



THE UNIVERSITY OF
WARWICK

Boris Gänsicke

High-speed Observations
of
White Dwarfs

Why high speed?

$$R_{wd} \approx R_{\oplus} \approx 0.01R$$
$$M_{wd} \approx 0.6 M$$



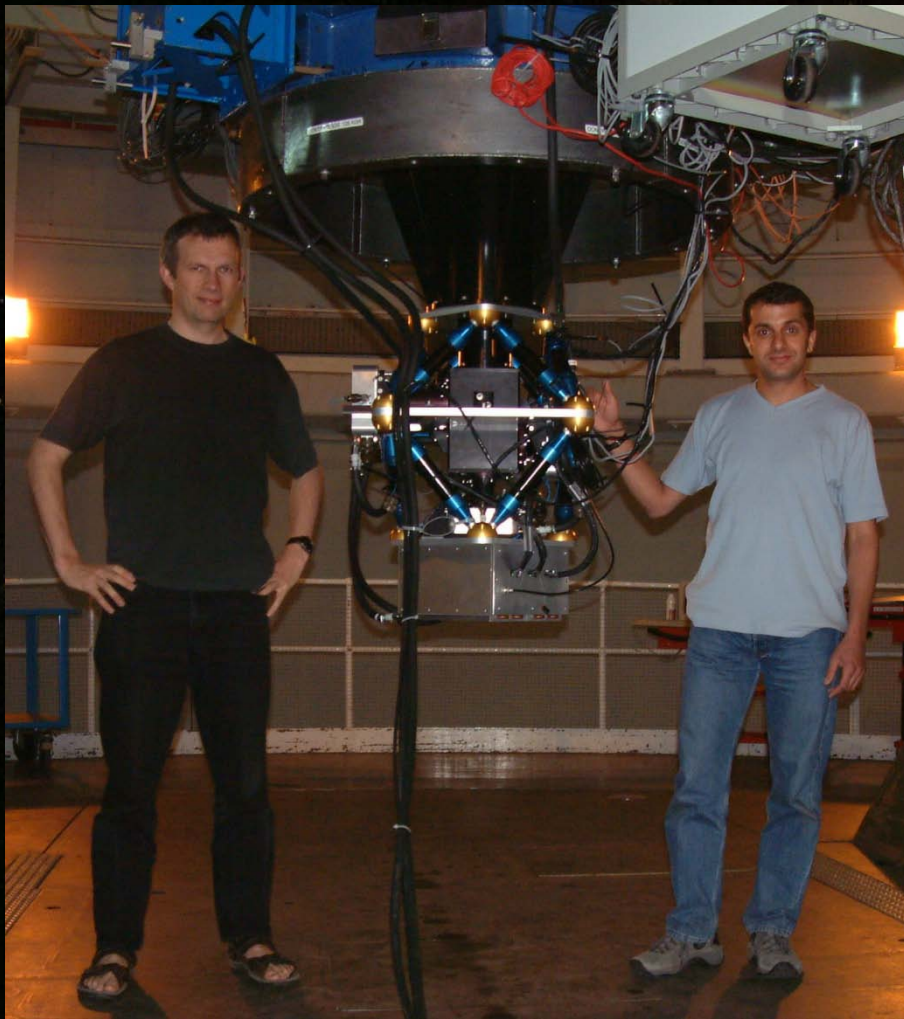
Why high speed?

Dynamical time scale:
(free fall)

$$\tau_{\text{dyn}} = \frac{R}{\dot{R}} = \frac{R}{v_{\text{ff}}} = \frac{R}{\sqrt{2GM/R}} = \sqrt{\frac{R^3}{2GM}}$$
$$\tau_{\text{dyn}} \approx \frac{1}{\sqrt{G\bar{\rho}}} \approx 1\text{s}$$

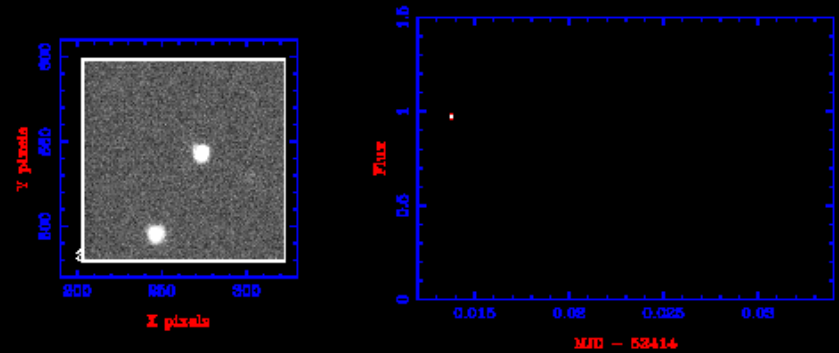
$$R_{\text{wd}} \approx R_{\oplus} \approx 0.01R$$
$$M_{\text{wd}} \approx 0.6 M$$

The main player: ULTRACAM

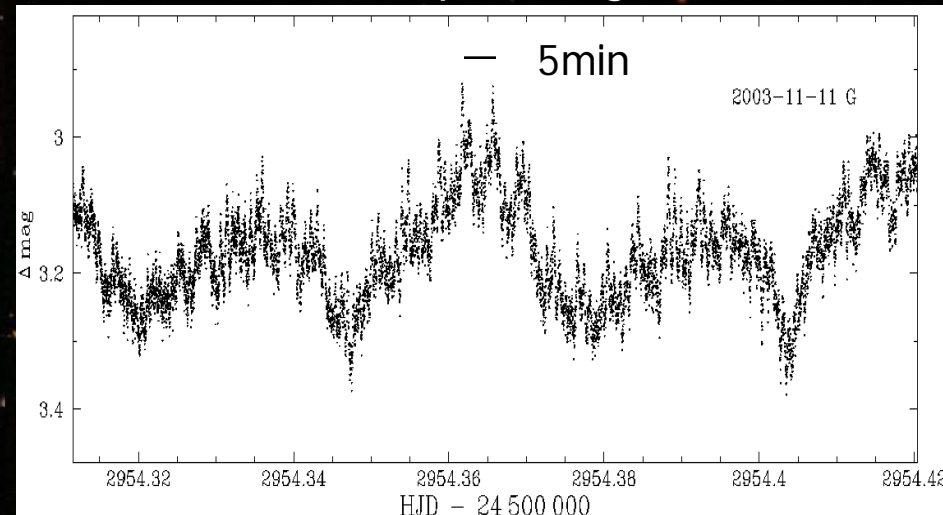


Dhillon et al. 2007, MNRAS 378, 825

NN Ser: an eclipsing WD+MS binary

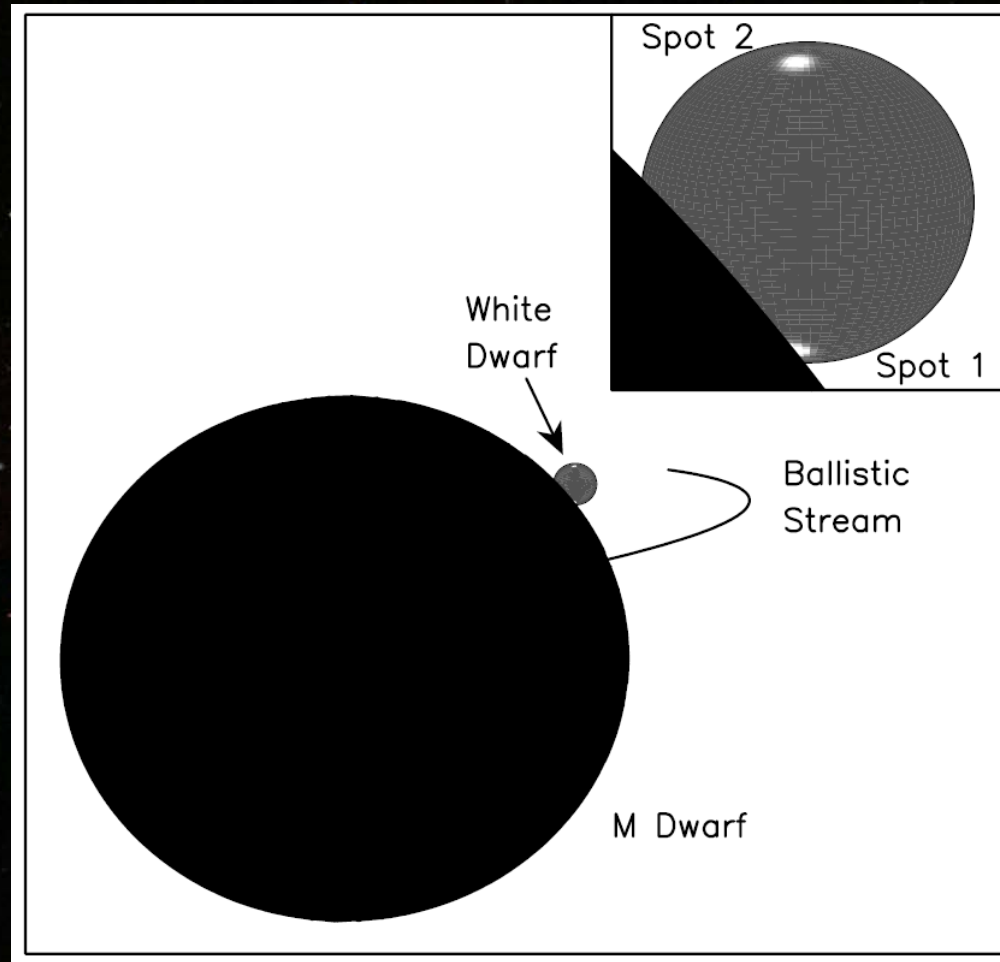
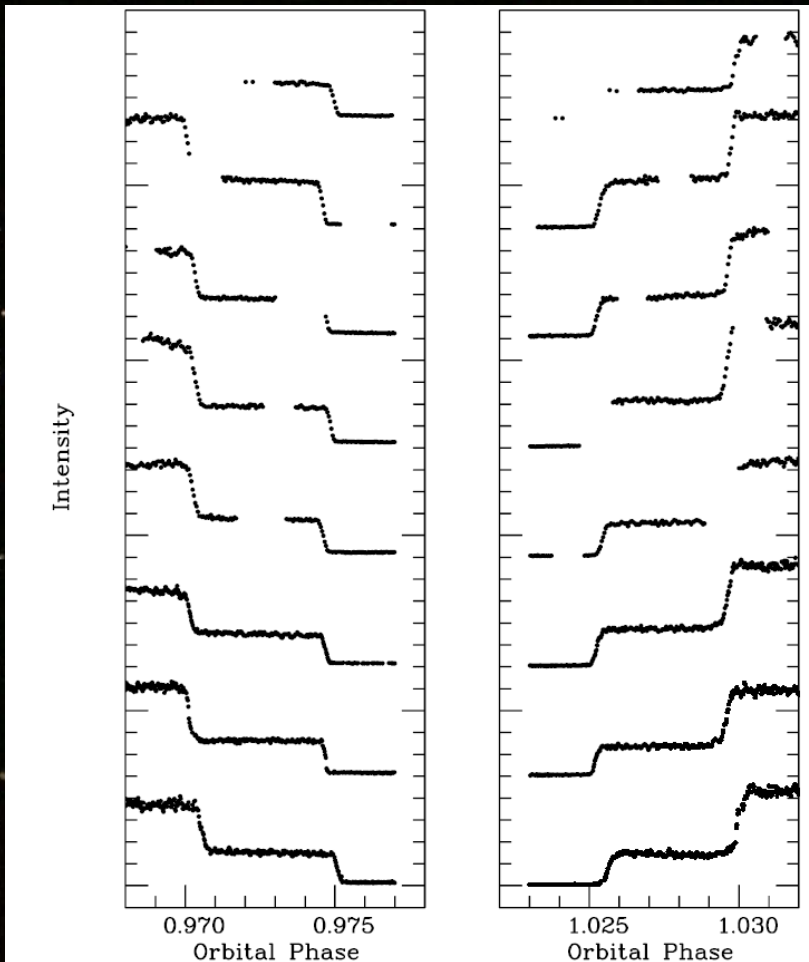


HS2331+3905: a pulsating white dwarf



... and some other high-speed instruments ...

- OPTIMA (Kanbach et al. 2003, SPIE Conf. Ser., 4841, 82)
- Agile (Mukadam et al. 2011, PASP 123, 1423)
- UCT CCD & SALTICAM (e.g. O'Donoghue et al. 2006, MNRAS 372, 151)

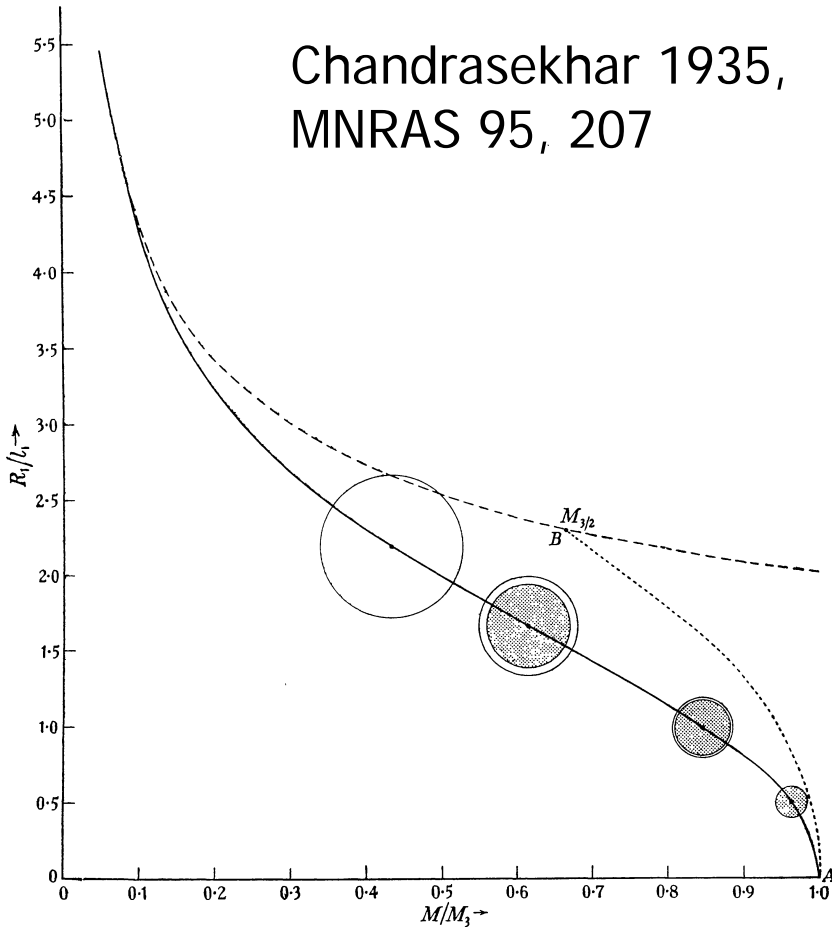


Road map for today

1. Eclipsing detached white dwarf binaries & mass radius relations
2. Eclipsing interacting white dwarf binaries & SN Ia progenitors
3. Eclipsing double white dwarfs & GWR orbital decay
4. Pulsating white dwarfs, single & in binaries

White dwarfs: electron degenerate stars, but...

