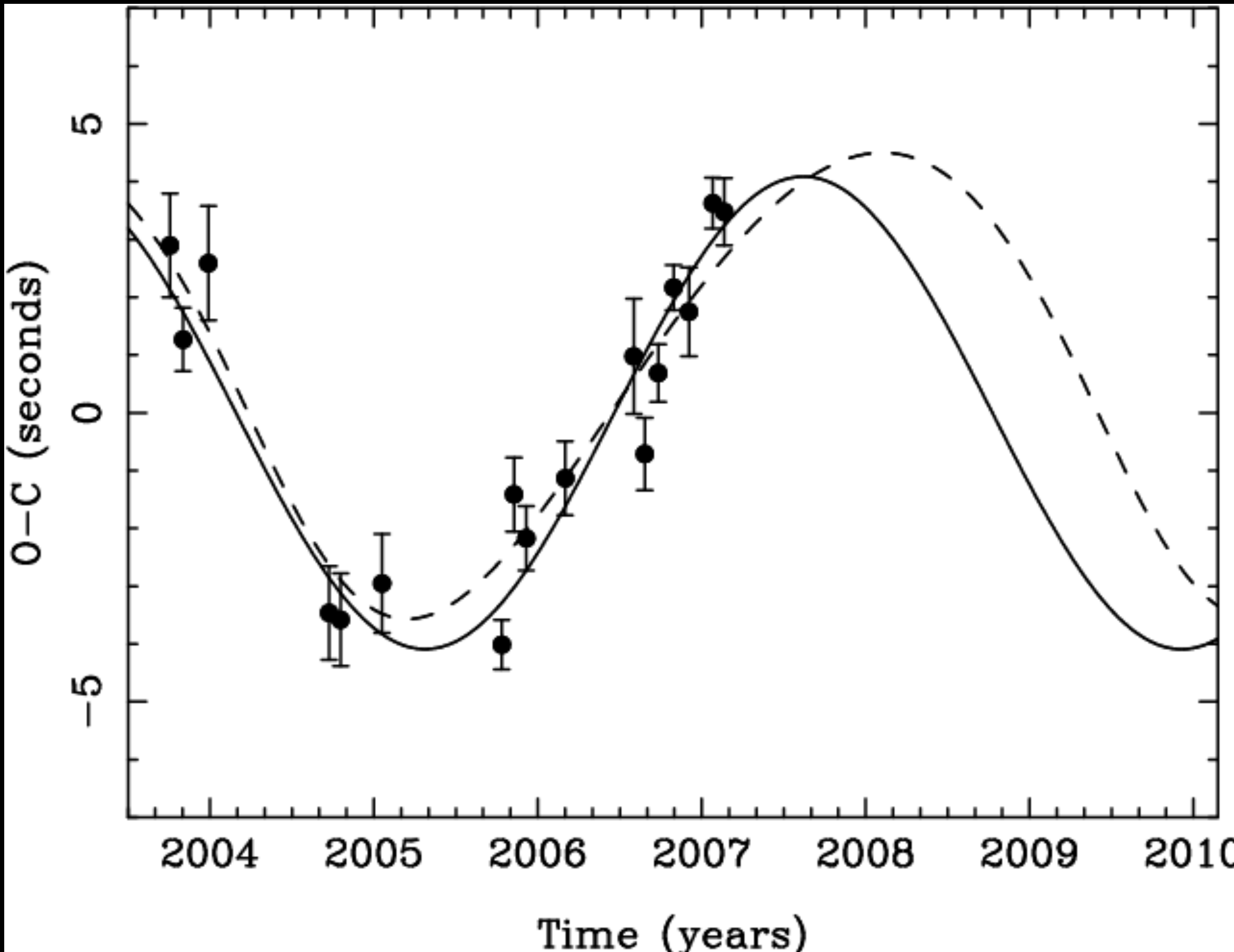
WD0214−0823_262s_period
O−C (s)
10
0
−10
2004
2004.5
2005
2005.5
2006
2006.5
2007
Time (years)



