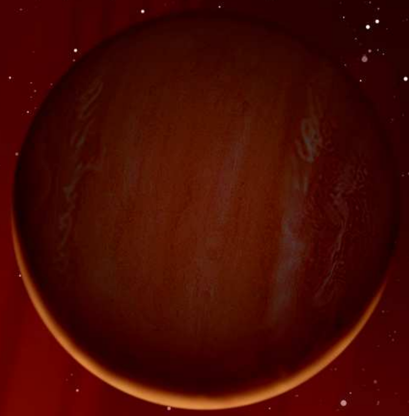
Late stage evolution of planetary systems: the case of V 391 Pegasi b

[Silvotti et al. 2007, Nature 449, 189]



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and

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HST meeting, Bologna 29-31/01/2008

Exoplanets

270 candidates (26 multiplanetary systems)

Detection methods:

RVs (256)

Transits (34)

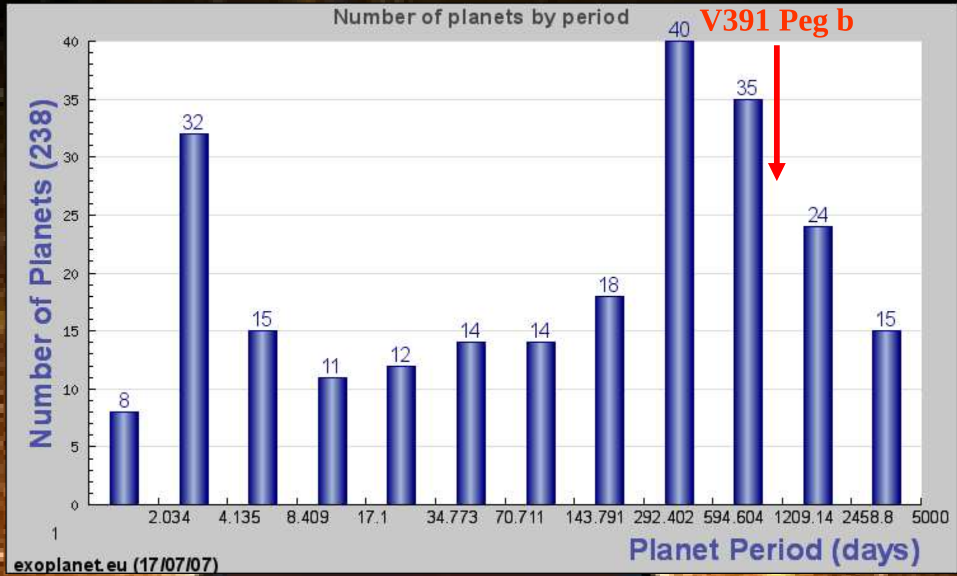
Microlensing (4)

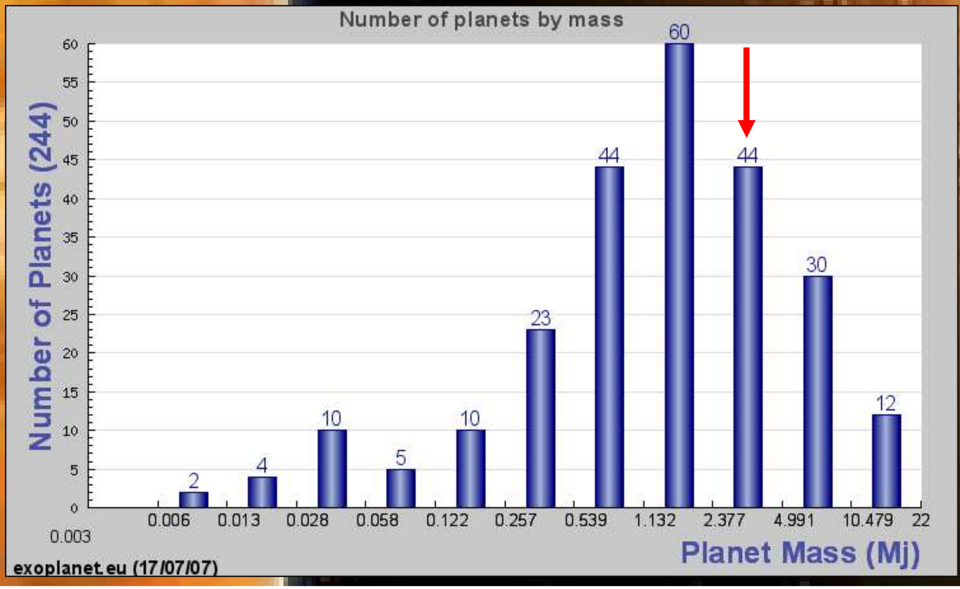
Direct imaging (4)

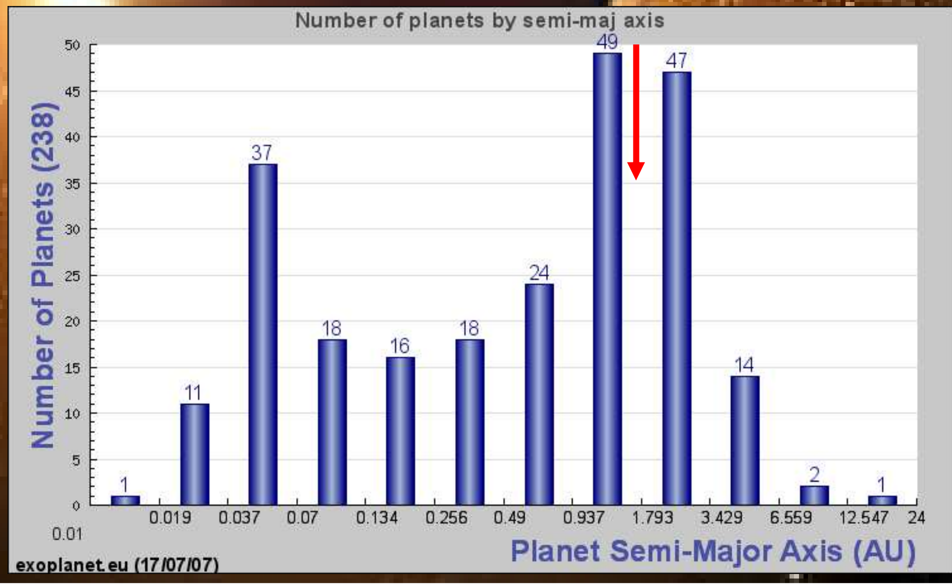
Timing: planets around pulsars (4),

HB stars (1, V391Peg b) and WDs (1?)