Chandrasekhar 1935,
MNRAS 95, 207



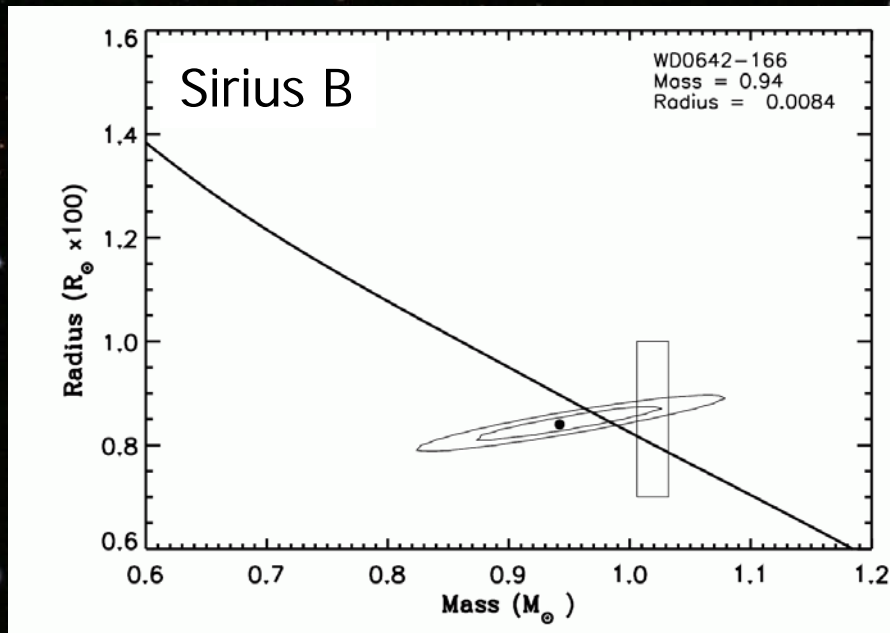
Corrections to the equation of state,
core-composition, finite-temperature,
He & H envelopes, magnetic fields...
See e.g.:

- Hamada & Salpeter 1961, ApJ 134, 971
- Vennes et al. 1995, A&A, 296, 117
- Panei et al. 2000, A&A 353, 970
- Suh & Mathews 2000, ApJ 530, 949
- Althaus et al. 2005, A&A 441, 689

White dwarfs in astrometric binaries

Astrometric orbit, Kepler's 3rd law $\Rightarrow M_{\text{wd}}$

Spectroscopic surface gravity, GR redshift, "flux scaling factor" $\Rightarrow R_{\text{wd}}$



$$M_{\text{wd}} = 0.94 \pm 0.05 M_{\odot}$$

$$R_{\text{wd}} = 0.0084 \pm 0.0025 R_{\odot}$$

$$T_{\text{eff}} = 24790 \pm 100 \text{ K}$$

5% precision in M

25% precision in R

see e.g. Barstow et al. 2005, MNRAS 362, 1143; Holberg et al. 2012, AJ 143, 68

Stellar parameters from eclipsing binaries

Accurate masses and radii of normal stars

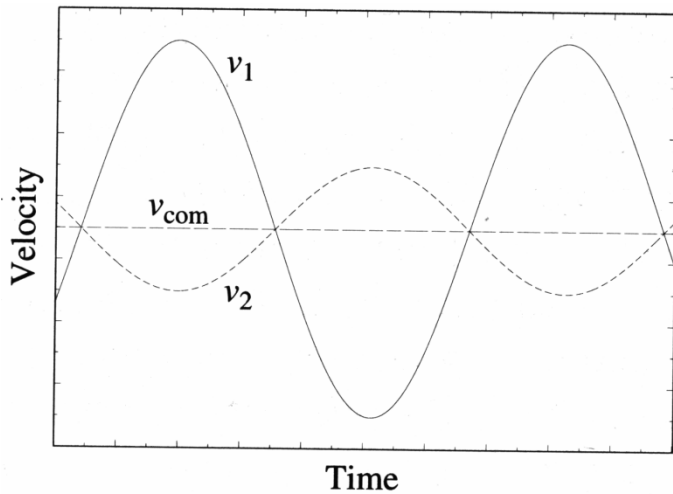
J. Andersen

Copenhagen University Observatory, Brorfeldevej 23, DK-4340 Tølløse, Denmark

Summary. Binary stars are the main source of fundamental data on stellar masses and radii (M , R). Considerable progress has been made in recent years in the quality and quantity of such data, and stellar masses and radii of high accuracy have led to a number of qualitatively new and interesting results on the properties and evolution of normal stars. This paper reviews the current status of fundamental M and R determinations which (i) have errors $\leq 2\%$, the limit for non-trivial results in many applications, and (ii) can be presumed valid for single stars. These two conditions limit the discussion to data from *detached, double-lined eclipsing binary systems*.

Andersen 1991, A&ARv 3, 91

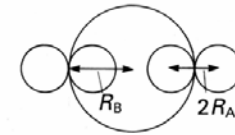
Stellar parameters from eclipsing binaries: A primer



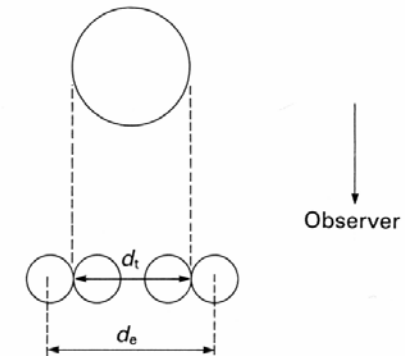
$$\frac{M_1}{M_2} = \frac{v_2}{v_1}$$

$$M_1 + M_2 = \frac{P}{2\pi G} \frac{(v_1 + v_2)^3}{\sin^3 i}$$

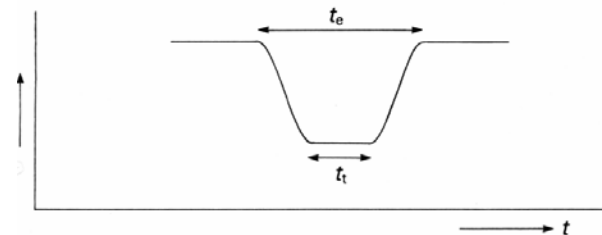
(a)



(b)



(c)

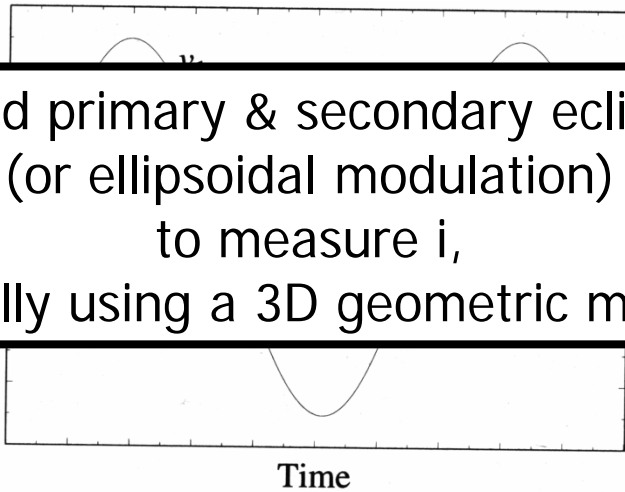


$$R_A = \pi a \frac{t_e - t_t}{2P}$$

$$R_B = \pi a \frac{t_e + t_t}{2P}$$

Stellar parameters from eclipsing binaries: A primer

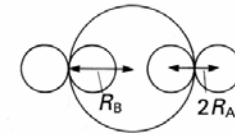
Need primary & secondary eclipse
(or ellipsoidal modulation)
to measure i ,
usually using a 3D geometric model



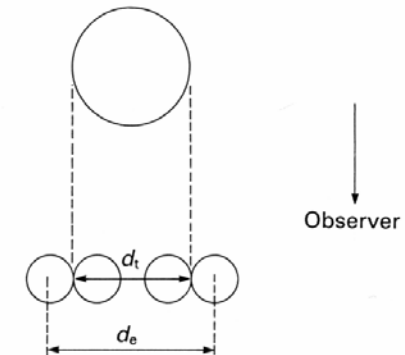
$$\frac{M_1}{M_2} = \frac{v_2}{v_1}$$

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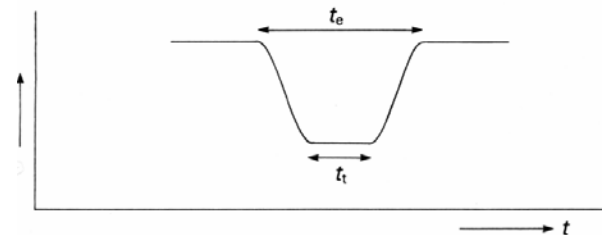
(a)



(b)



(c)



$$R_A = \pi a \frac{t_e - t_t}{2P}$$

$$R_B = \pi a \frac{t_e + t_t}{2P}$$

V471 Tau – the first eclipsing WD binary

A NEW ECLIPSING BINARY CONTAINING A VERY HOT WHITE DWARF

BURT NELSON

Mount Laguna Observatory
Astronomy Department
San Diego State College

AND

ARTHUR YOUNG*

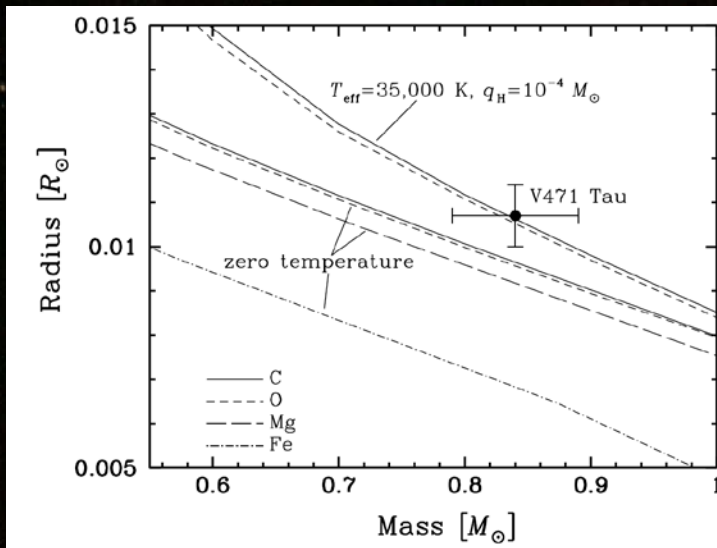
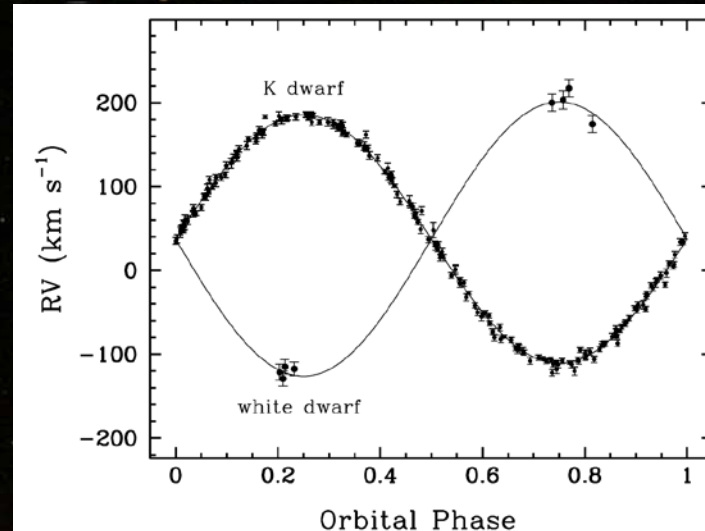
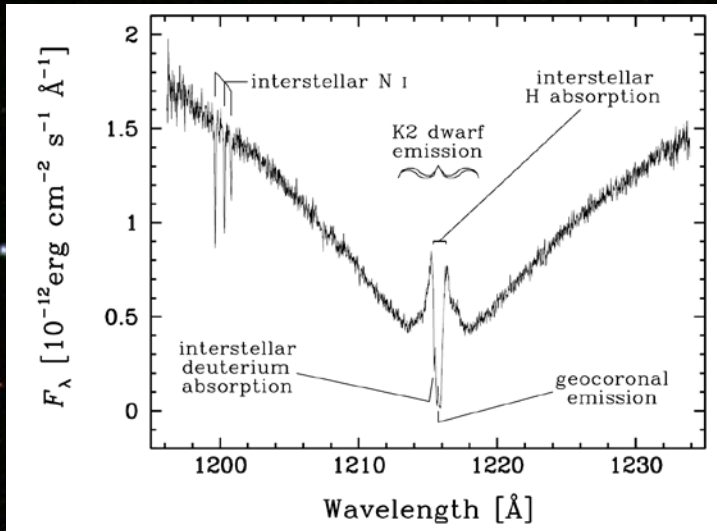
Kitt Peak National Observatory†
Tucson, Arizona

Received March 6, 1970

A new eclipsing binary has been discovered in which one of the stars is shown to be a hot white dwarf. The eclipse is total, and considerable fundamental information about white dwarfs appears to be obtainable.