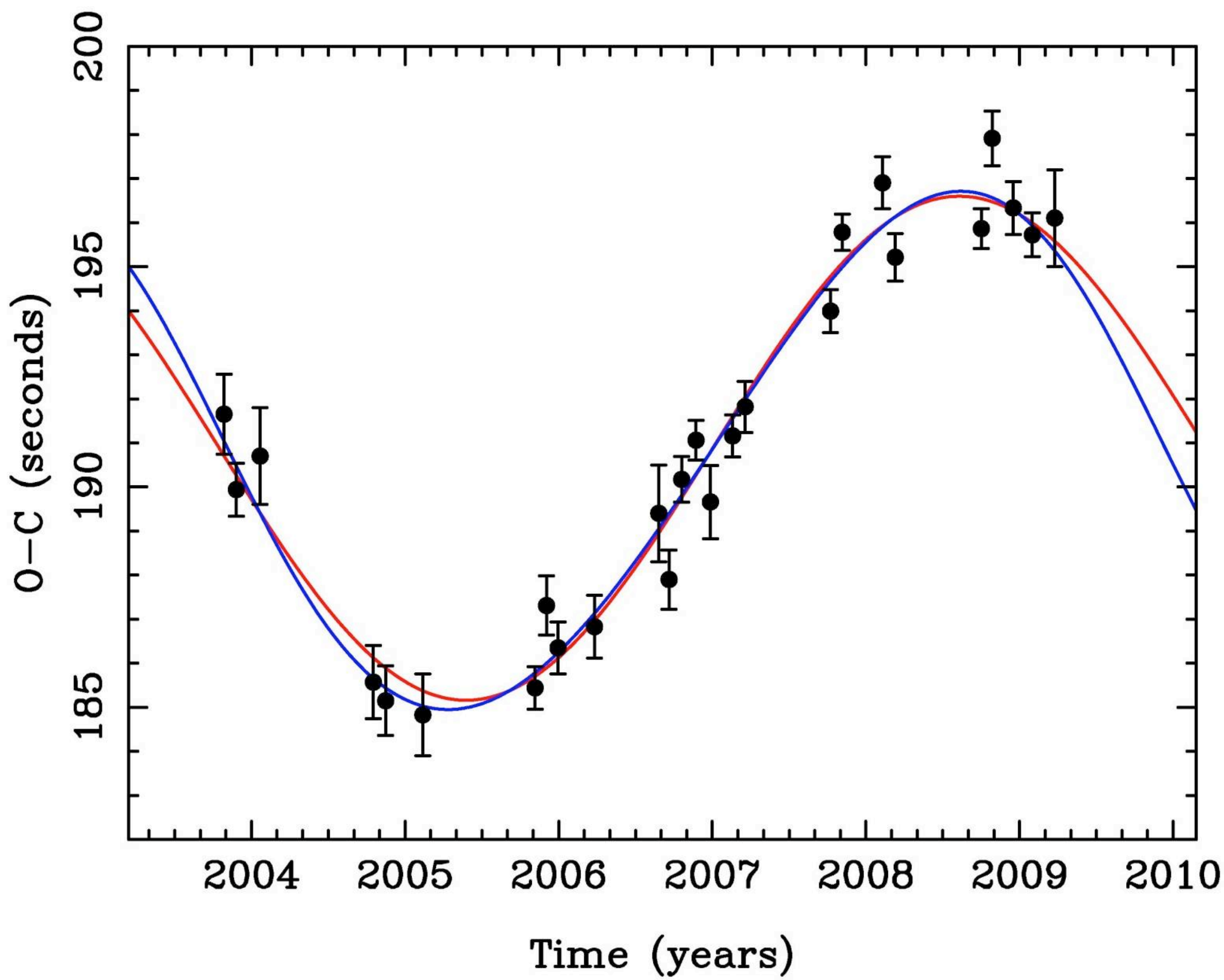
WD1354+0108_198s_period
O−C (s)
2
0
−2
2005
2006
2007
2008
2009
Time (years)

GD66 Lightcurve



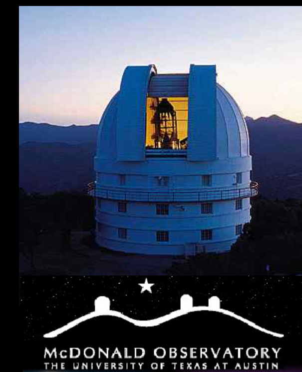


5
0
−5
O−C (seconds)
2004
2005
2006
2007
2008
2009
2010
Time (years)



200
195
190
185
O−C (seconds)
2004
2005
2006
2007
2008
2009
2010
Time (years)

Current Results of Planet Search



- We have evidence for ***the first planet in orbit around a white dwarf star!***
- The planet mass is about 2 M_J. The period is about 7 years.
- We have found a planet in a system that is ***dynamically similar to our own!***
- Evidence for 1-2 more in sample of 16 stars: **3/16**!