≈ 5% of stars have planets







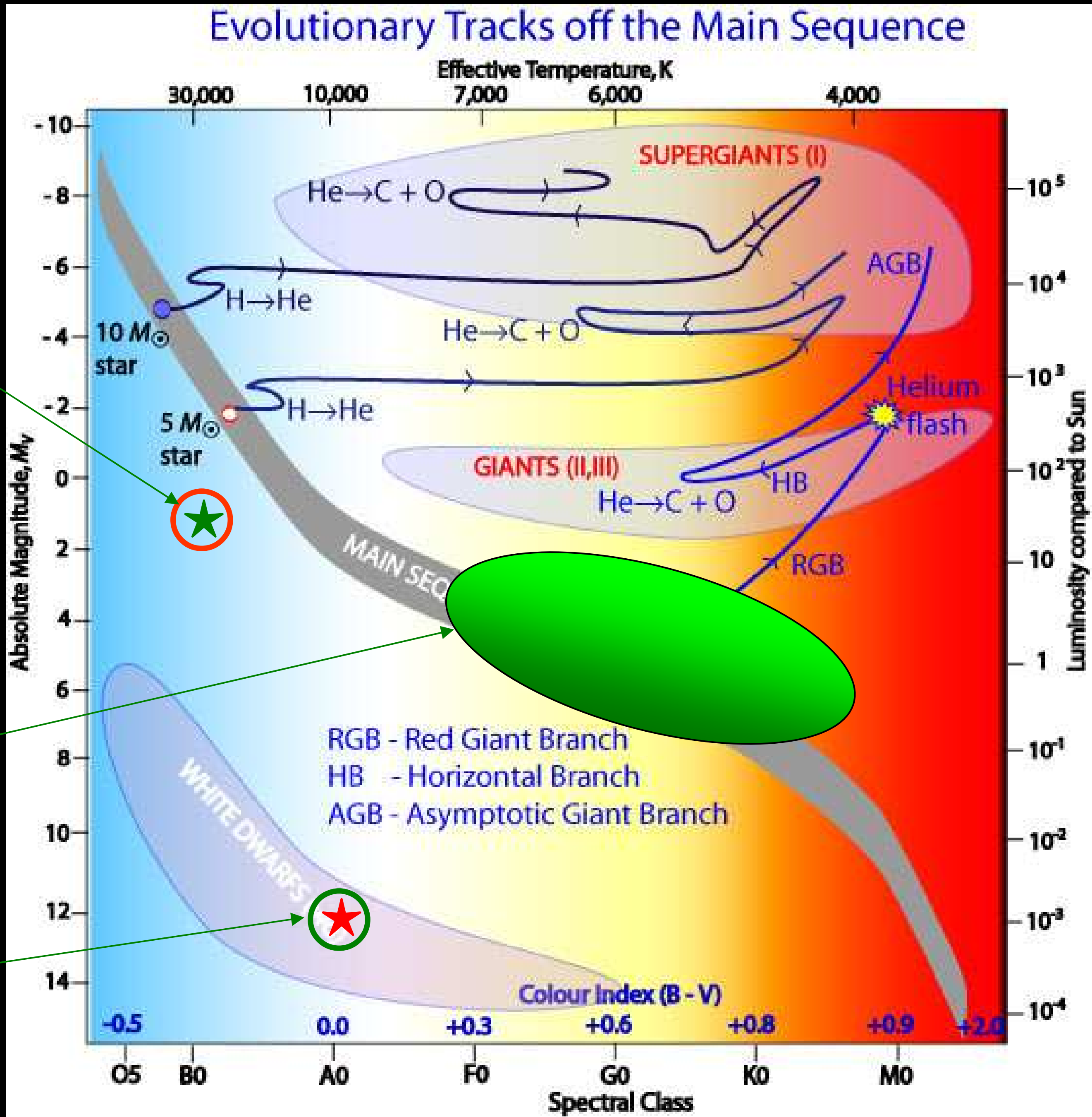
V 391 Pegasi:

a 29,000 K EHB (sdBV) star near central He exhaustion (age of ~100 Myr after the ZAHB)

known exoplanets

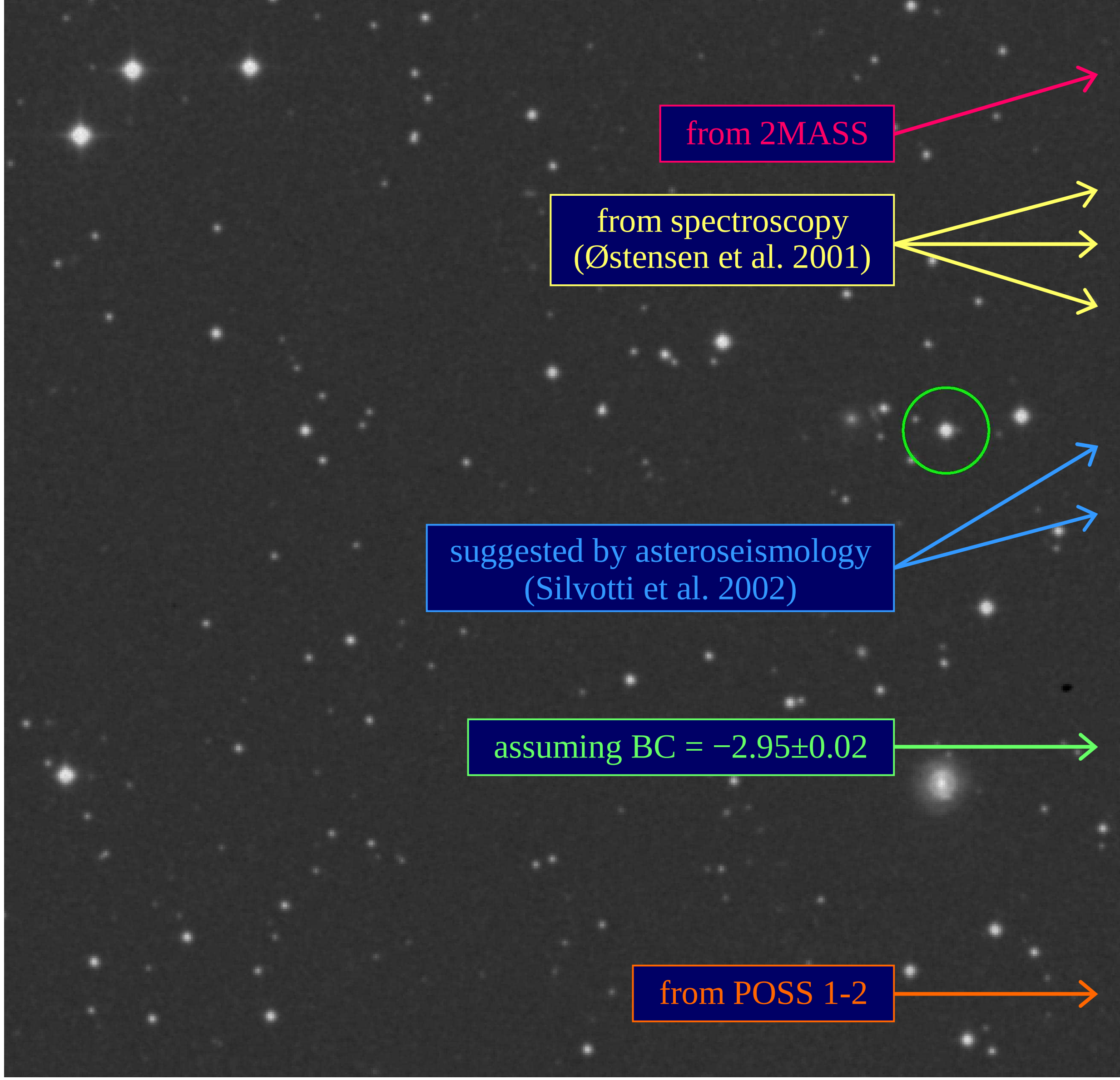
GD 66:

a 12,000 K DAV white dwarf [planet candidate, Mullally et al. 2008]



V 391 Peg (or HS2201+2610):

a core He burning Extreme HB star
belonging to the hot subdwarf B (sdB) class



from 2MASS → J, H, K

from spectroscopy (Østensen et al. 2001) → T_{eff}, log*g*, log(N(He)/N(H))

suggested by asteroseismology (Silvotti et al. 2002) → M/M_{SUN}, M_{ENV}/M_{SUN}