Nelson & Young 1970, PASP 82, 699

... 30 years later ...



$$M_{\text{wd}} = 0.84 \pm 0.05 M_{\odot}$$

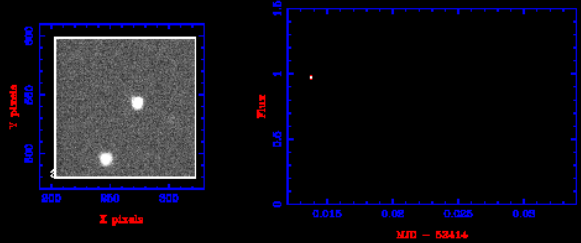
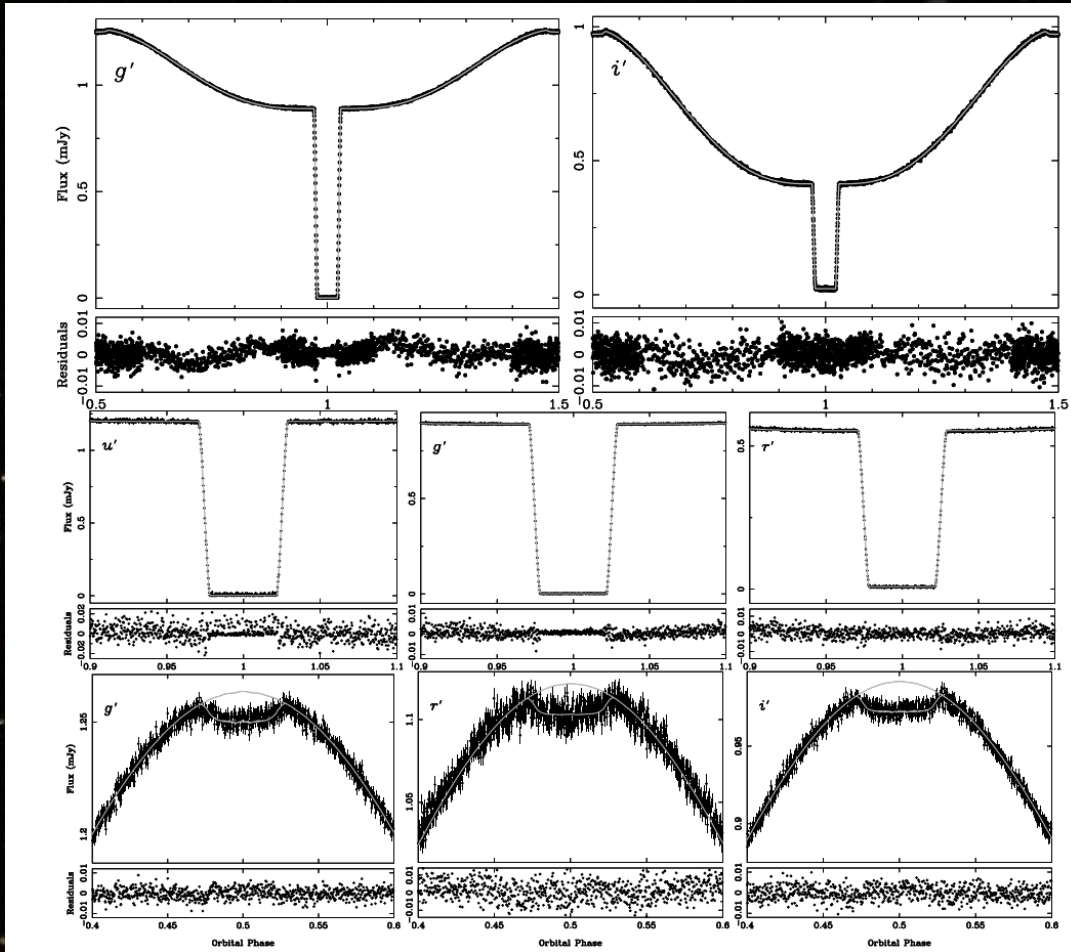
$$R_{\text{wd}} = 0.0109 \pm 0.0007 R_{\odot}$$

$$T_{\text{eff}} = 35125 \pm 1275 \text{ K}$$

Werner & Rauch 1997, A&A 324, L25

O'Brien et al. 2001, ApJ 563, 971

NN Ser: a hot DAO WD + very low mass dM



$$M_{\text{wd}} = 0.535 \pm 0.012 M$$

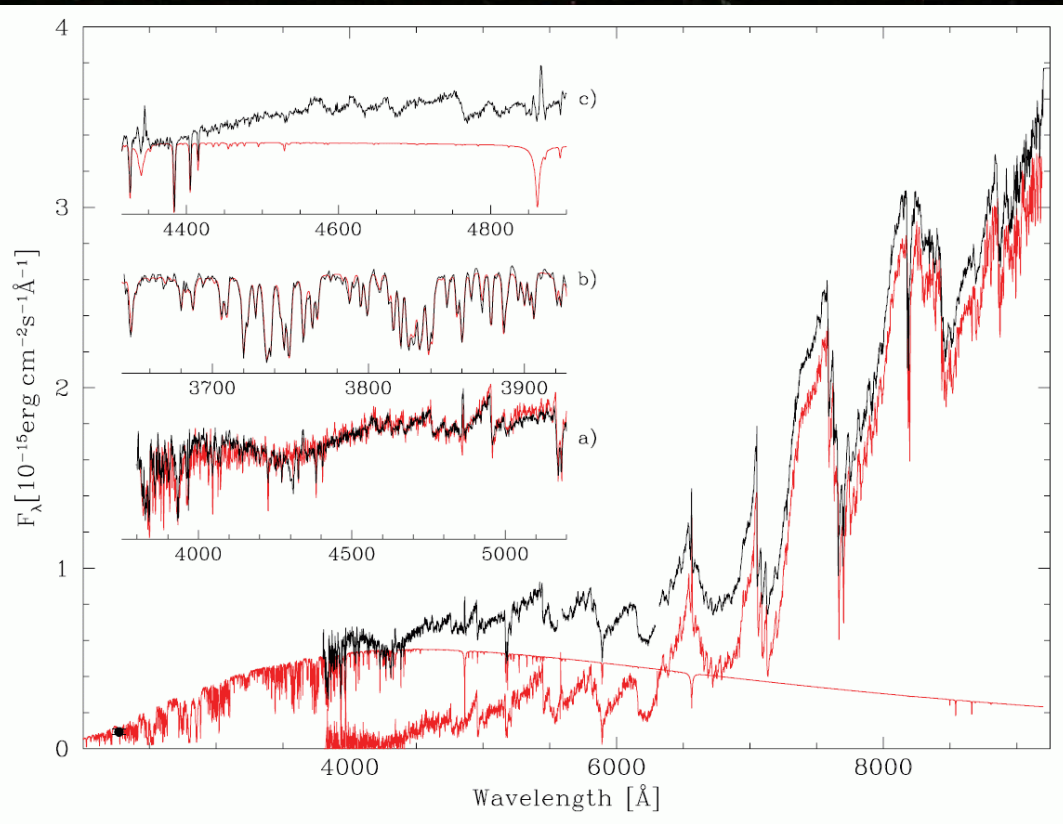
$$R_{\text{wd}} = 0.0211 \pm 0.0002 R$$

$$T_{\text{eff}} = 57000 \pm 3000 \text{ K}$$

1-2% precision in M, R

Parsons et al. 2010, MNRAS 402, 2591

SDSSJ1210+3347: a cool DZ + dM



$$M_{\text{wd}} = 0.415 \pm 0.010 M$$

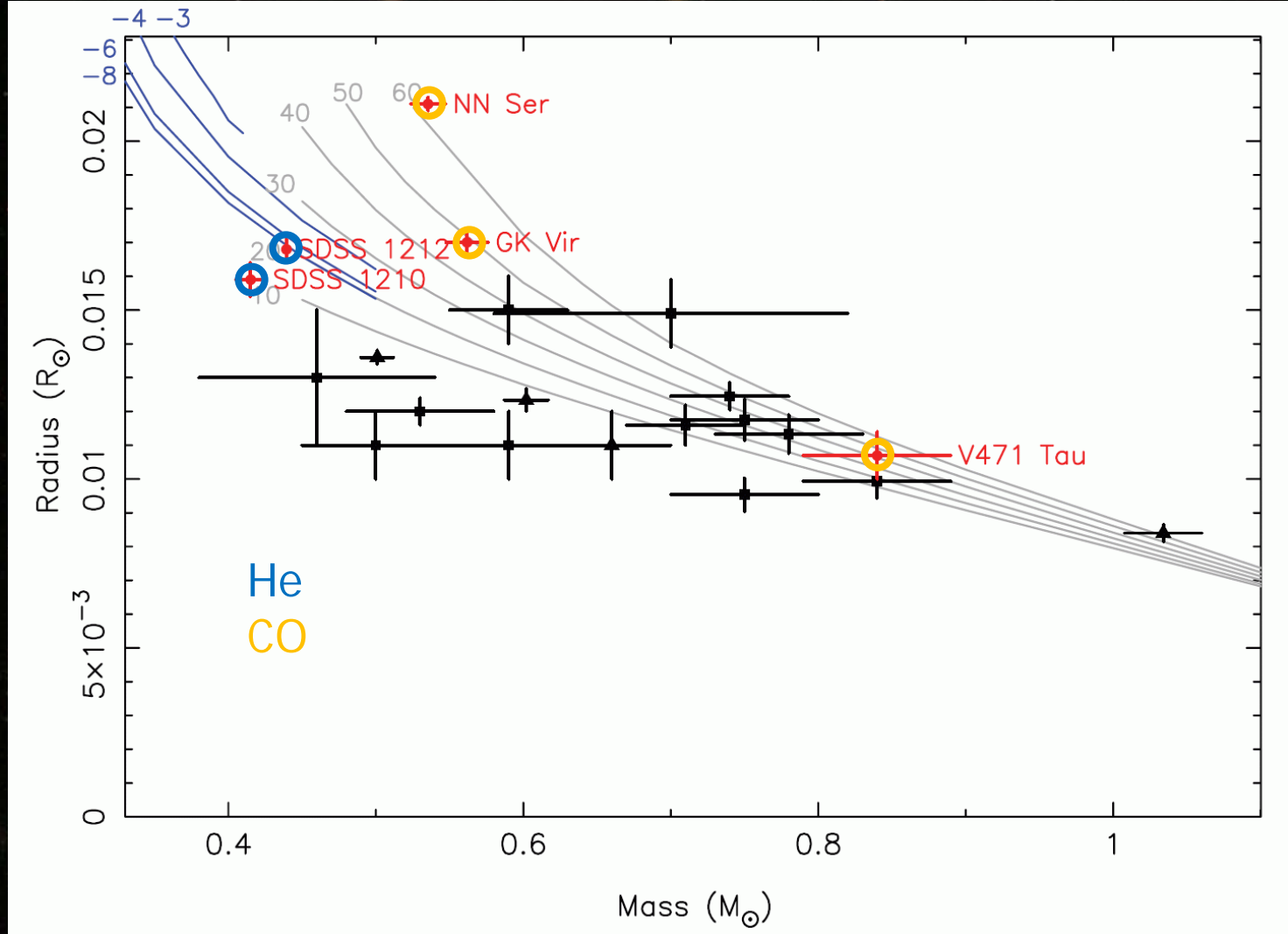
$$R_{\text{wd}} = 0.0157 - 0.0161 R$$

$$T_{\text{eff}} = 6000 \pm 200 \text{ K}$$

... a definite He-core WD ...