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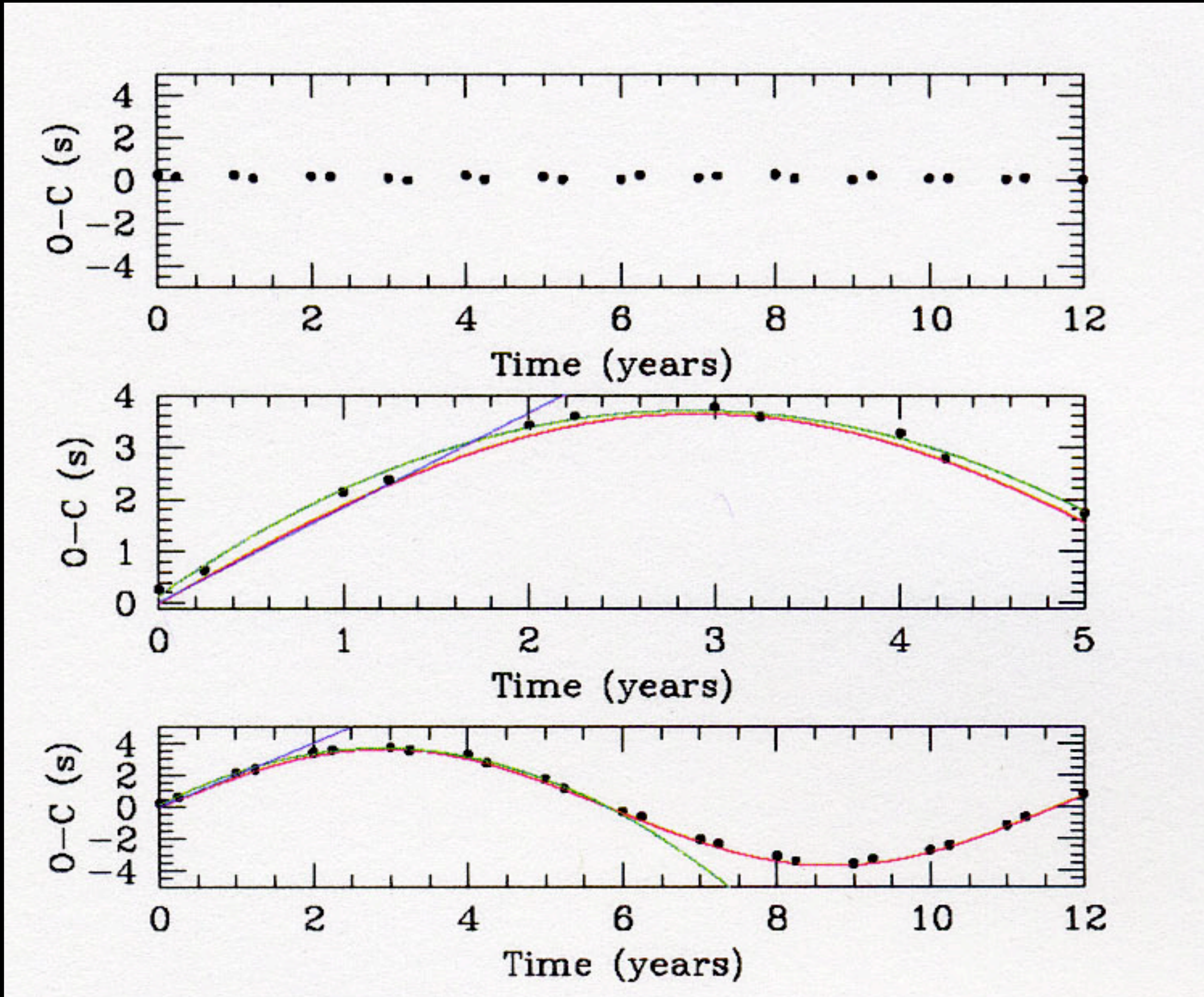