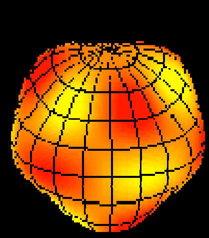
assuming BC = −2.95±0.02 → M_V

from POSS 1-2 → pm

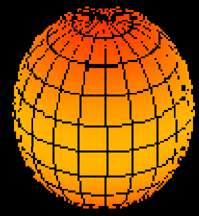
U=13.35±0.03 B=14.35±0.02 V=14.57±0.02
J=15.17±0.05 H=15.16±0.10 K=15.38±0.20
T_{eff} [K] = 29,300 ± 500
log*g* [cgs units] = 5.4 ± 0.1
log(N(He)/N(H)) = −3.0 ± 0.3
$M/M_{SUN} \cong 0.50 \pm 0.05$
$M_{ENV}/M_{SUN} \lesssim 0.005$
R/R_{SUN} (M, *g*) = 0.23 ± 0.03
L/L_{SUN} (T_{eff}, R) = 35 ± 9
M_V (L, BC) = 3.84 ± 0.28
d (V, M_V) [pc] = 1300 ± 200
Age [Gyr] ≳ 10
pm ≲ 20 mas/yr ($v_{TAN} \lesssim 120$ km/s)

V 391 Peg is a nonradial pulsator

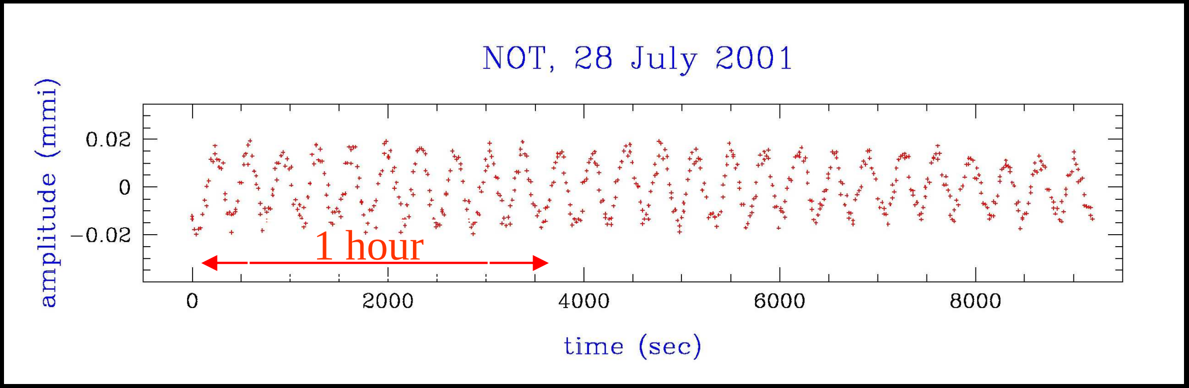
(4 or 5 p-mode pulsation periods of about 6 min [Østensen et al. 2001, Silvotti et al. 2002] + 1 g-mode near 54 min [Lutz et al. 2007])



l=5, m=3



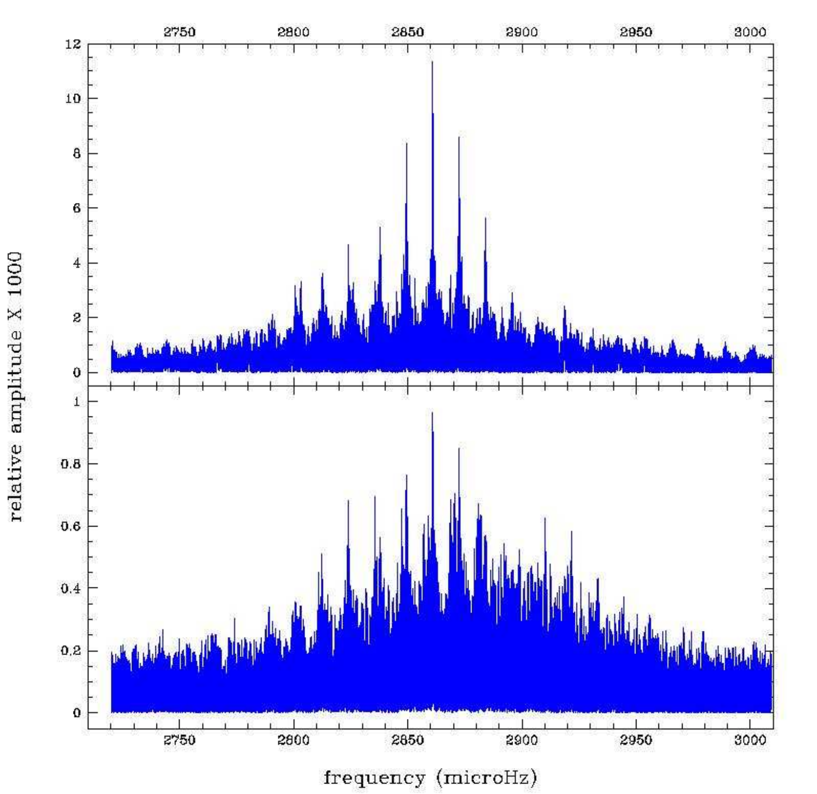
l=2, m=0

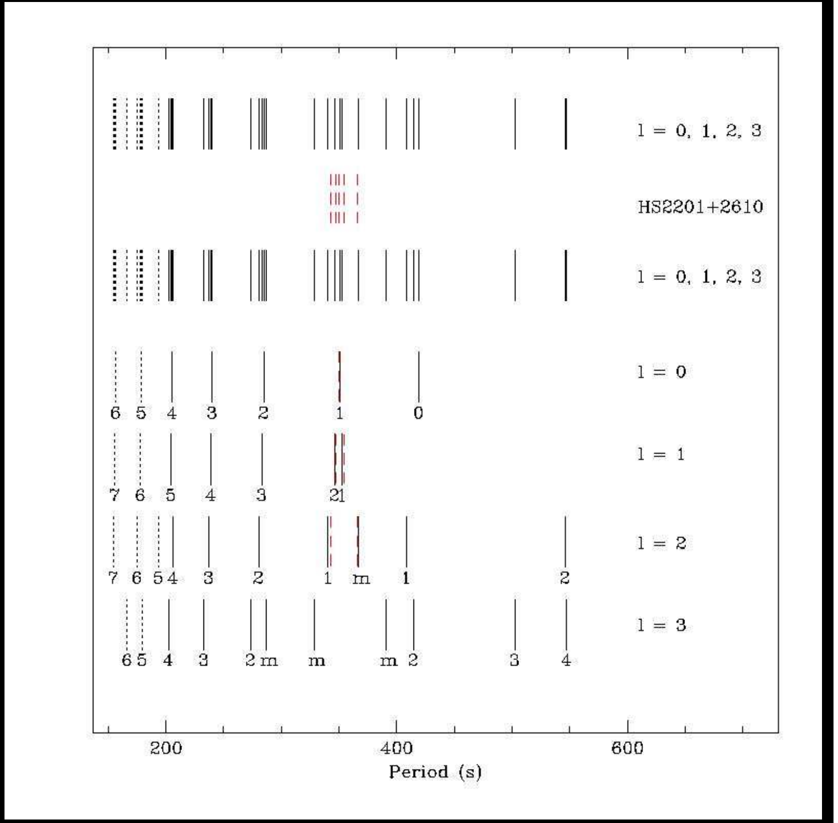


Amplitude Spectrum

(5 years of data)