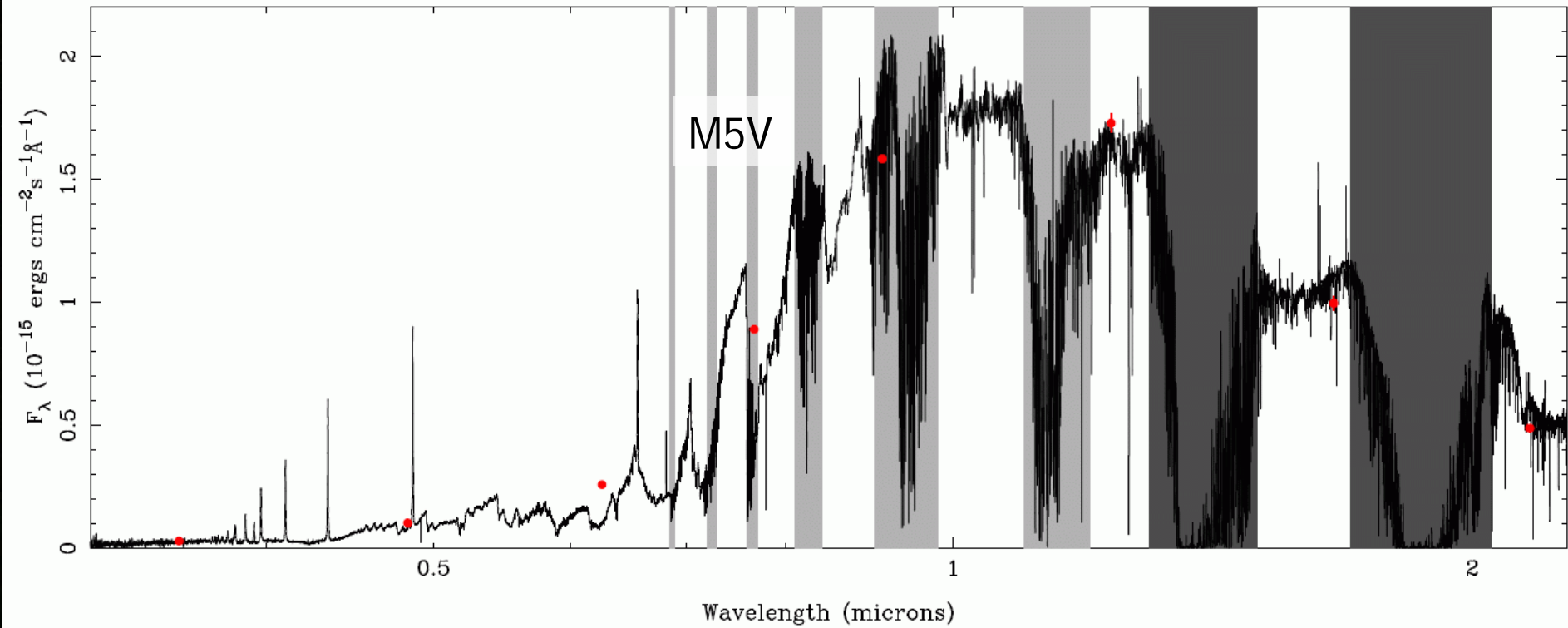
Pyrzas et al. 2012, MNRAS 419, 817

A first look at the M-R plane: no surprises so far



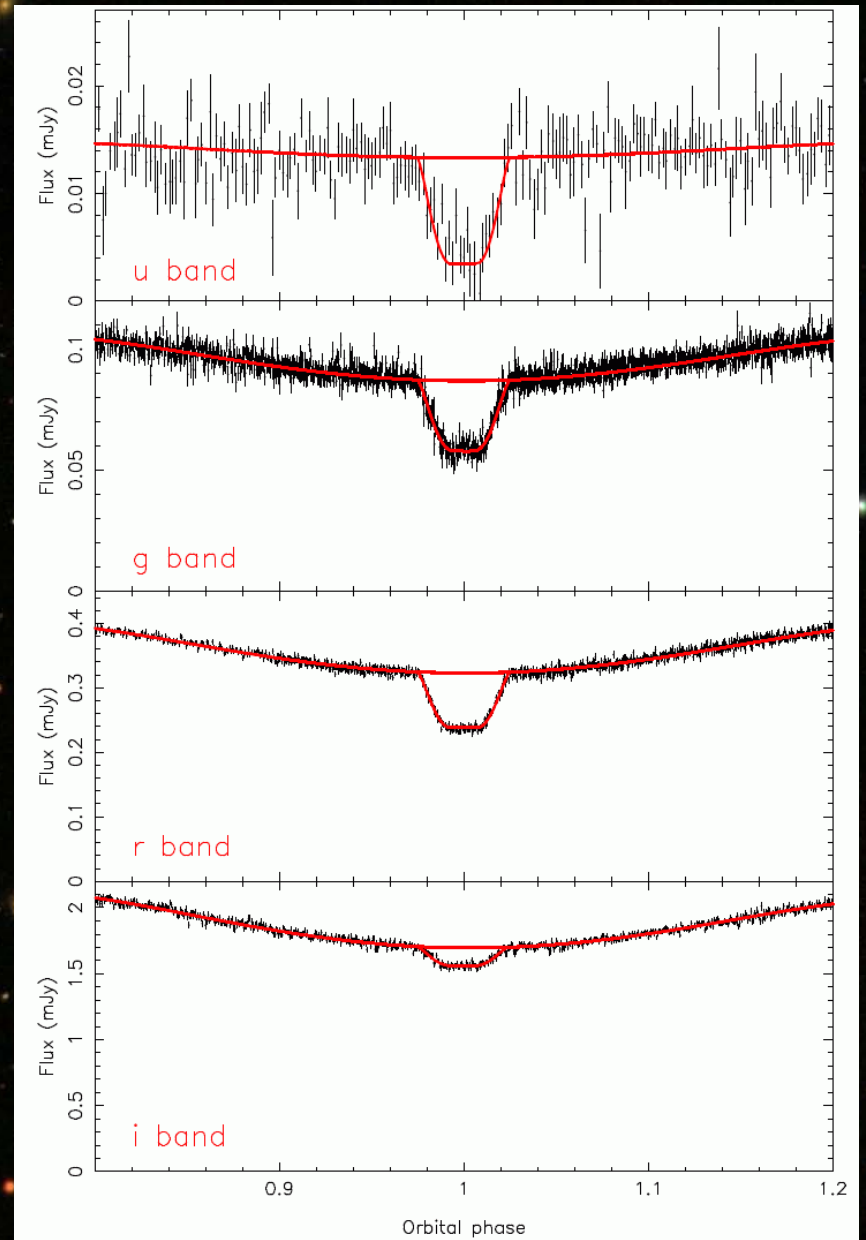
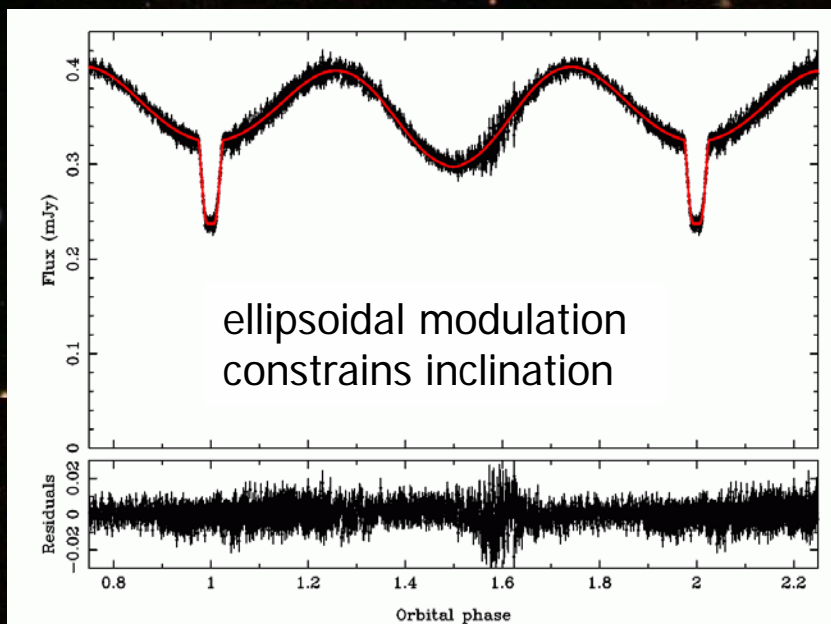
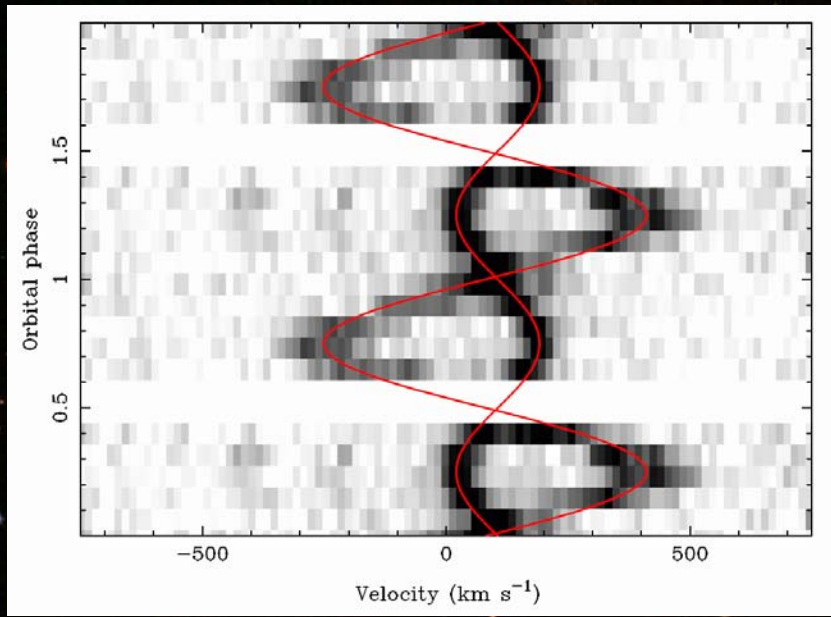
Parsons et al. 2012, MNRAS 420, 3281

SDSSJ0138–0016: an ultracool WD + dM

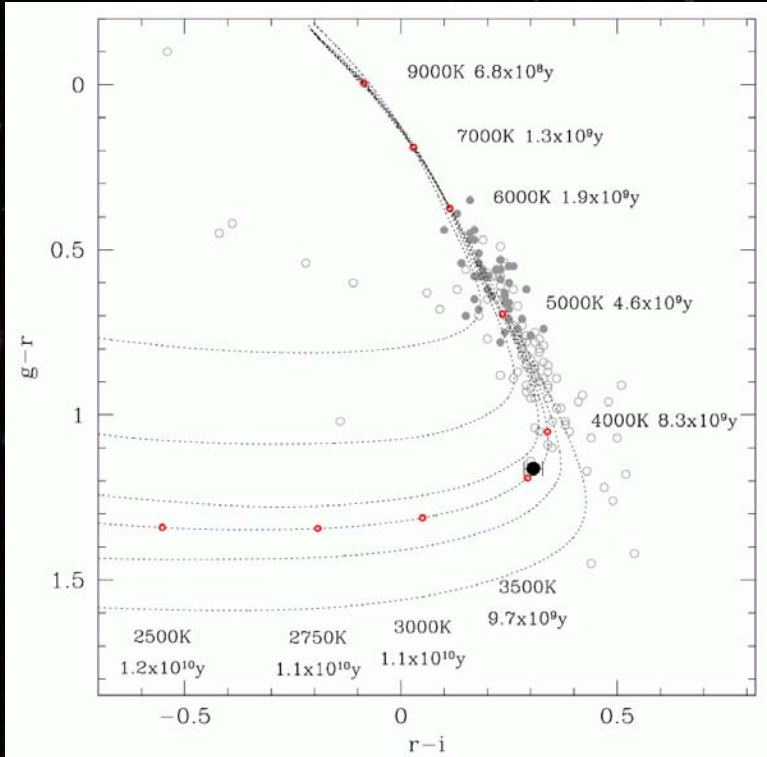


Parsons et al. 2012, MNRAS 426, 1950

X-Shooter spectroscopy & ULTRACAM photometry



The coolest white dwarf with model-independent M & R



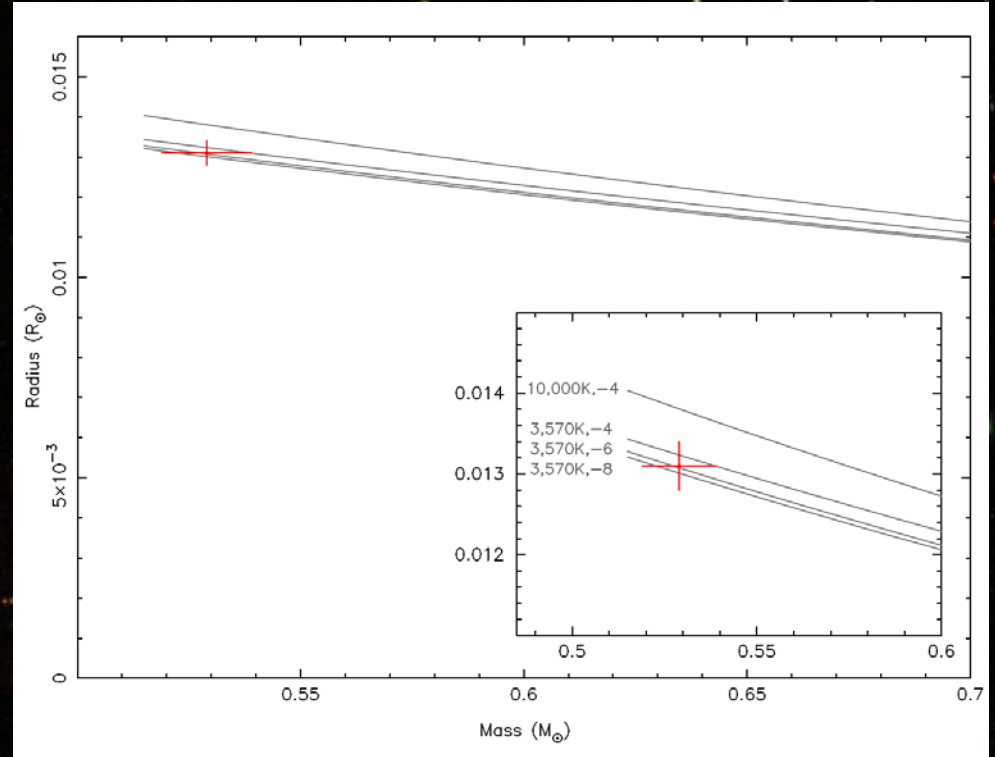
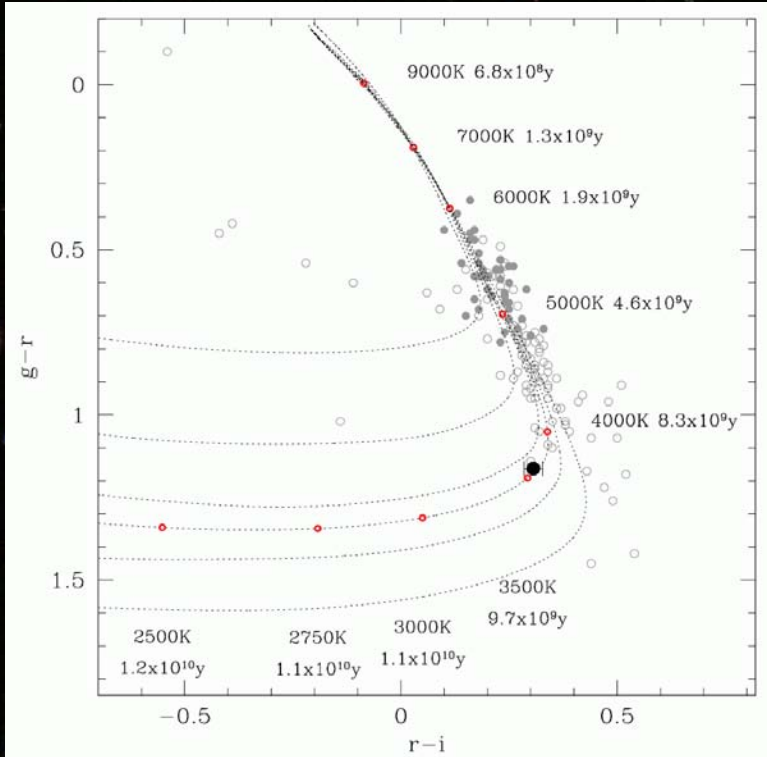
$$M_{\text{wd}} = 0.529 \pm 0.010 M_{\odot}$$

$$R_{\text{wd}} = 0.0131 \pm 0.0003 R_{\odot}$$

$$T_{\text{eff}} = 3570 \pm 100 \text{ K}$$

\Rightarrow cooling age: $9.5 \pm 0.3 \text{ Gyr} \dots$

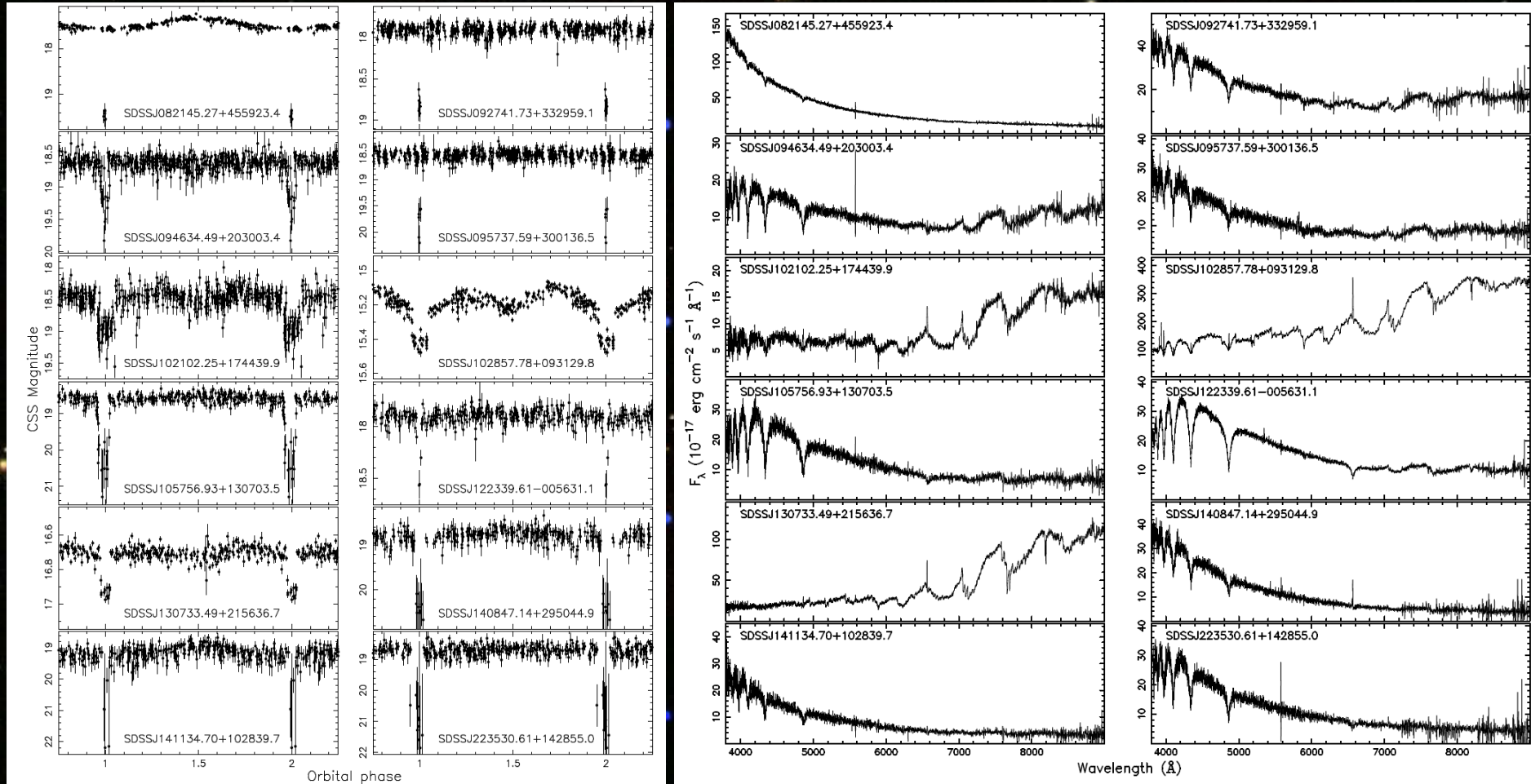
Spot-on the theoretical M-R relation



⇒ excellent test of ultracool WD atmospheres once IR colours are measured

Parsons et al. 2012, MNRAS 426, 1950

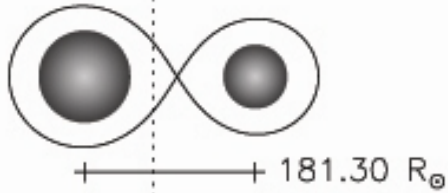
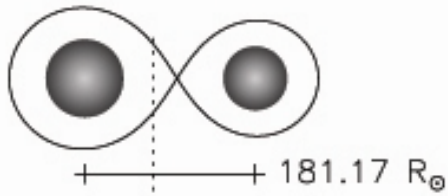
More to come: >60 eclipsing WD binaries known...