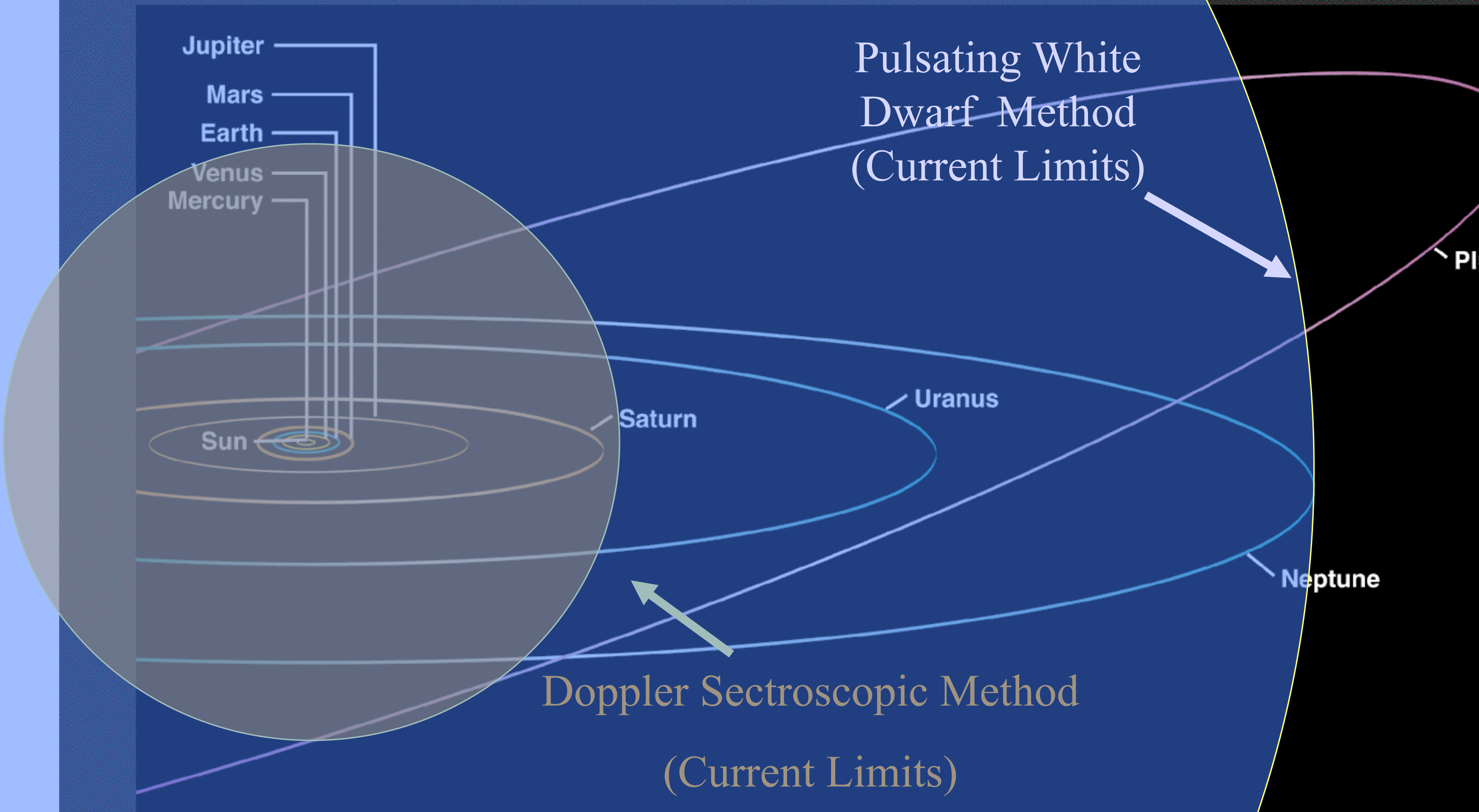
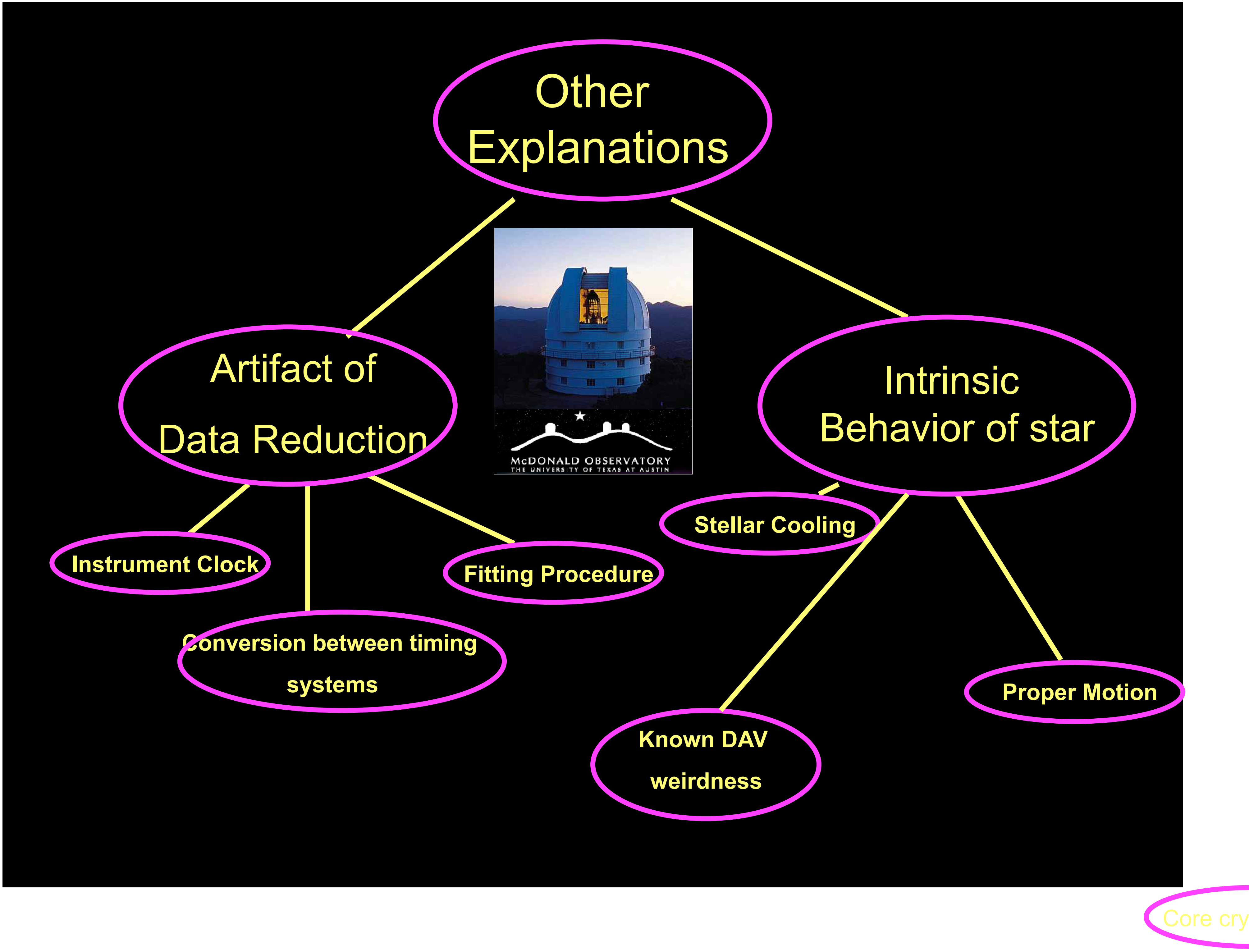
Early Warnings