After prewhitening of the 3 main frequencies at 2860.94, 2824.10 and 2880.69 μHz



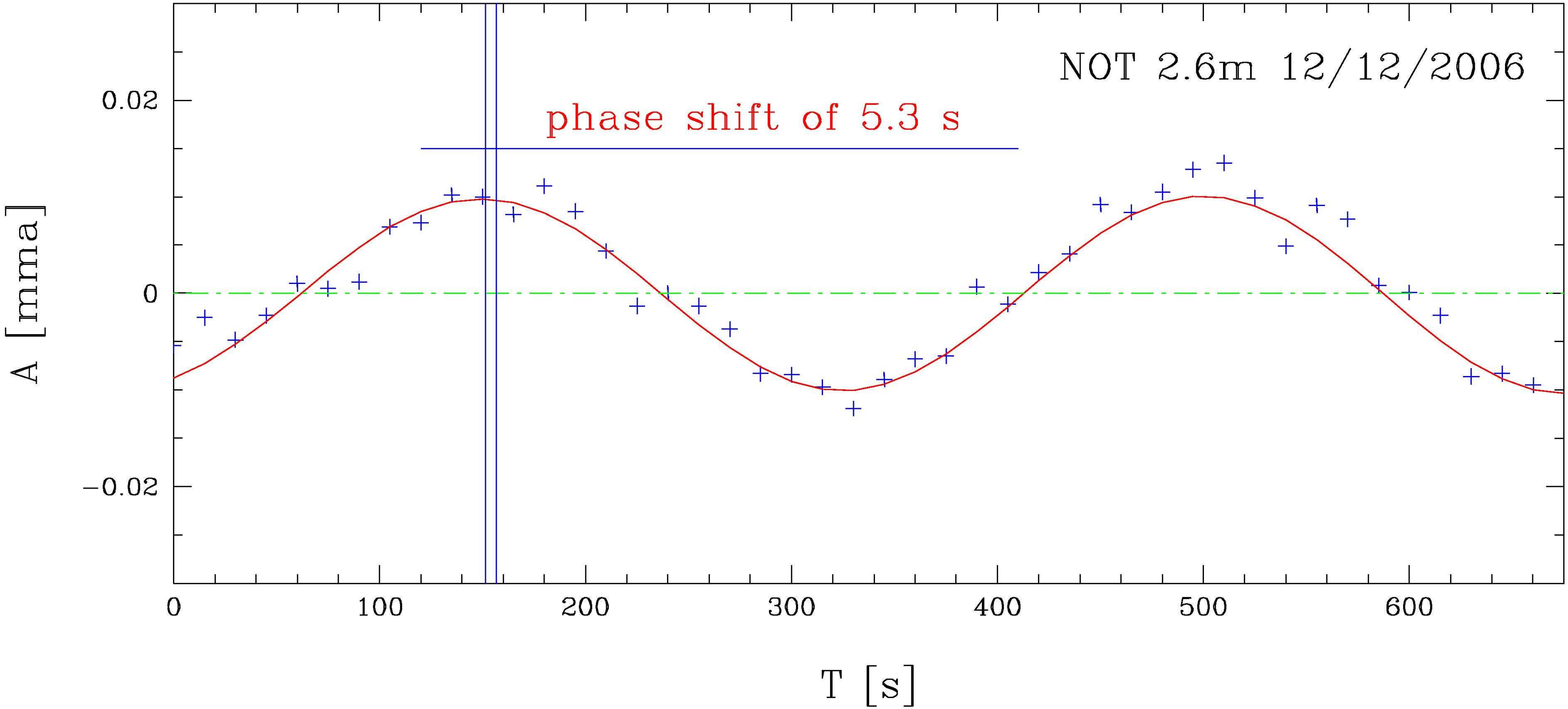


(preliminary) mode identification

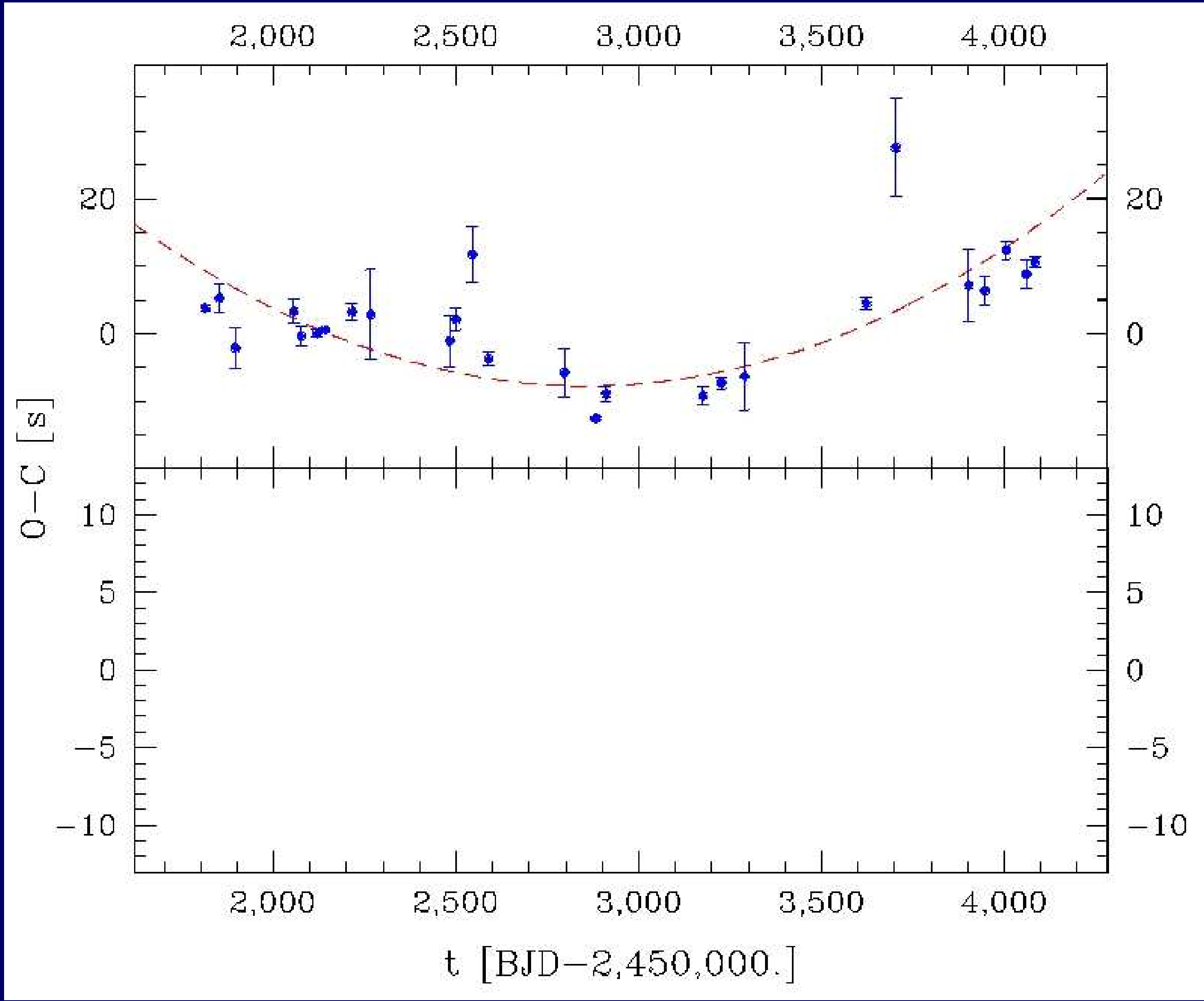
[Silvotti et al. 2002, Charpinet's models]

The O-C (or timing) method

When a pulsation period changes linearly in time, the O-C diagram has a parabolic shape. In our case, the phase shift expected for a secular variation (due to the evolutionary change of the stellar structure) of $dP/dt \approx 10^{-12}$ (or 1 s in about 30,000 yrs) is about 2 s per year.