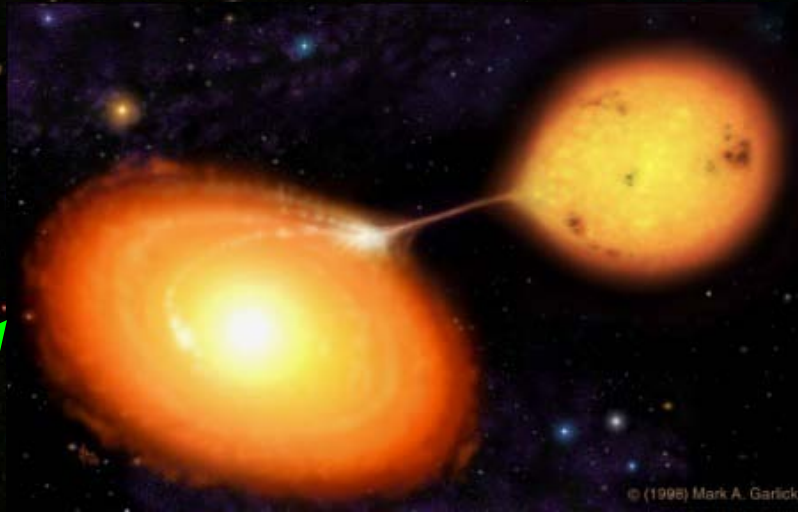
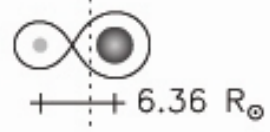
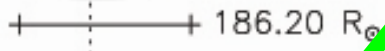
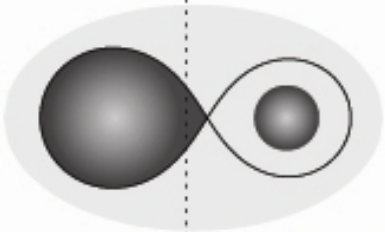
Road map for today

1. Eclipsing detached white dwarf binaries & mass radius relations
2. Eclipsing interacting white dwarf binaries & SN Ia progenitors
3. Eclipsing double white dwarfs & GWR orbital decay
4. Pulsating white dwarfs, single & in binaries

Cataclysmic variables



Common Envelope



???

Common knowledge: the WD mass should be eroded by classical nova eruptions (e.g. Yaron et al. 2005, ApJ 523, 398)

Early (mostly indirect) measurements

CV white dwarfs

Warner (1973): $\langle M_{\text{wd}} \rangle \sim 1.2 M$

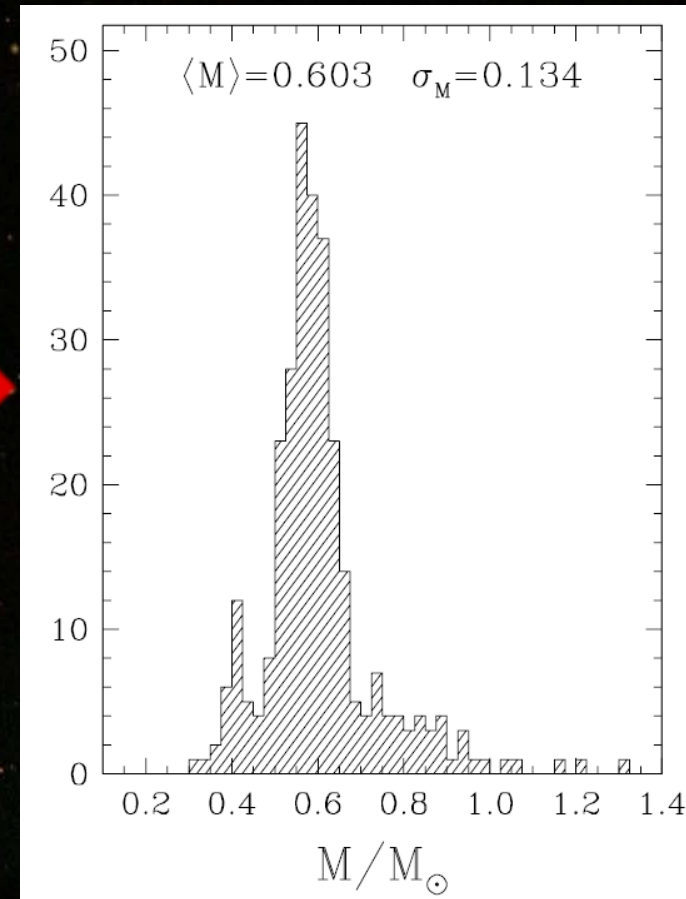
Ritter (1976): $\langle M_{\text{wd}} \rangle \sim 1.0 M$

Robinson (1976): $\langle M_{\text{wd}} \rangle \sim 1.0 M$

Ritter (1984): $\langle M_{\text{wd}} \rangle \sim 0.95 M$



Single white dwarfs



Liebert et al. (2005, ApJS 156, 47)

Early explanations

Warner (1974): Mass growth in CVs

Livio & Soker (1984): Common envelope evolution

Ritter & Burkert (1986): Observational selection effects

Early explanations

Warner (1974): Mass growth in CVs

Livio & Soker (1984): Common envelope evolution

Ritter & Burkert (1986): Observational selection effects

$$L_{\text{acc}} \propto M_{\text{wd}}/R_{\text{wd}} \quad \text{with} \quad R_{\text{wd}} \propto M_{\text{wd}}^{-\alpha}$$

⇒ CVs with more massive white dwarfs are more luminous

But: this bias should be small in deep samples

Table 2. Parameter values adopted for computing the selection functions shown in Figs. 1–6. The values of the remaining parameters are listed in Table 1. The last column contains the mean white dwarf mass of the function $p_{1,o} = S_1 p_{\text{SWD}}$

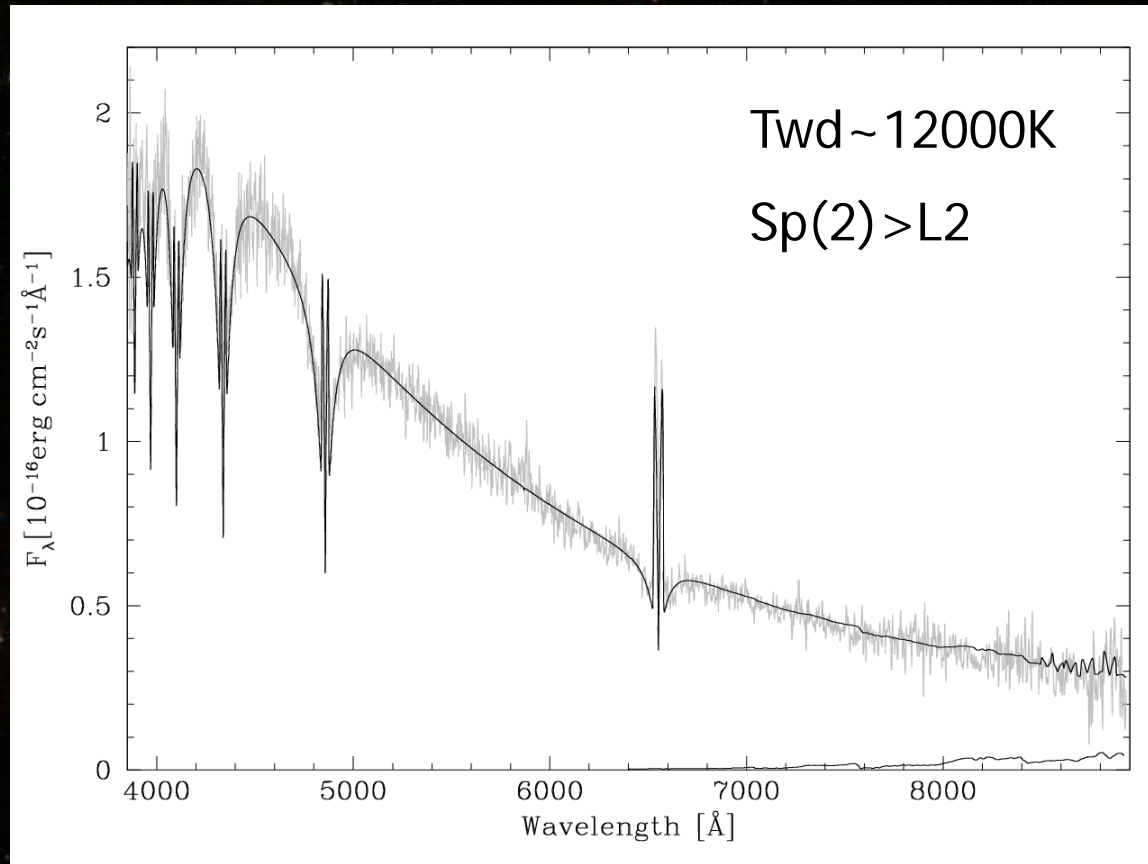
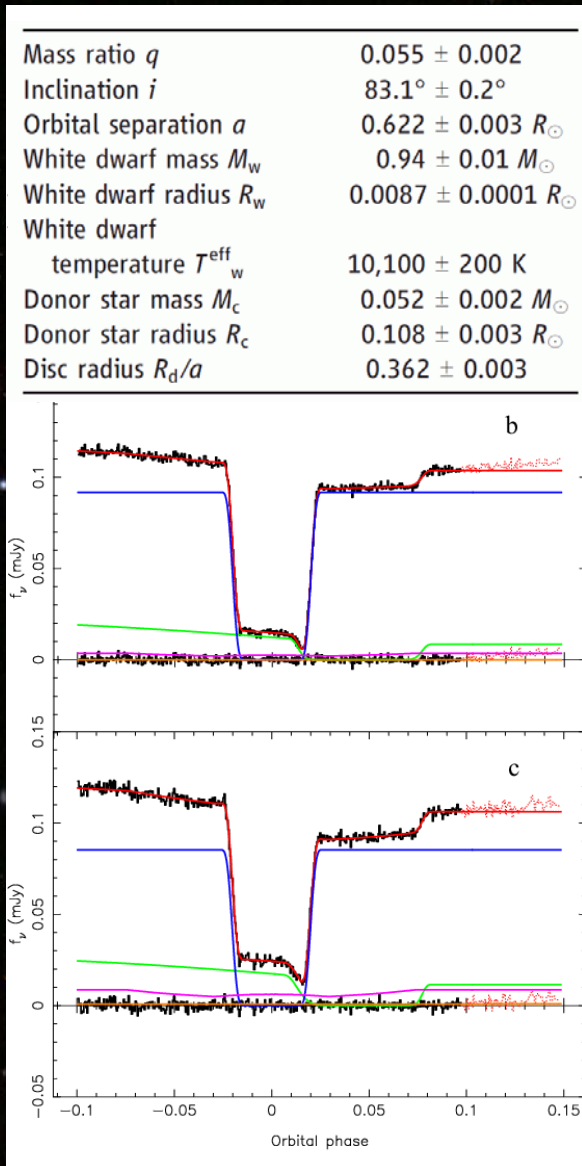
No.	$\frac{M_{2,l}}{M_{\odot}}$	$M_{2,u}$	$p_{2,i}$	j	$\frac{\tau}{\tau_{\text{out}}}$	m_V	Remarks	$\frac{\langle M_{\text{WD}} \rangle}{M_{\odot}}$
1	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	1	10.0		0.909
2	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	\dot{J}_{GR}	1	10.0		0.883
3	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_p$	1	10.0		0.869
4	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0		0.982
5	0.1	$M_{2,\text{max}}$	$\sim(M_{2,i} - M_{2,l})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0		0.956
6	0.1	$M_{2,\text{max}}$	const.	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0		0.940
7	0.1	$M_{2,\text{max}}$	$\sim(M_{2,u} - M_{2,i})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0		0.913
8	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	5	10.0		0.979
9	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	20	10.0		0.972
10	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0	DN only	1.017
11	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0	NL only	0.725
12	0.1	$0.2 M_{\odot}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0	$\triangle P \lesssim 2^{\text{h}}$	0.776
13	0.2	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0	$\triangle P \lesssim 2^{\text{h}}$	1.121
14	0.2	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	10.0	$\triangle P \lesssim 2^{\text{h}}$ DN only	1.230
15	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	12.5		0.901
16	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	15.0		0.782
17	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	17.5		0.694
18	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	10	20.0		0.658
19	0.1	$M_{2,\text{max}}$	$\delta(M_{2,i} - M_{2,\text{max}})$	$\dot{J}_{\text{GR}} + \dot{J}_{\text{VZ}}$	1	10.0	Without BC	0.846