Pasachoff, Astronomy: From the Earth to the Universe, 6/e
Figure 7.20/Planetary orbits, side view


Other Explanations
Artifact of Data Reduction
Intrinsic Behavior of star
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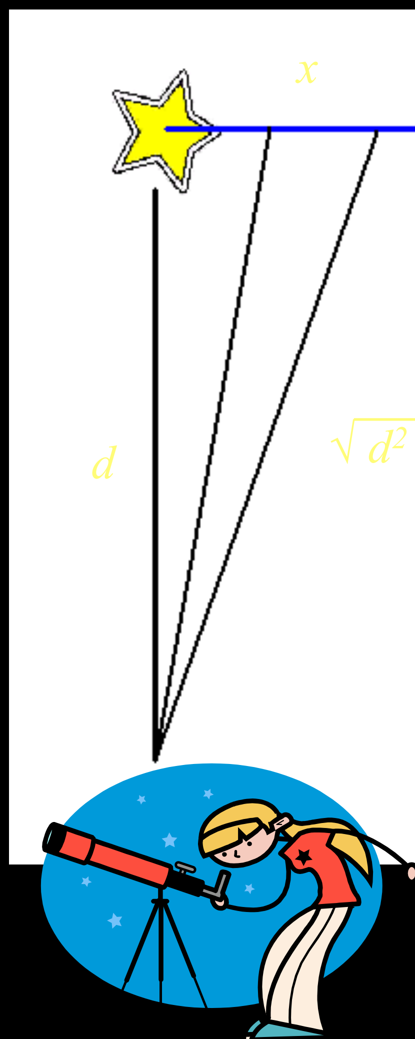
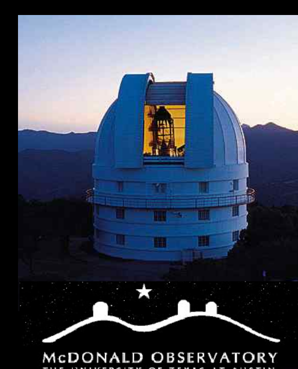
Instrument Clock
Conversion between timing systems
Fitting Procedure
Stellar Cooling
Known DAV weirdness
Proper Motion
Core cry