The O-C diagram of the main pulsation frequency f_1



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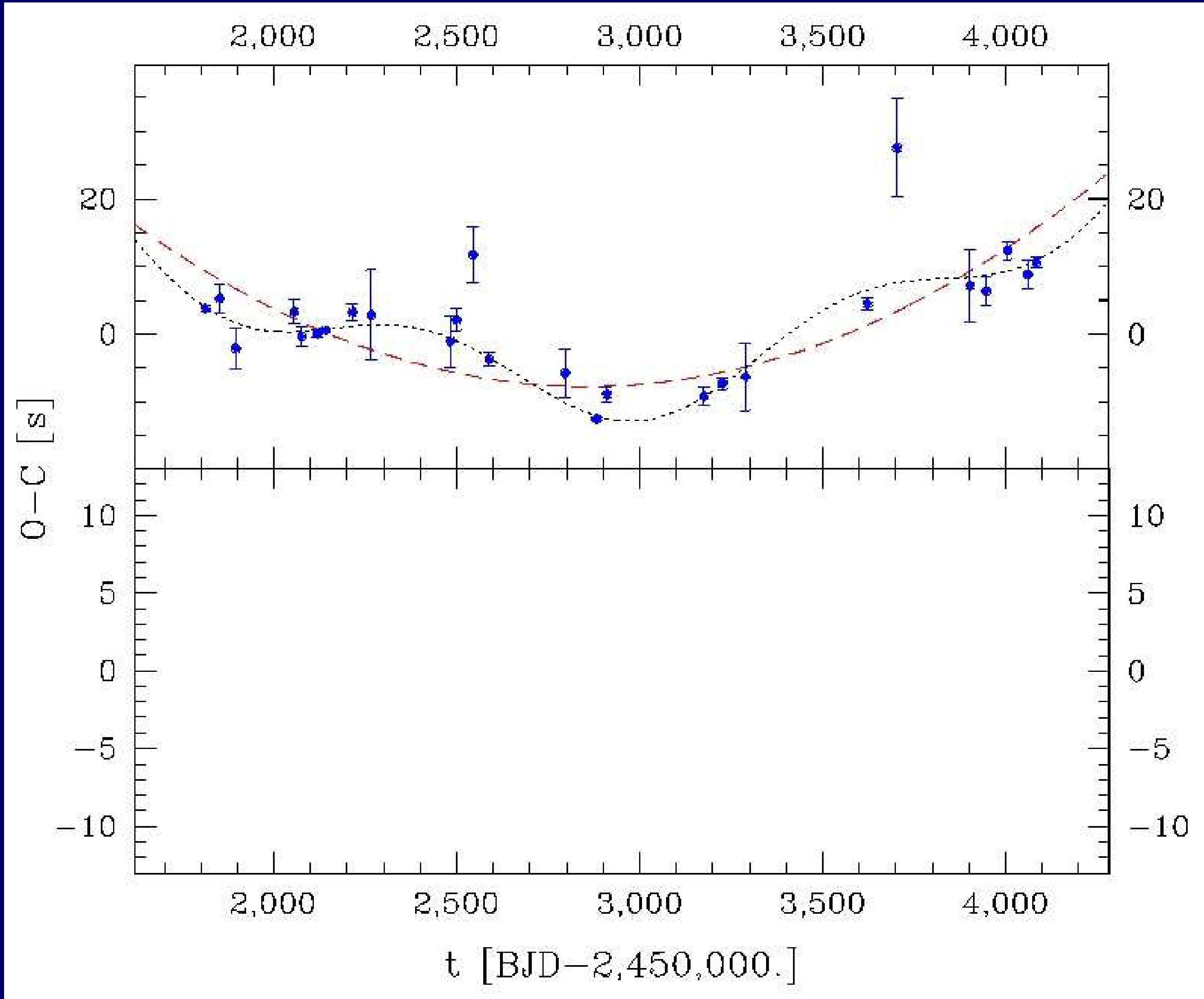

When a sinusoidal component is added to the 2° order polynomial the fit is significantly improved !

(red. χ^2 from 14.1 to 2.7)