SDSS

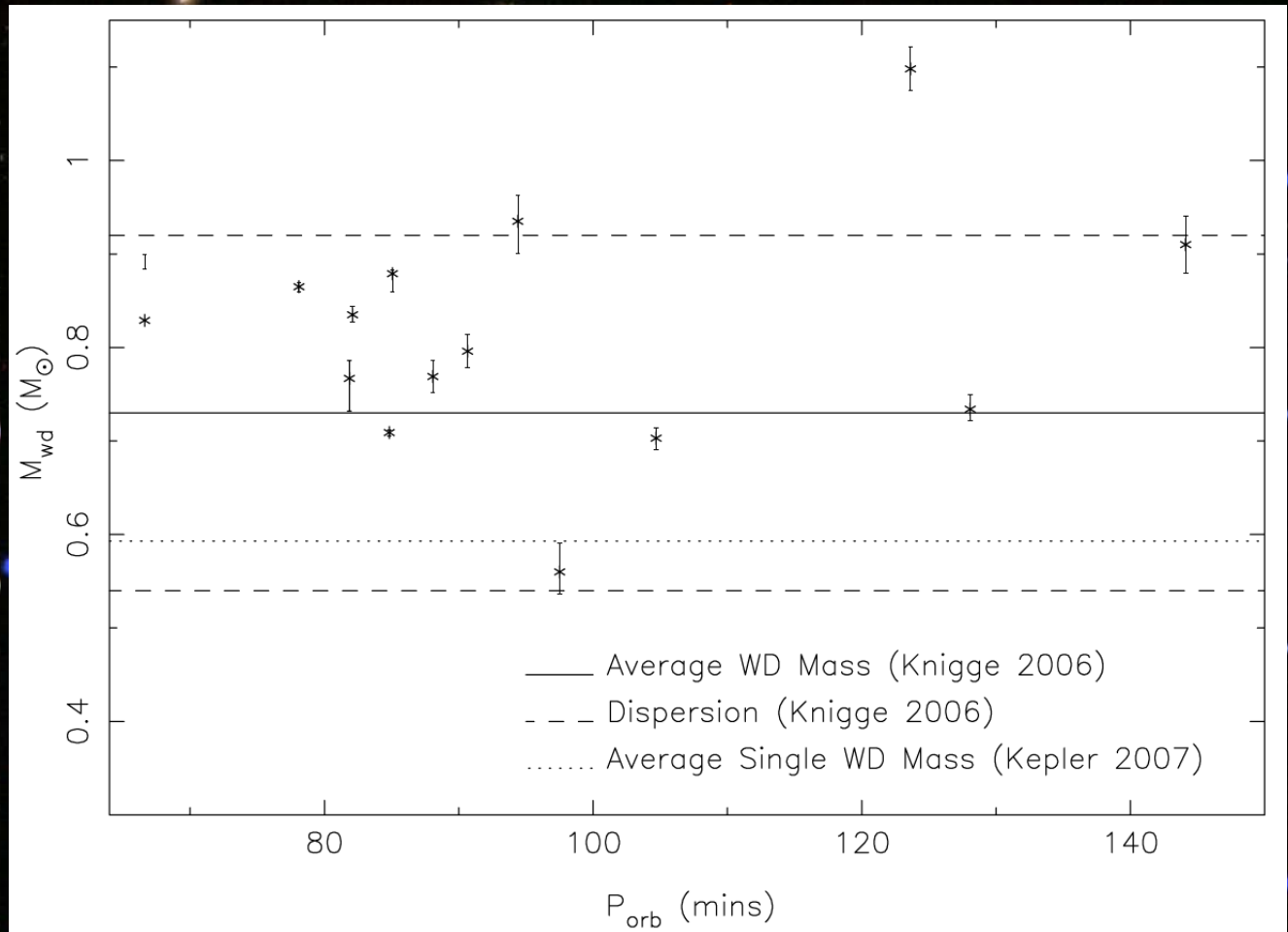
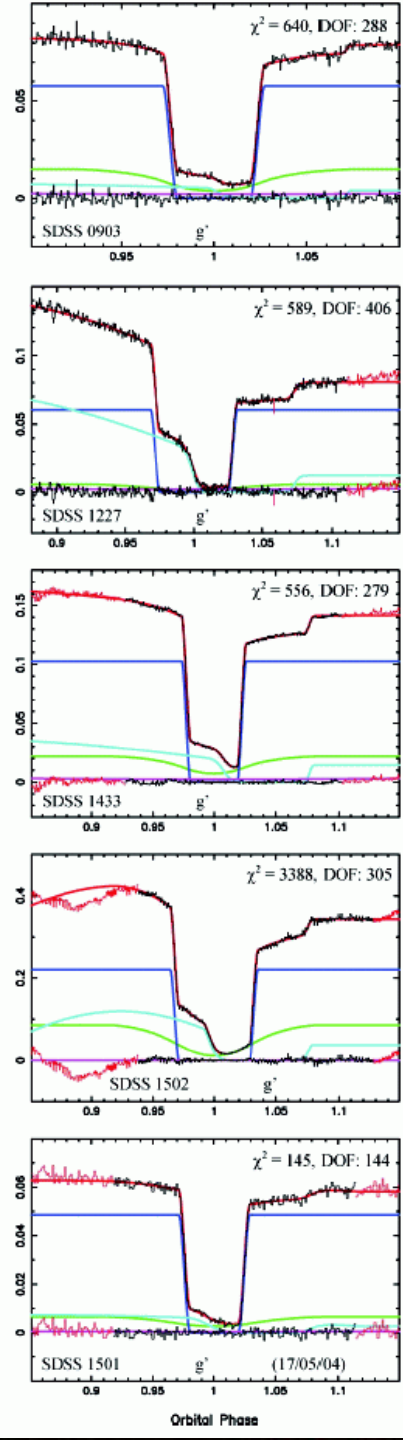


Ritter & Burkert (1986)

SDSS1035+0551: The first definite brown dwarf donor

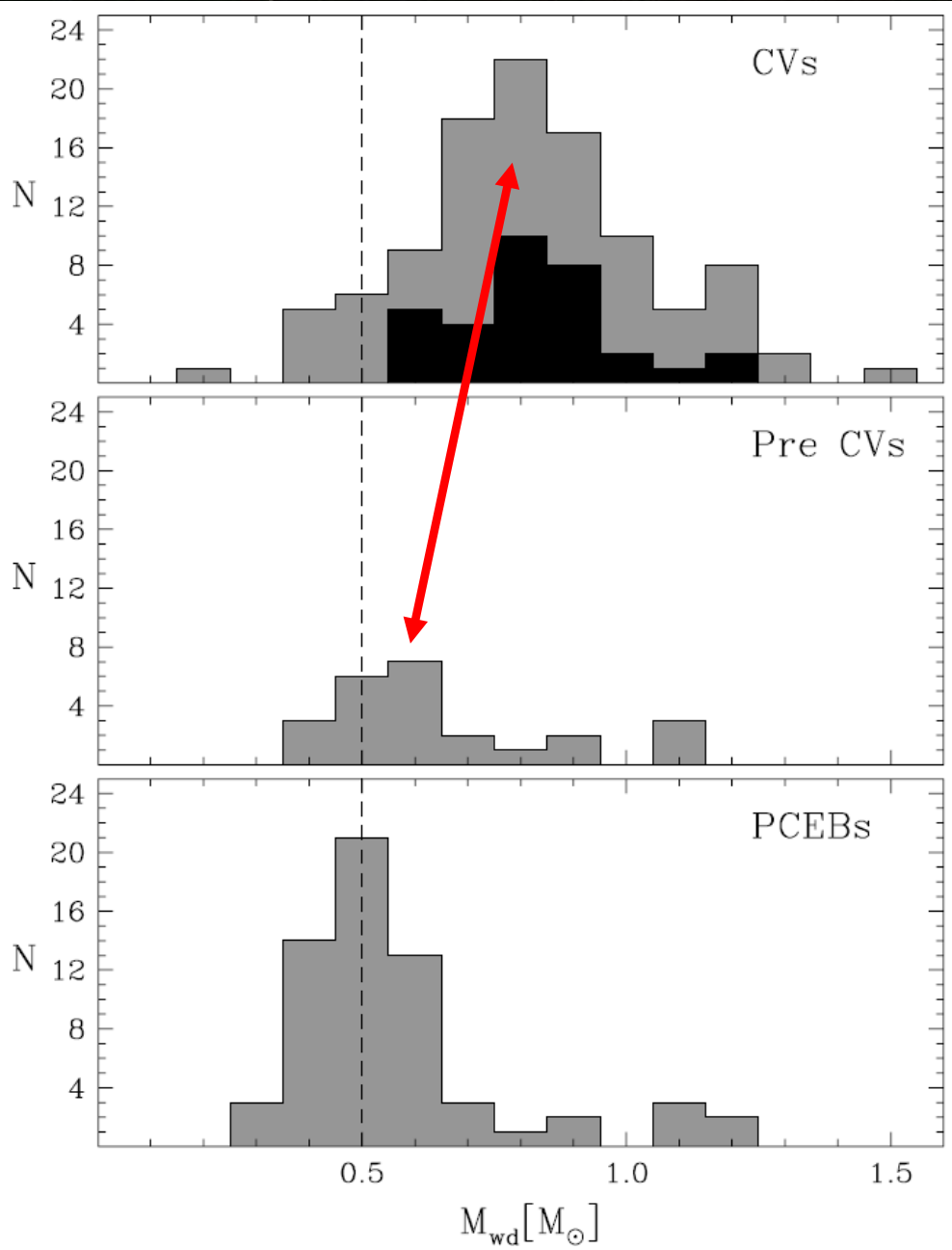


CV primary masses from SDSS



Feline et al. (2004),
Littlefair et al. (2006, 2007, 2008),
Savory et al. (2011)

CVs versus pre-CVs and PCEBs



$$\langle M_{wd} \rangle = 0.83 \quad 0.23 M$$

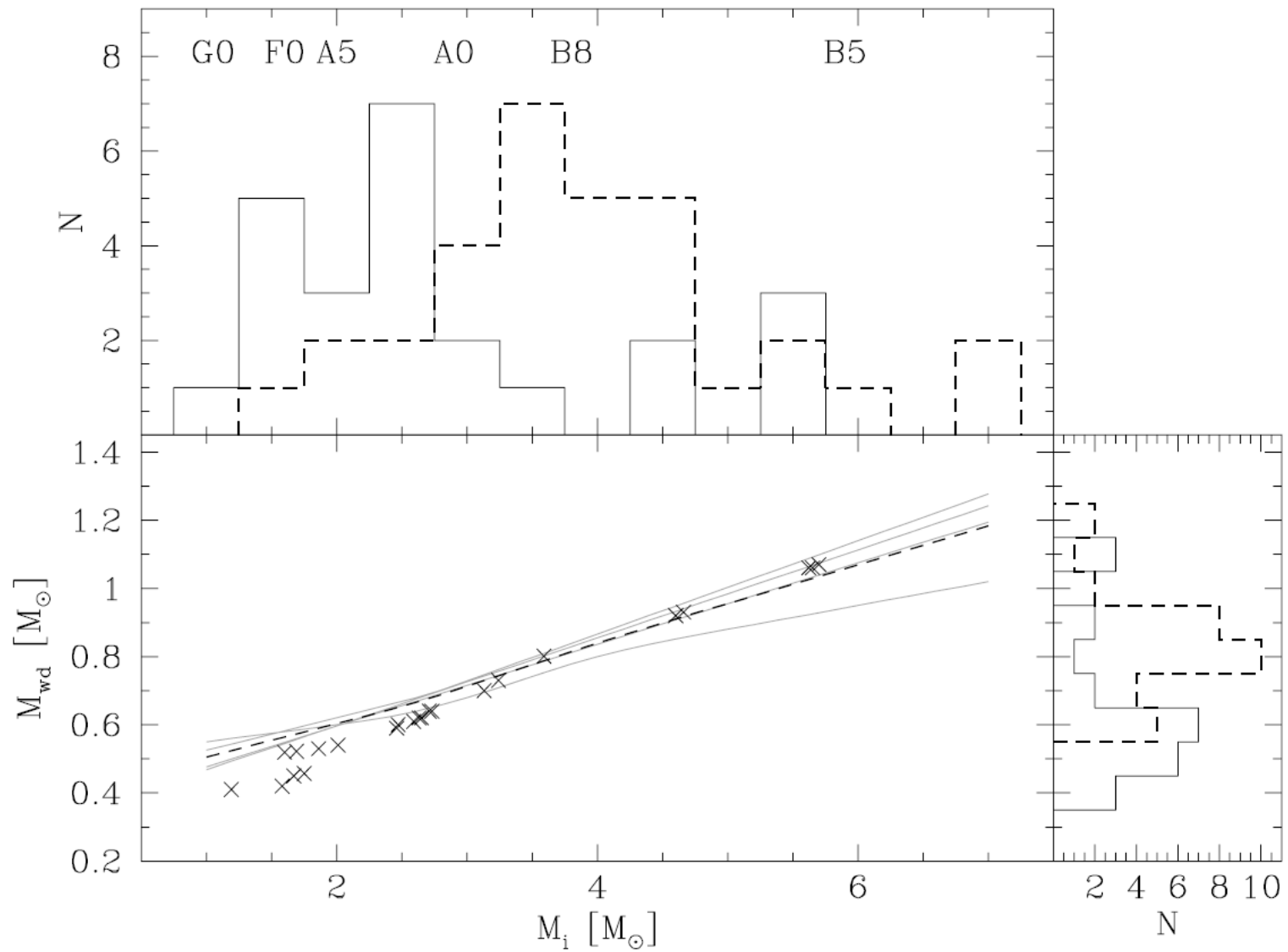
$$\langle M_{wd} \rangle = 0.67 \quad 0.21 M$$