Proper motion creates a $\dot{P}$ term

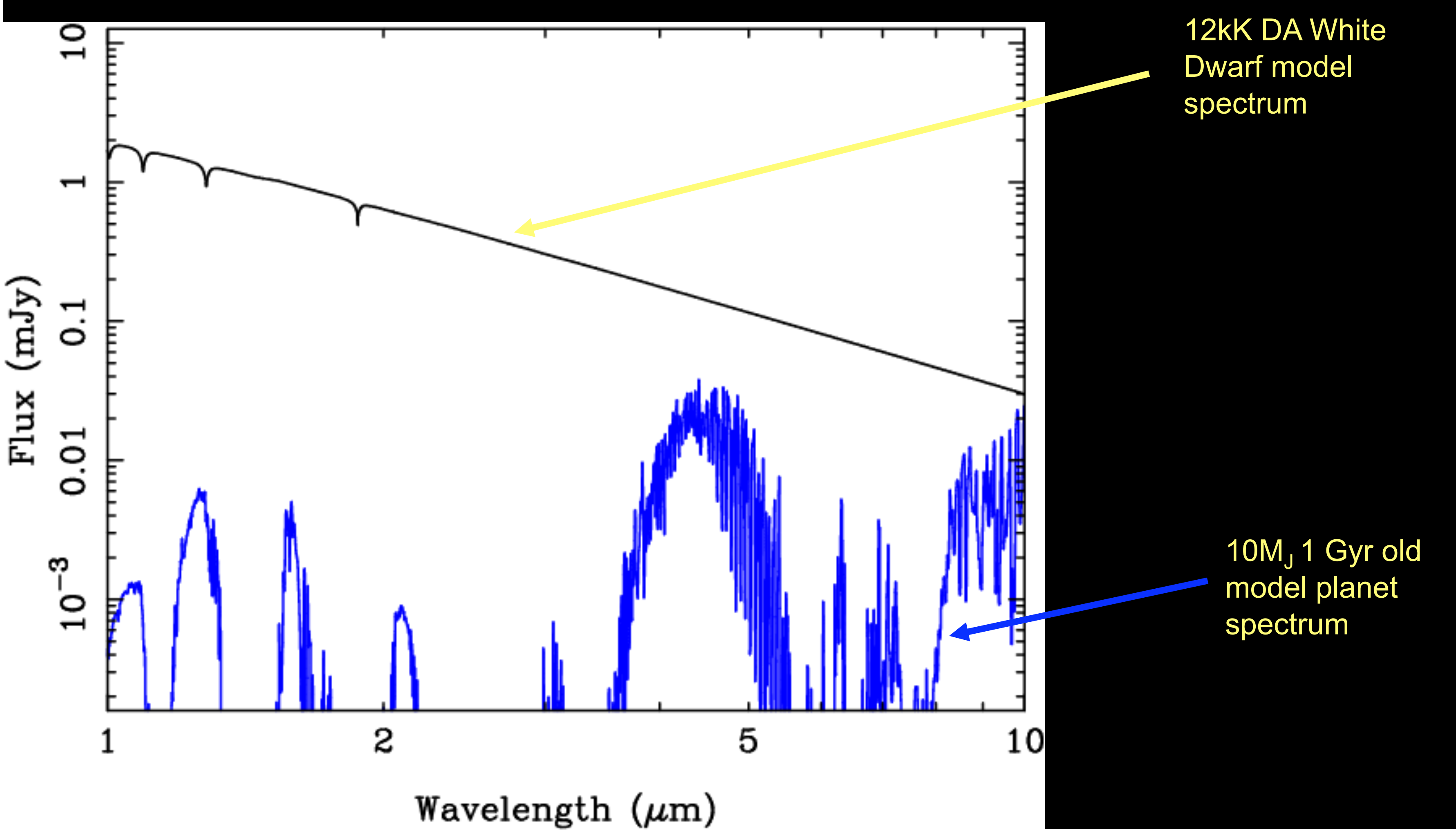


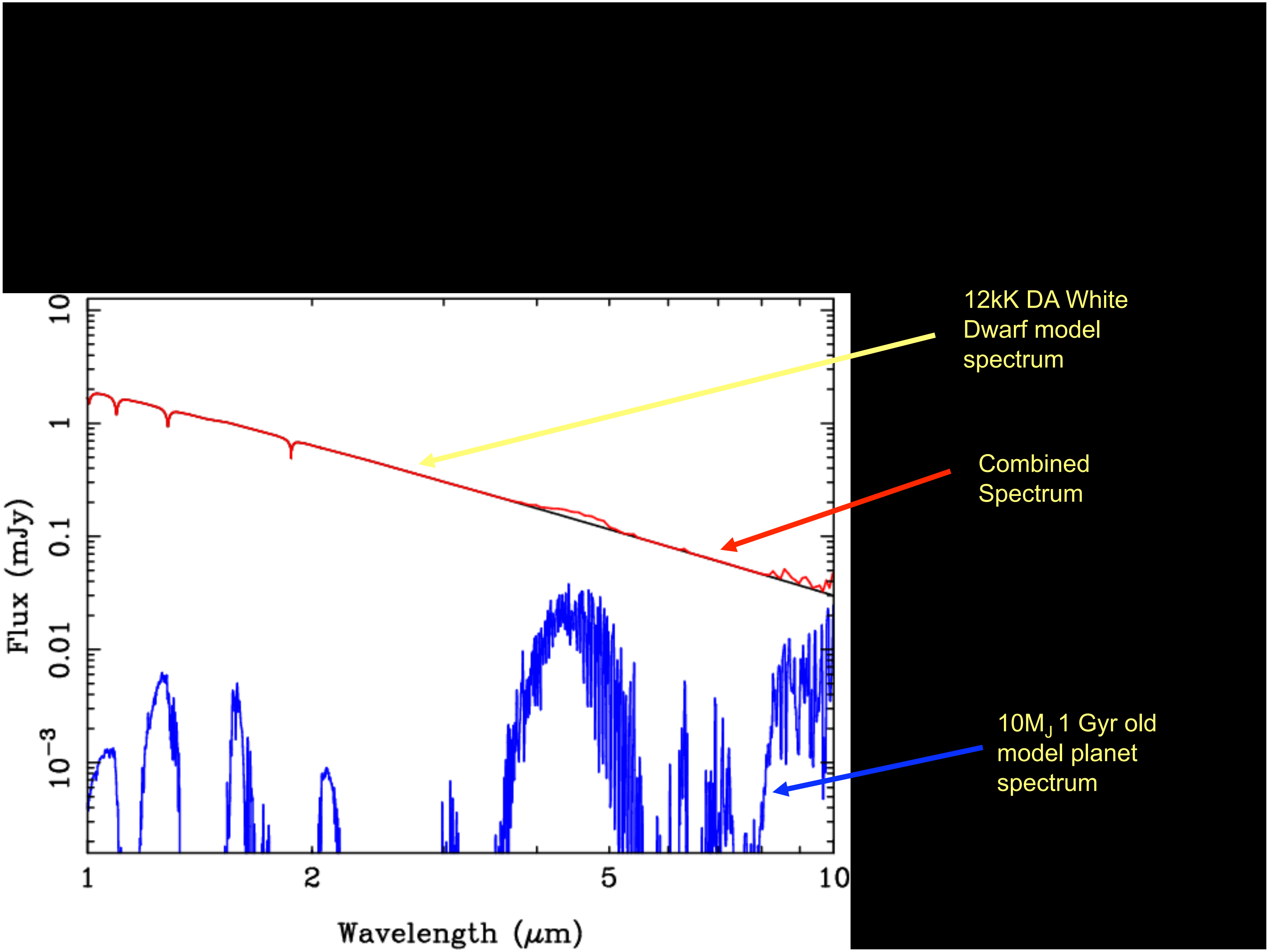