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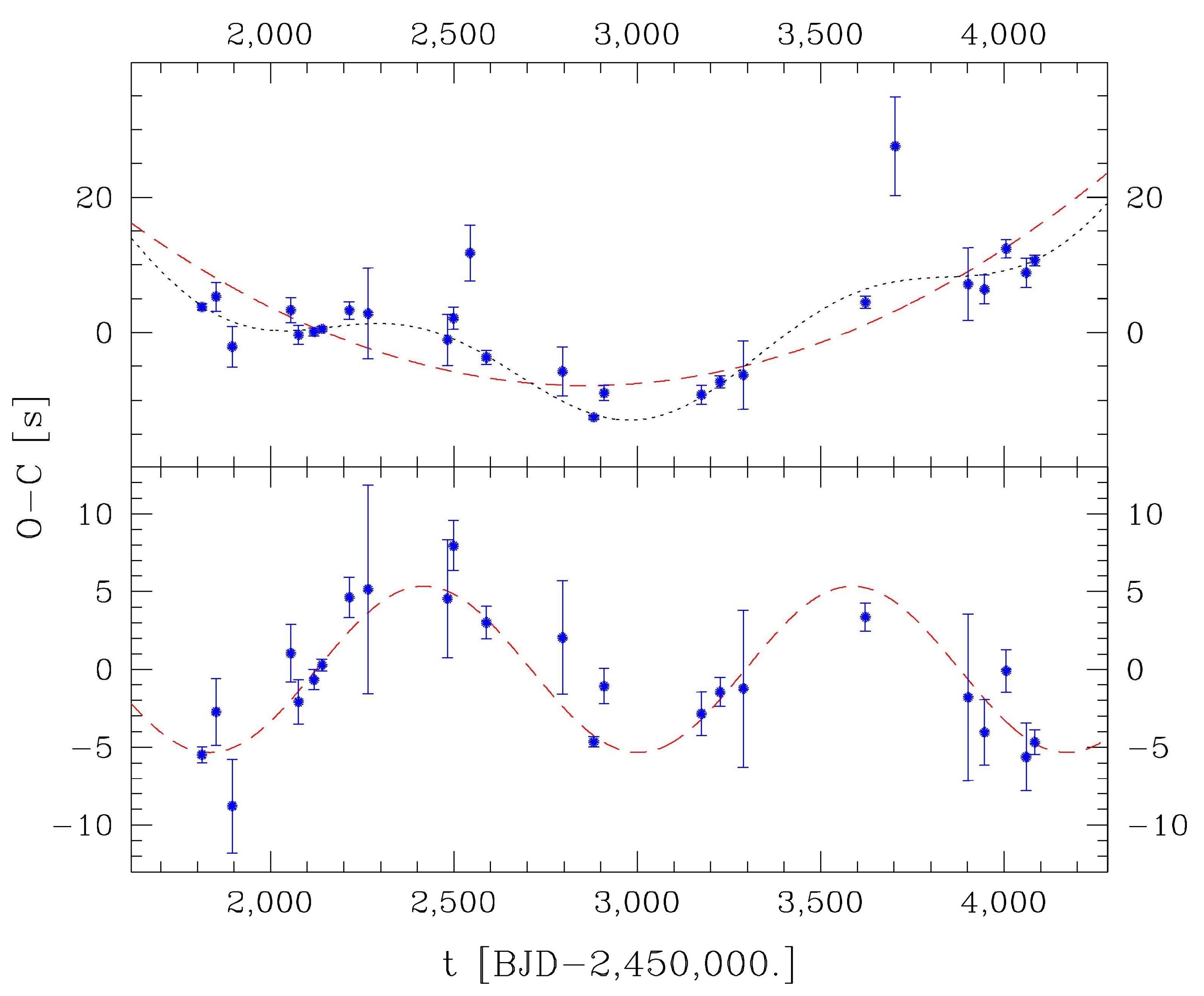
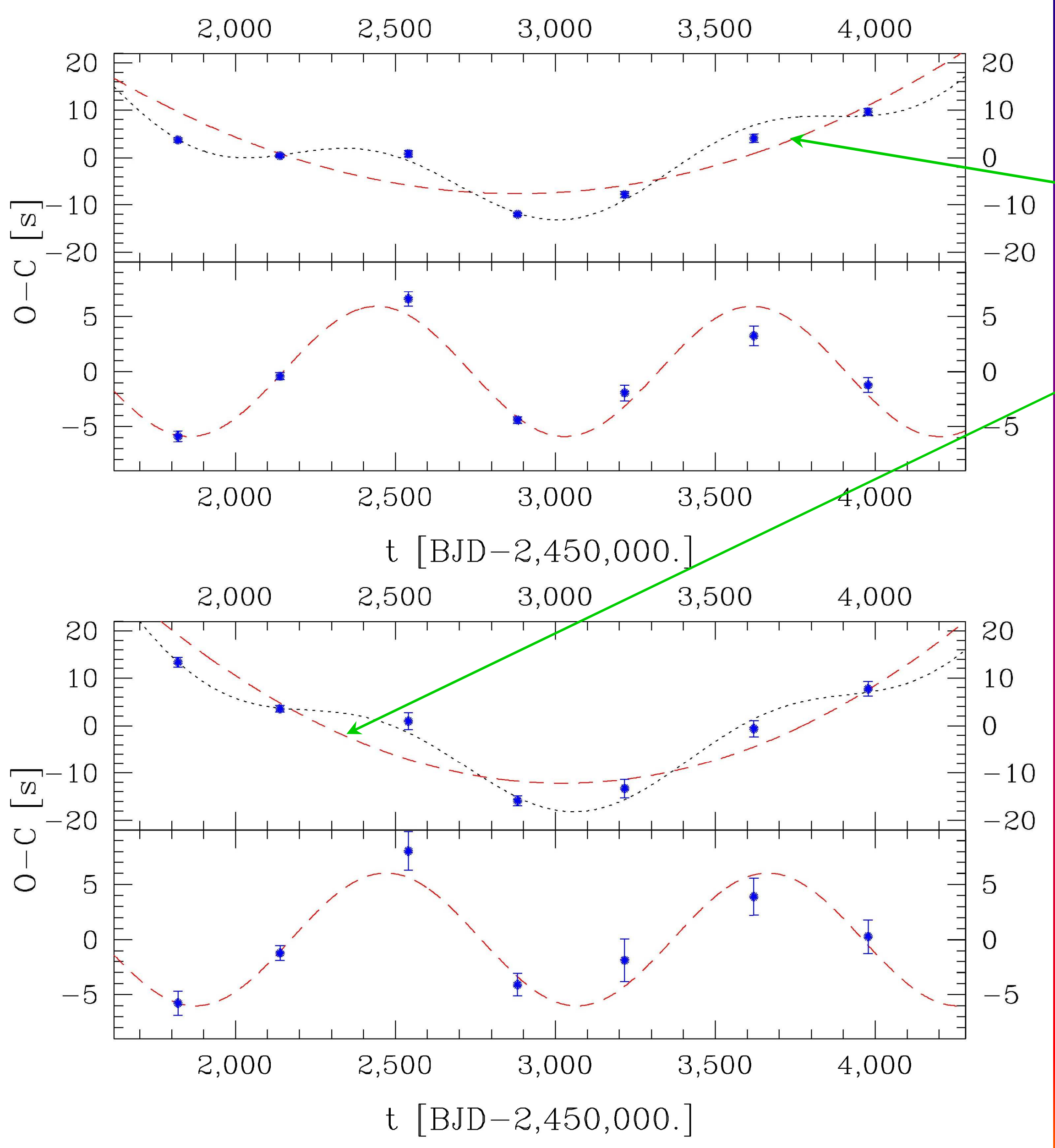


When a sinusoidal component is added to the 2° order polynomial the fit is significantly improved !

(red. χ^2 from 14.1 to 2.7)

The O-C diagram of f_1 (A_1=1%) vs f_2 (A_2=0.4%) with 1 point per season



$dP_1/dt = (1.46 \pm 0.07) \times 10^{-12}$

$\Rightarrow \tau_{ev} = P/(dP/dt) = 7.6 \times 10^6$ yr

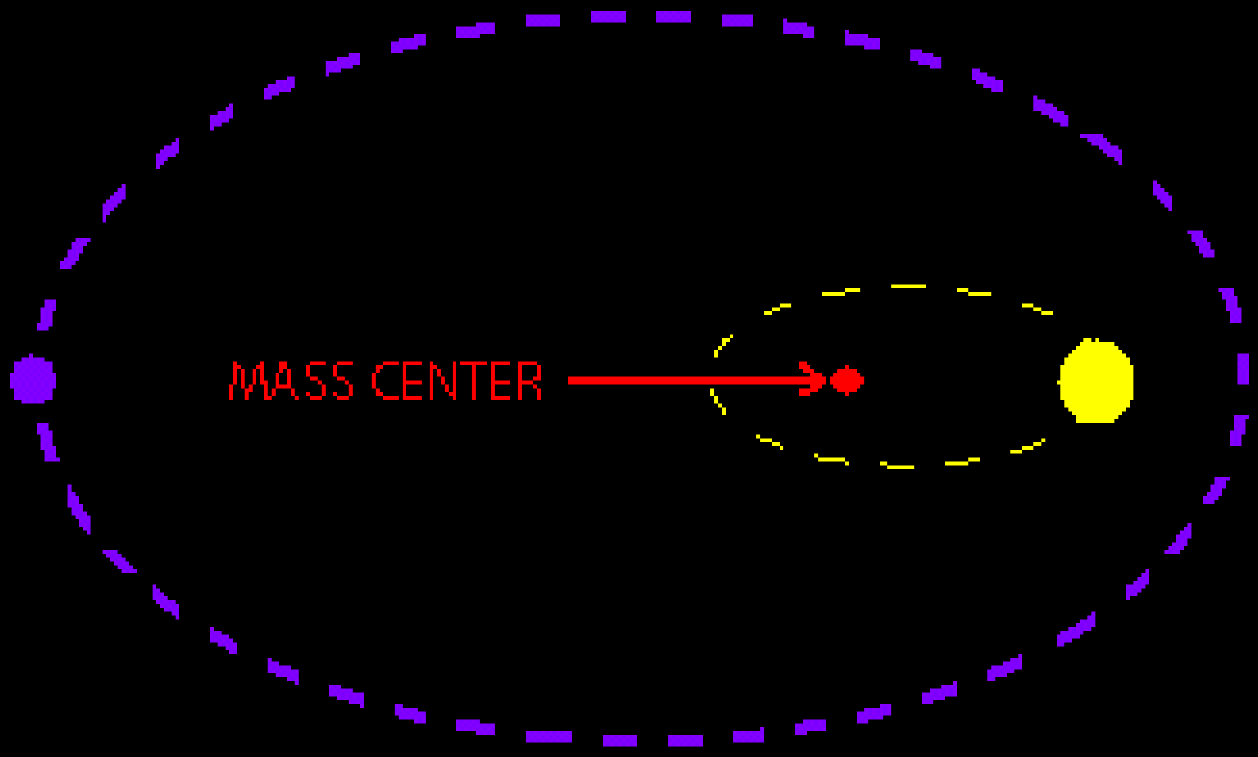
$dP_2/dt = (1.97 \pm 0.18) \times 10^{-12}$