$$\langle M_{wd} \rangle = 0.58 \quad 0.20 M$$

Zorotovic et al. 2011,
A&A 536, 42

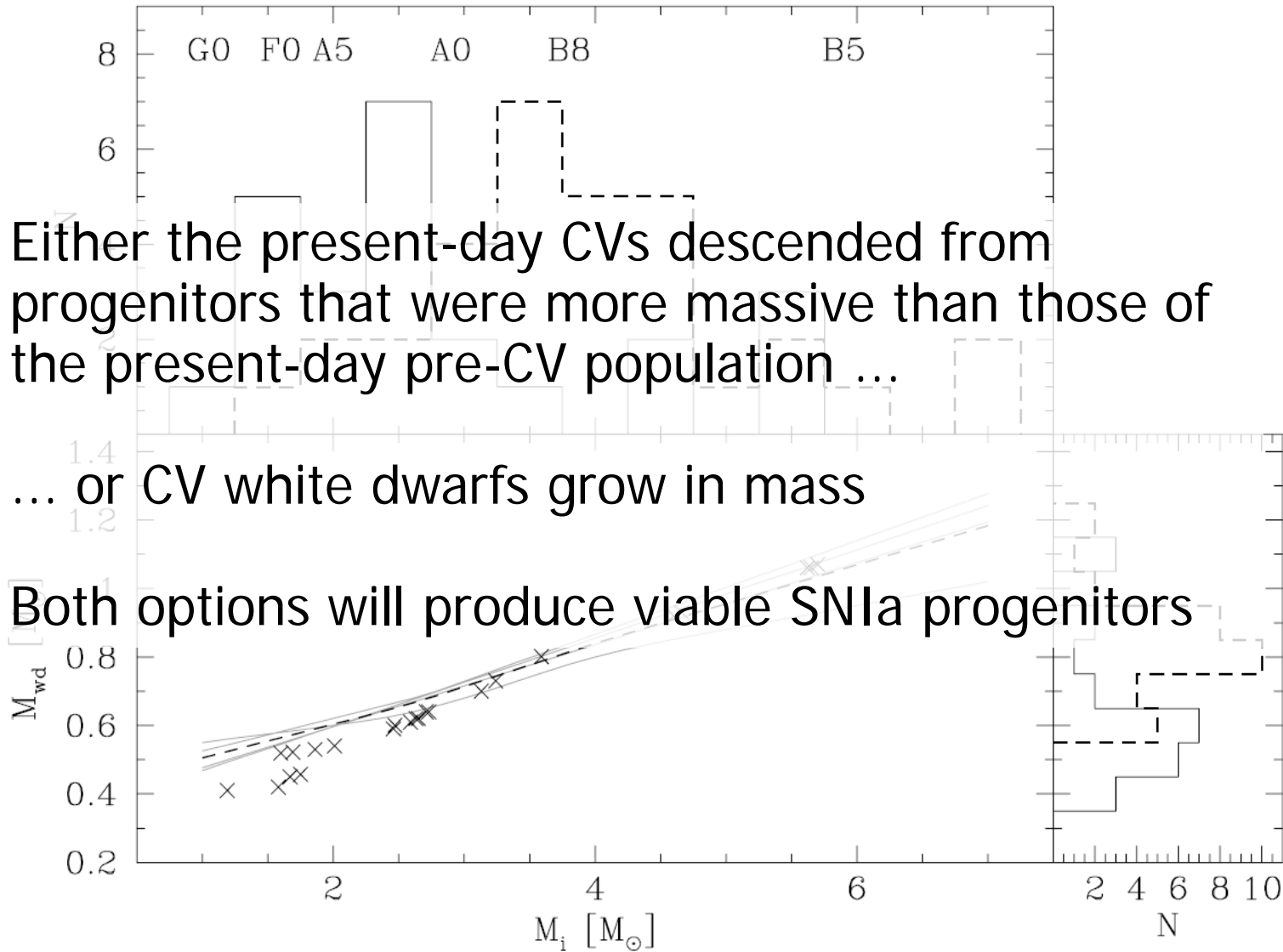
Initial-to-final mass relation

Zorotovic et al. 2011, A&A 536, 42



Initial-to-final mass relation

Zorotovic et al. 2011, A&A 536, 42

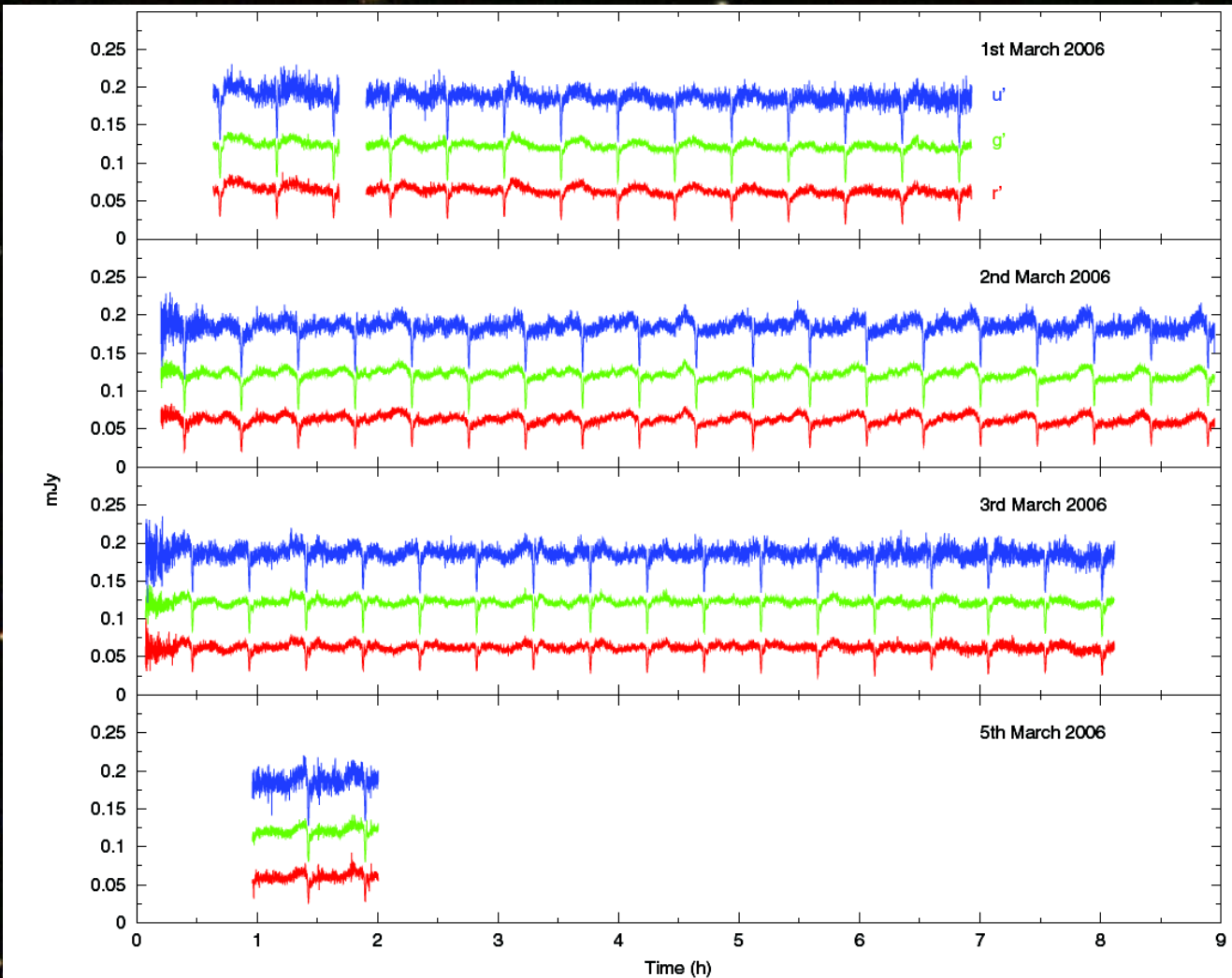


Road map for today

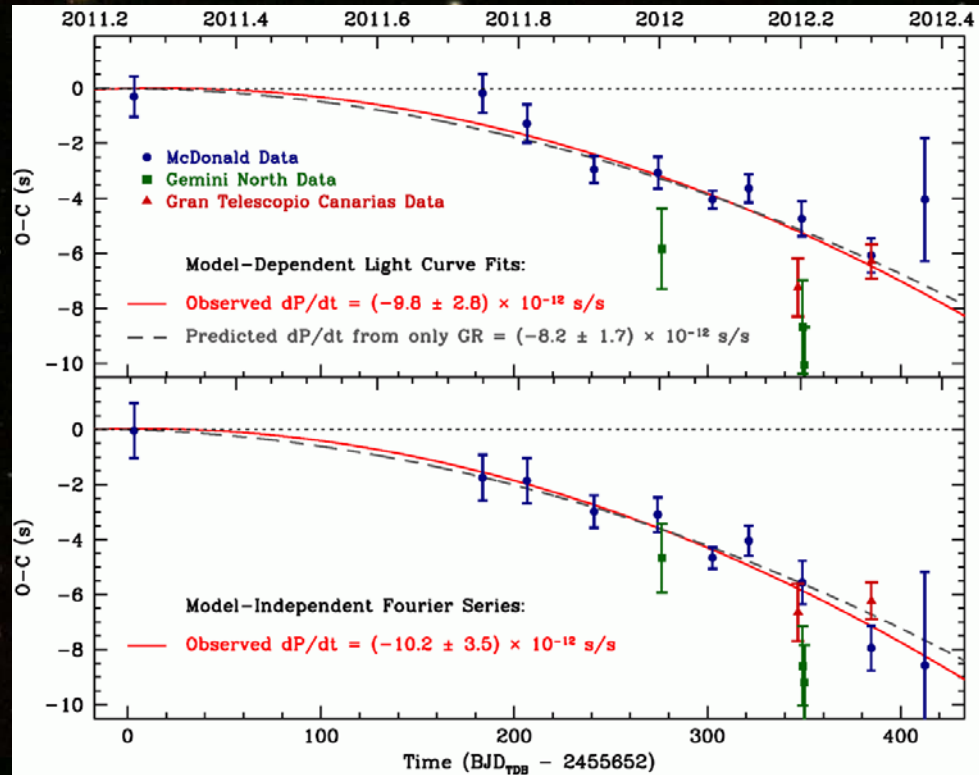
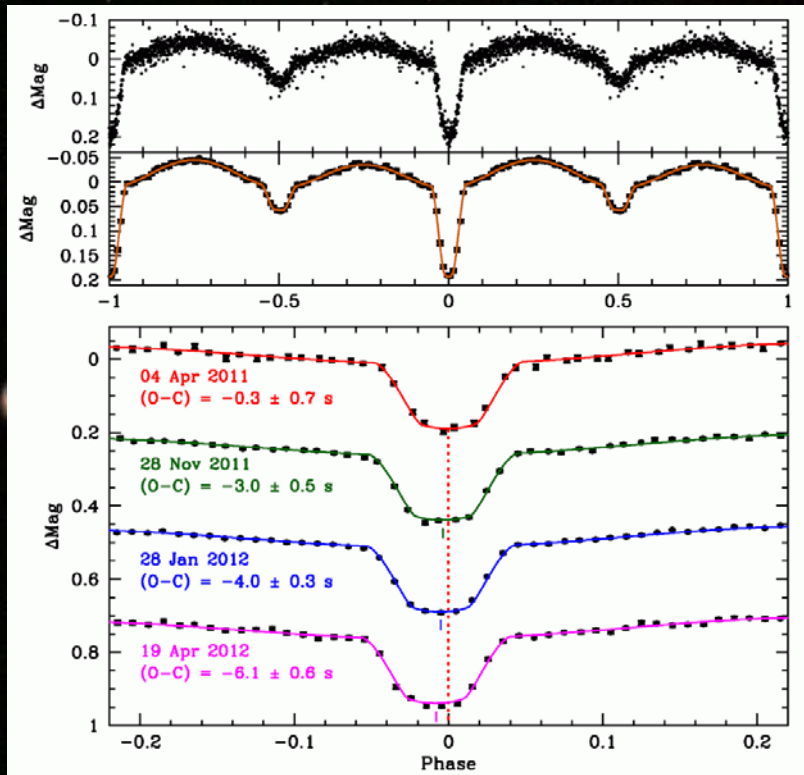
1. Eclipsing detached white dwarf binaries & mass radius relations
2. Eclipsing interacting white dwarf binaries & SN Ia progenitors
3. Ultra-short period eclipsing double white dwarfs & period evolution
4. Pulsating white dwarfs, single & in binaries

SDSS J0926+3624, a double-degenerate CV: $P_{\text{orb}}=28\text{min}$

$M_{\text{wd}} = 0.85 \pm 0.04 M_{\odot}$
 $M_2 = 0.035 \pm 0.003 M_{\odot}$



SDSS J0106-1000, a detached double WD: $P_{\text{orb}}=12.8\text{min}$



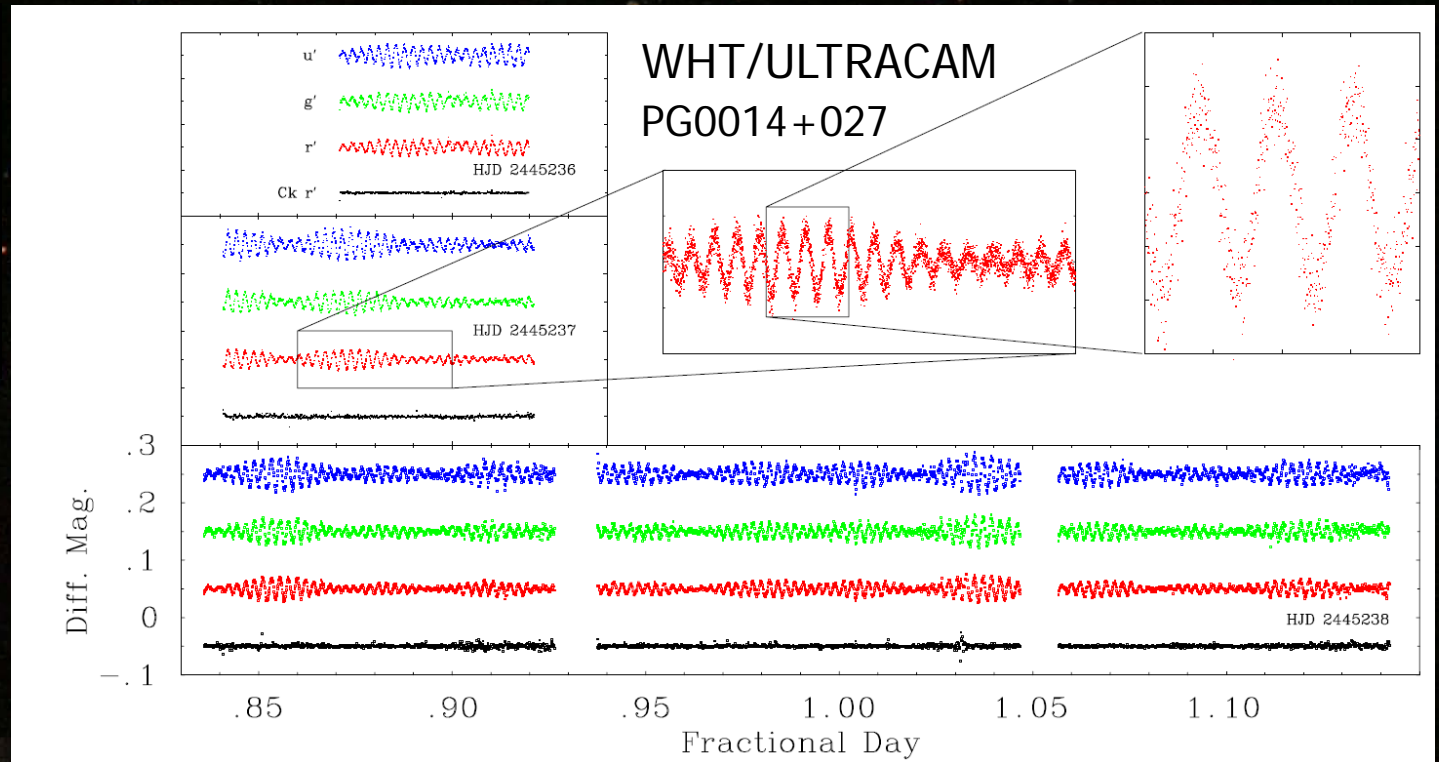
Orbital decay due to gravitational wave radiation

Kilic et al. 2011, MNRAS 413, L101
Hermes et al. 2012, ApJ 757, L21

Road map for today

1. Eclipsing detached white dwarf binaries & mass radius relations
2. Eclipsing interacting white dwarf binaries & SN Ia progenitors
3. Eclipsing double white dwarfs & GWR orbital decay
4. Pulsating white dwarfs, single & in binaries