Other Effects – Proper Motion

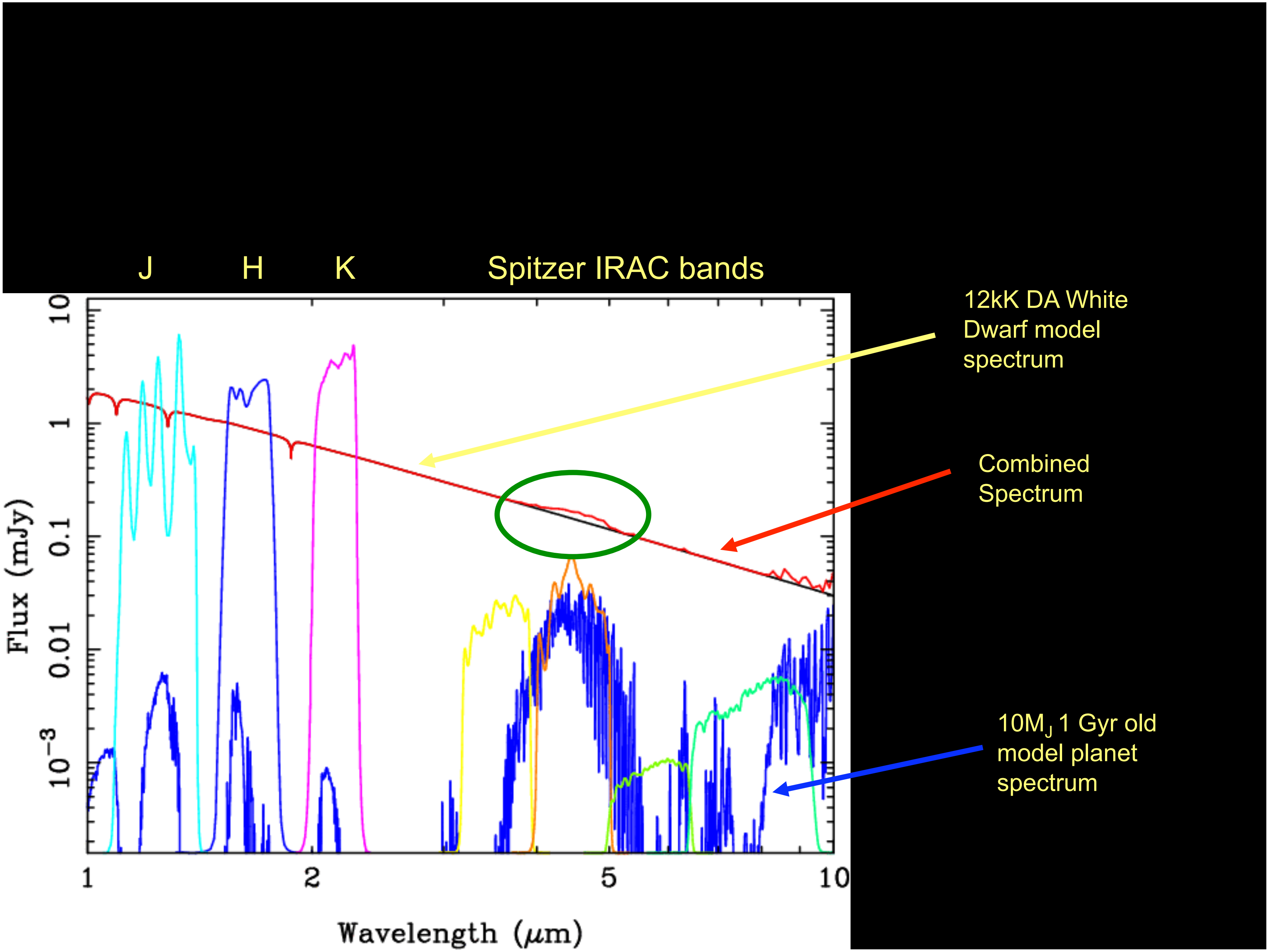
- μ= 133 mas/yr
- $$\dot{P}_{\rm pm} = 2.430 \times 10^{-18} P \mu^2 d,$$