$\Rightarrow \tau_{ev} = P/(dP/dt) = 5.5 \times 10^6$ yr

The absolute values of dP_1/dt and dP_2/dt match relatively well theoretical expectations for EHB evolved models (Charpinet et al. 2002). But their positive sign is more difficult to explain and suggests that the star is expanding.

Simplest (and basically unique) interpretation for the sinusoidal component of the O-C diagrams:

The timing of the pulsation is cyclically advanced or delayed
by about 5 sec due to the presence of a secondary low-mass body.
Depending on its position around the barycentre of the system, the star
is closer to or more distant from us by 5.3 light seconds (or ~1.600.000 km).



Orbital parameters

P_{ORB}	1,170 ± 44 d (3.20 ± 0.12 yr)
T_0 (epoch of max time delay)	2,452,418 ± 96 BJD
e (assumed)	0.0
$a_s \sin i$ (star projected orbital radius)	1,600,000 ± 190,000 km
$v_s \sin i$ (star projected orbital velocity)	99 ± 12 m/s
$f(M_1,M_2)$*	$(1.19 \pm 0.43) \times 10^{-7}\ M_{SUN}$
a (distance from the star) **	1.7 AU
maximum elongation **	0.0012 arcsec
v_p (planet orbital velocity) **	15.8 km/s
$M_2 \sin i$ **	3.2 M_{JUP}

*mass function = $4\pi^2(a_s \sin i)^3/G\,P^2_{ORB} = (M_2 \sin i)^3/(M_1+M_2)^2$

** assuming $M_1 = 0.5\ M_{SUN}$ and $M_2 << M_1$

The low-mass companion is likely a giant planet !

depending on the inclination we obtain:

$0° \leq i \leq 2.5°$ ⟶ star

$2.5° \leq i \leq 14°$ ⟶ BD

$14° \leq i \leq 90°$ ⟶ giant planet

⇒

assuming a random distribution of orbital plane inclinations there is a 97% probability that
V 391 Peg b is the 1st planet around a post-RGB star !
(And one of the oldest planets known)

Temperature of V 391 Peg b

From the thermal balance equation:

Stefan-Boltzmann constant

Bond albedo

$$4\sigma\, T_{eff}^{\,4} = (1\text{–}A)\, E_S + 4\, \varepsilon_P$$

$E_S = L/(4\pi\, a^2) = 1.6 \times 10^7$ erg/cm^2/s is the incoming flux from the star ($\cong$ 12 × solar constant of our Earth)

Assuming A=0.343 (like Jupiter) and $\varepsilon_P \ll E_S$

we obtain $T_{eff} \cong 470$ K ($\Rightarrow$ bb max. at ~6.2 μm)

Most likely scenario

V 391 Peg b never entered the RG envelope (maximum radius of the sdB progenitor at the RGB tip of about 0.7 AU). Due to the strong stellar mass loss, the orbit of the planet was tighter in the past ($r \approx$ 1AU during the MS).

This value is obtained when tidal interaction can be neglected for a sufficiently large orbital distance r respect to the stellar radius $R_\star$. In this case the variation of the orbit [Zahn 1977]:

mass loss

tidal interaction $\propto (R_\star/r)^8$

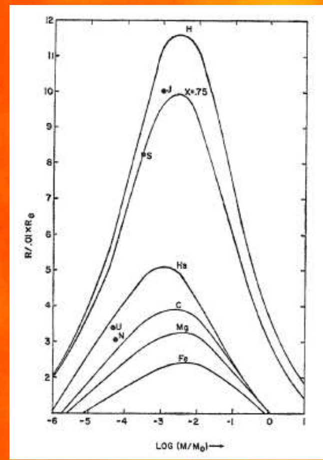
$$\mathbf{1/r(dr/dt) = -1/M_\star\,(dM_\star/dt) + [1/r(dr/dt)]_{tidal}}$$

is easily integrated and the orbital radius is given by: $\mathbf{r(t) = r_0[M_\star/M_\star(t)]}$

Other possible scenarios

1) Common-envelope

The orbital distance is reduced because of significant tidal forces, causing the planet to transfer angular momentum to the star. Moreover, at $R_\star/r \approx 0.7$, the star fills its Roche lobe [Eggleton 1983] and the mass transfer to the planet starts, causing the planet to rapidly spiral into the giant atmosphere. Here accretion is disrupted and the spiral-in due to accretion stops. The planet may survive if the spiral-in due to friction is sufficiently low.

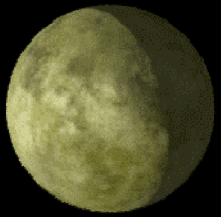


2) WD merging scenario

The sdB star was created from the merging of two low-mass He WDs (20% of sdB stars could be formed in this way, Han et al. 2003) and V 391 Peg b is a “2° generation” He planet (with a radius half of Jupiter, Zapolsky & Salpeter 1969), similar to the “2° generation” pulsar’s planets and to the planets supposed to orbit massive WDs, born from the merging of two CO WDs [Livio et al. 2005].

V 391 Pegasi b - SUMMARY

The detection of V 391 Peg b proves, for the 1st time, that:



1. planets with orbital distances < 2 AU can survive the RGB expansion of their parent star

   Note that only "HB planets" allow to isolate the effects of the RG expansion on a planetary system. WD planets must be strongly modified also by the AGB expansion, thermal pulses and PN ejection [Villaver & Livio 2007]

2. the timing method is an efficient tool to detect planets around evolved compact pulsators (sdBs and WDs)

   Note that: ★ it is not easy to use RVs or transits for high gravity objects like EHB stars or white dwarfs (IR imaging is a possibility for close WDs).

   ★ COROT and Kepler will not search for post-MS planetary systems !

Next steps: new data on V391 Peg

Time series photometry

Goals: rotational splitting
ellipticity
secondary planets

Runs (2007):

- ✓ May
- ✓ June
- ✓ July
- ✓ August
- ✓ September (~8 1-2m telescopes)
- ✓ October (WHT/ULTRACAM)
- ✓ December (NOT)

Total: 100 nights !