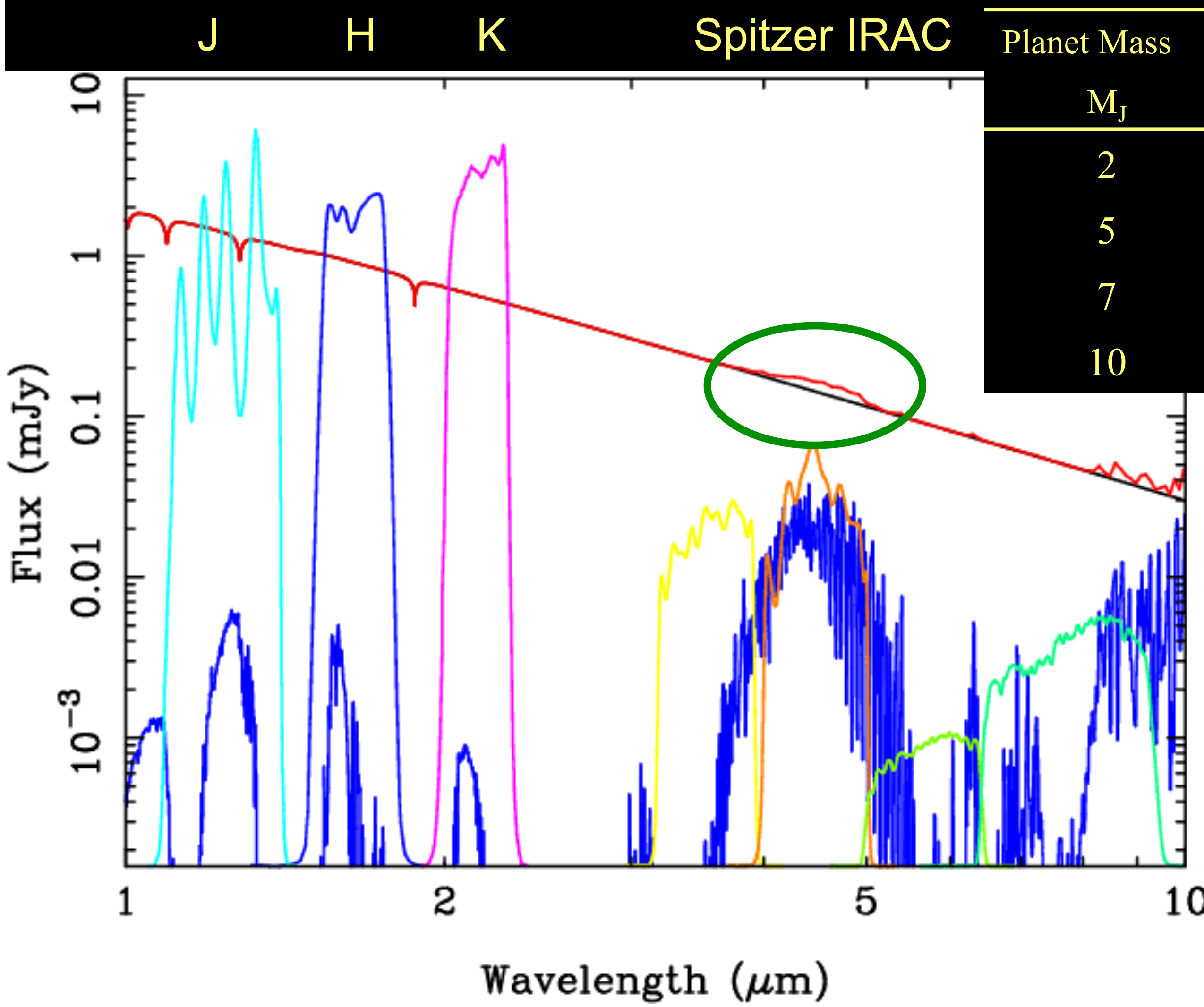
  Pajdosz (1995)
- P=302s d≈ 50pc
- $\dot{P}_{pm}$= 6.5 x 10^{-16}
- $\dot{P}_{obs}$ ~ 10^{-12}


12kK DA White Dwarf model spectrum
10M$_J$ 1 Gyr old model planet spectrum
Flux (mJy)
10
1
0.1
0.01
10^{-3}
1
2
5
10
Wavelength (μm)



12kK DA White Dwarf model spectrum
Combined Spectrum
$10M_J$ 1 Gyr old model planet spectrum
Flux (mJy)
10
1
0.1
0.01
10^{-3}
1
2
5
10
Wavelength (μm)


J
H
K
Spitzer IRAC bands
12kK DA White Dwarf model spectrum
Combined Spectrum
10M$_J$ 1 Gyr old model planet spectrum
Flux (mJy)
10
1
0.1
0.01
10^{-3}
1
2
5
10
Wavelength (μm)



Planet Mass M_J	Contrast at 4.5μm	Observing Time for 1σ detection
2	1.003	6.8hrs
5	1.043	111s
7	1.078	33s
10	1.127	13s

$$\frac{\text{Flux(Star + Planet)}}{\text{Flux(Star)}}$$

[redacted]