Spectroscopy

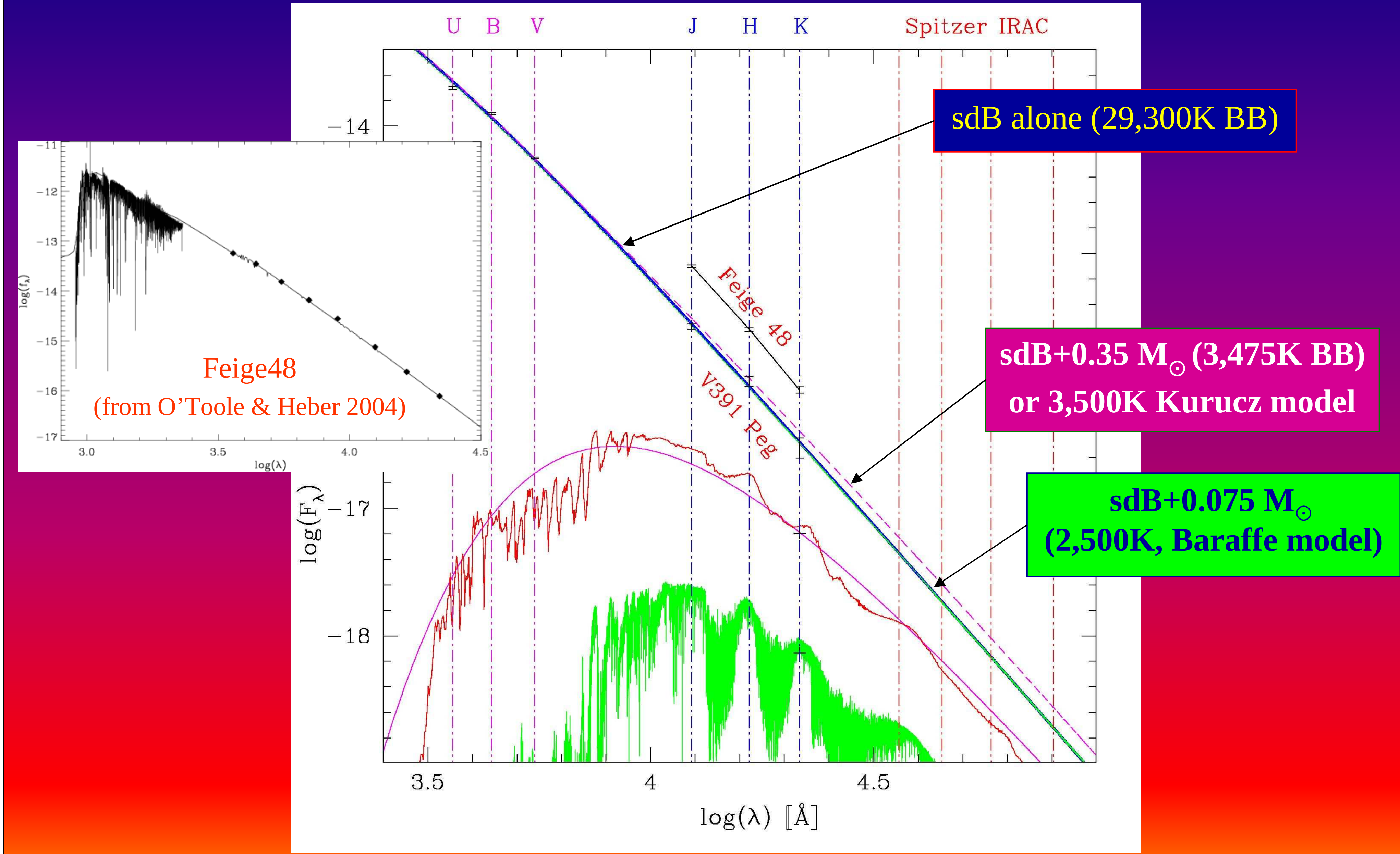
Goals: star rotational velocity
RV (star orbital motion)
time-resolved spectra
(mode identification)

Runs (2007):

- ✓ May (HET) [Edelmann, Heber et al.]
- ✓ September (HET) [Schuh et al.]

IR photometry ?

Spectral energy distribution



Next steps: searching for new systems similar to V391 Peg

Ground based time series photometry:

EXOTIME (EXOplanet search with the TIming MEthod)

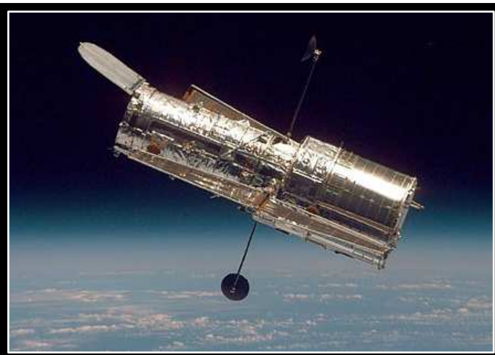
Collaborators: S. Schuh (Goëttingen), T. Oswalt (Melbourne), R. Janulis (Vilnius), and many others …

- ✓ LoI INAF small telescopes (Na, Bo, Ct)
- ✓ Target selection
- Observing proposals

Kepler - KASC

- Search for sdB/WD pulsators in the Kepler FoV

What can be done with HST ?



HST-NICMOS/WFC3IR is the best near-IR photometer
(still better than 8m class telescopes, at least in JH bands)

- ► high-precision near-IR photometry (with NICMOS or WFC3 IR)
  - ★ detect planets/BDs (for WD/sdB systems much closer than V391Peg)
  - ★ constrain inclination and companion mass (exclude stellar comp.)
  - ★ help to discriminate between diff. formation scenarios (debris disk detection)
    - → opt. spectr. (gas) [e.g. double-peaked CaII emissions, Gänsicke et al. 2006, 2007]
    - → far IR (dust) [see e.g. the "Spitzer WD survey", Mullally et al. 2007]
- ► UV time-series photometry (STIS FUV, ACS SBC or WFC3 UVIS)
  - ★ pulsation amplitudes → mode identification → stellar parameters

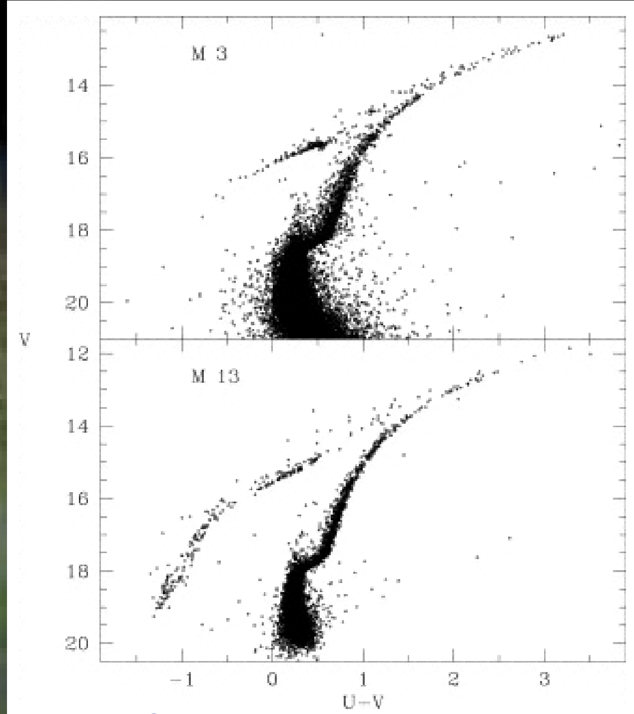
Planets around sdB and WD pulsators

(pulsating) sdBs with planets: 1/1

(pulsating) WDs with planets: 1/16

[Mullally et al. 2008, ApJ in press]

WHY ?



[from Ferraro et al. 1997]

[but see also Caloi & D'Antona 2005]

Could planets be responsible for the extreme mass loss of the sdB progenitors ?

or, in other words:

"Can planets influence the HB morphology ?"

[Noam Soker 1998, AJ 116, 1308]

THE END