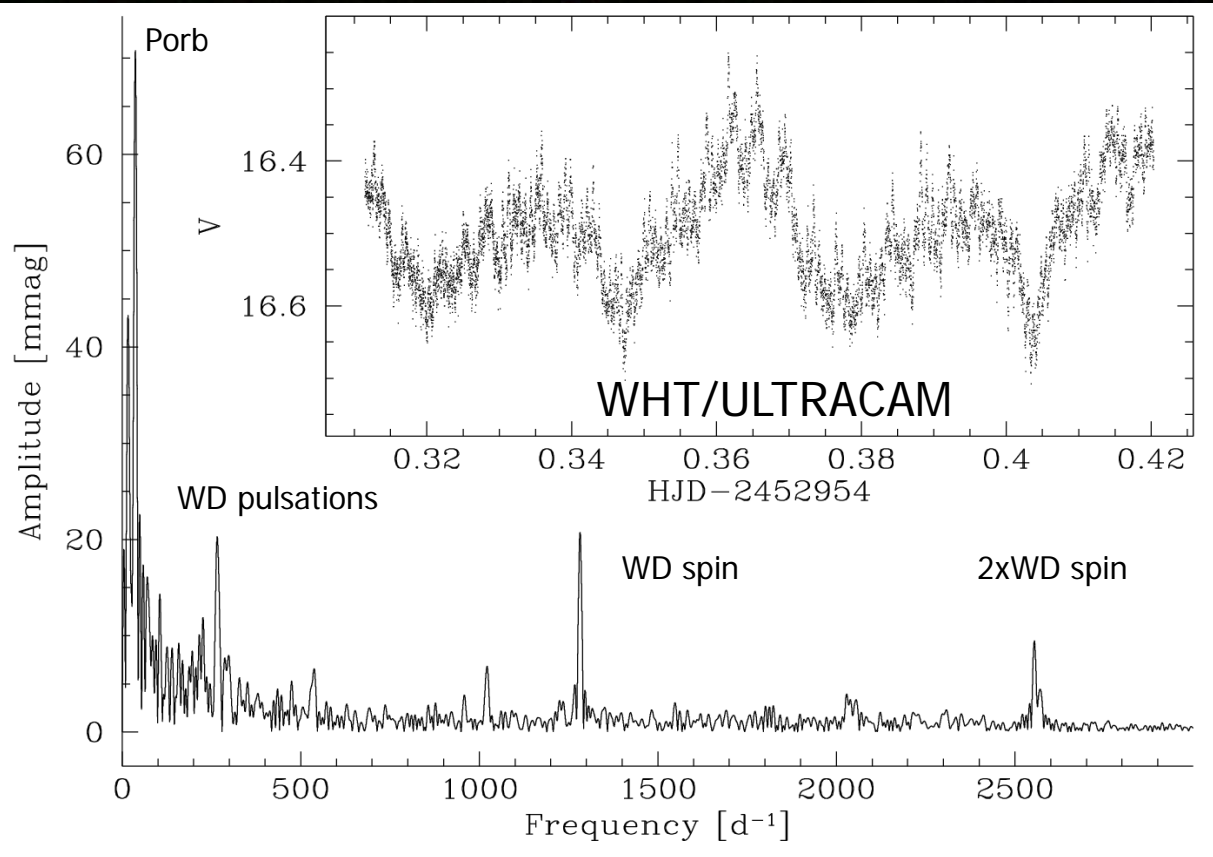
Asteroseismology



Jeffery et al. 2005, MNRAS 362, 66

Pulsation frequency spectrum provides information about mass, core composition, envelope mass, rotation rate, magnetic field...

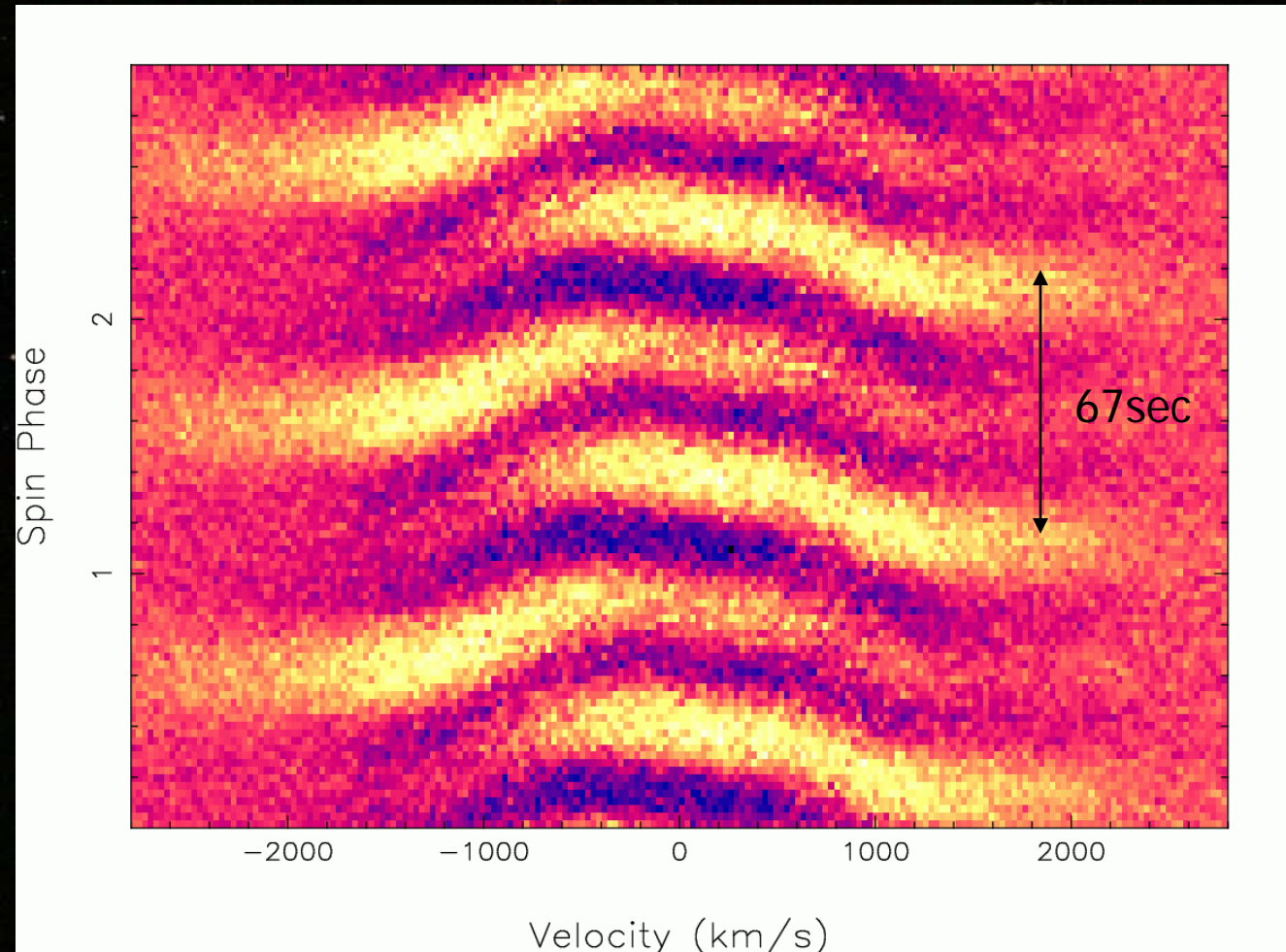
V455 And – the time-domain family pack



V455 And=HS2331+3905

- eclipsing
- brown dwarf
- pulsating WD
- rapidly rotating WD
- magnetic WD
- warped accretion disc

[Ultrafast spectroscopy]

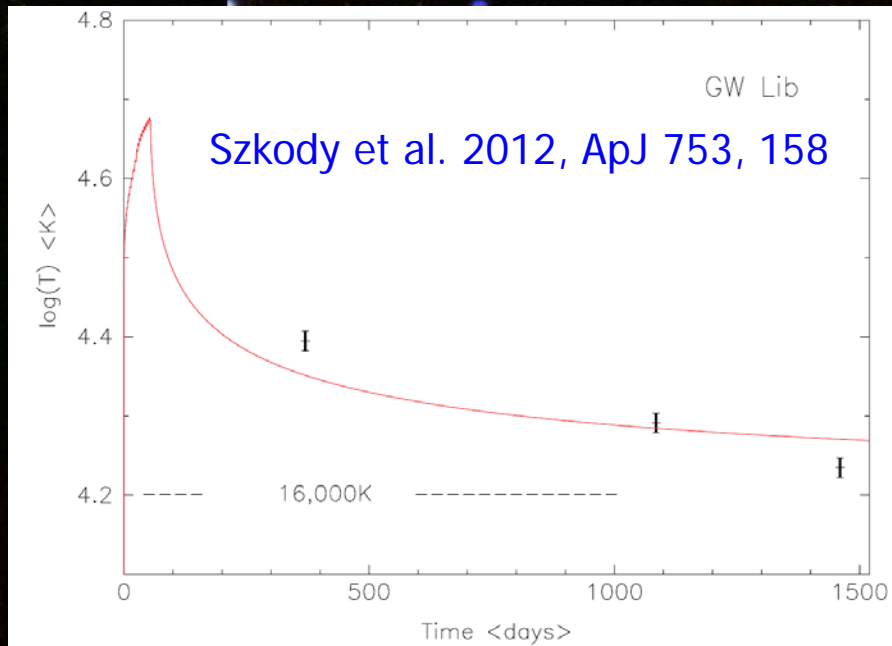
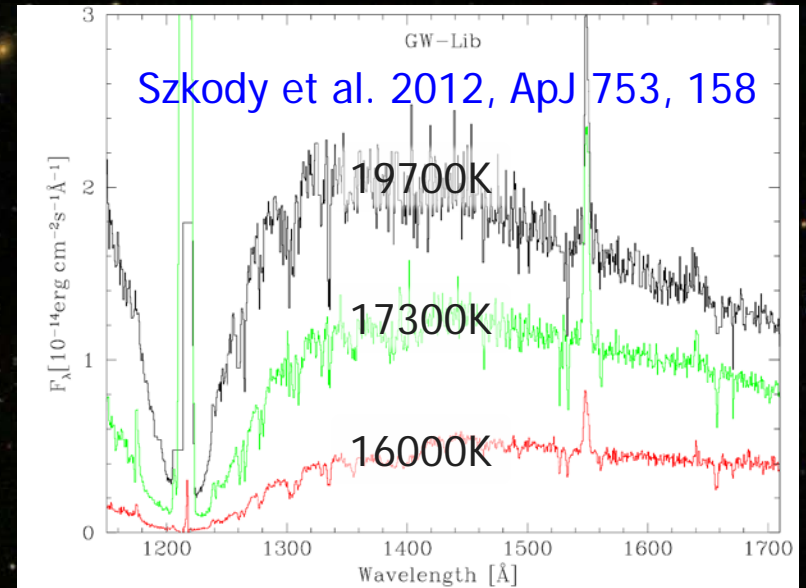
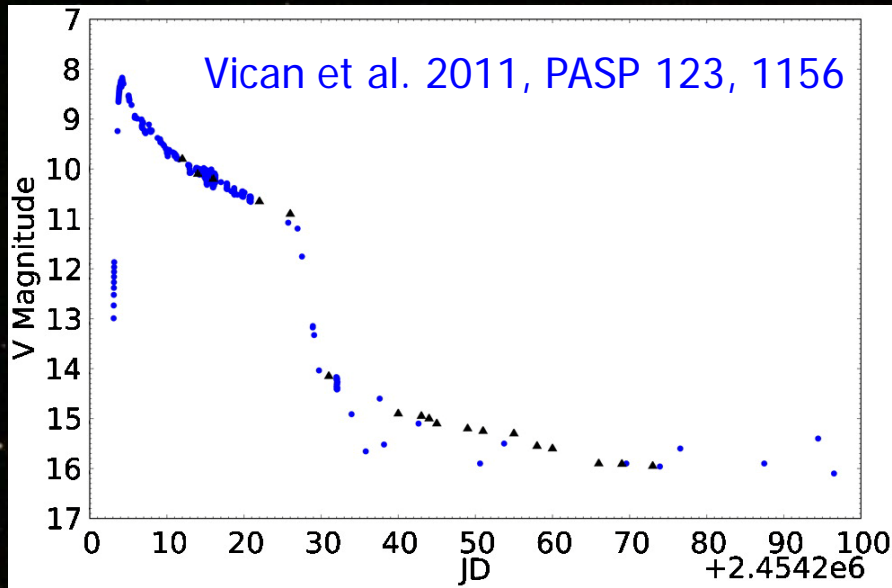


QUCam
spectroscopy

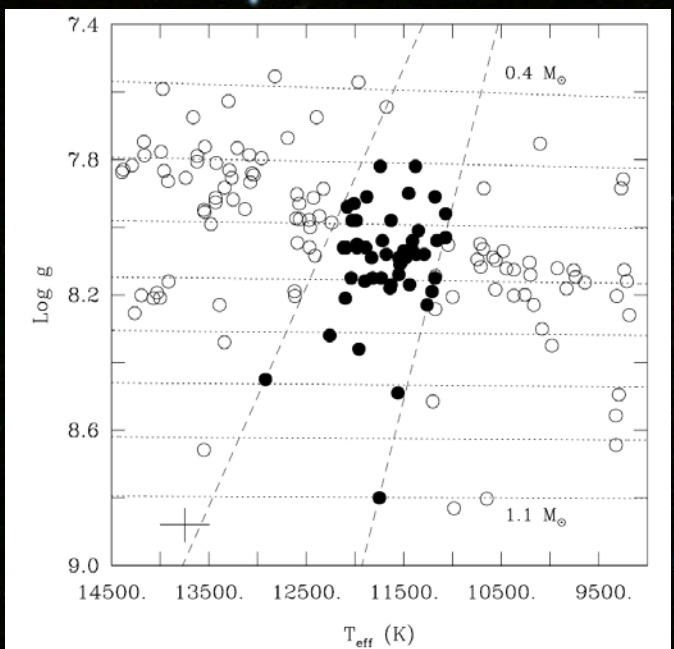
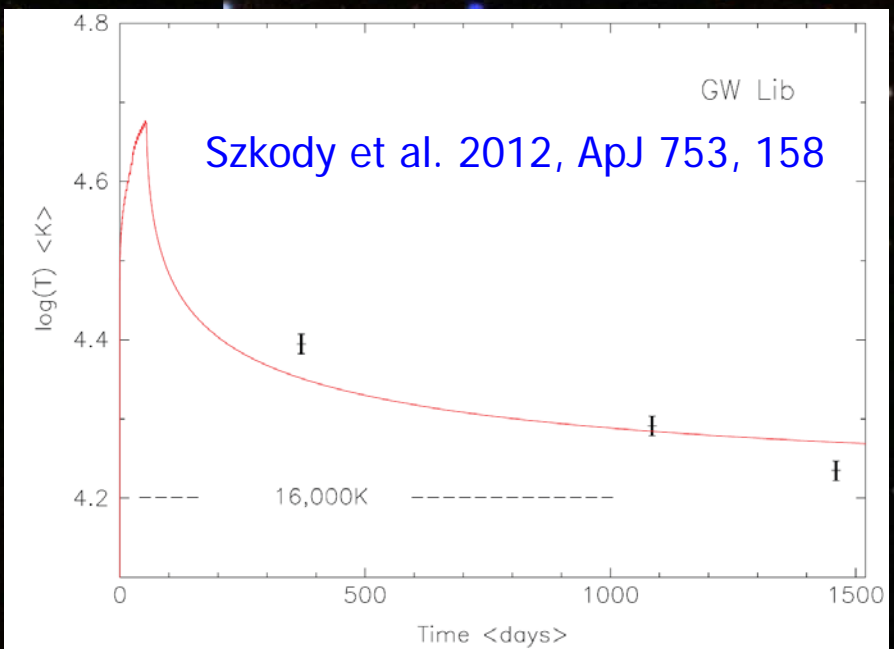
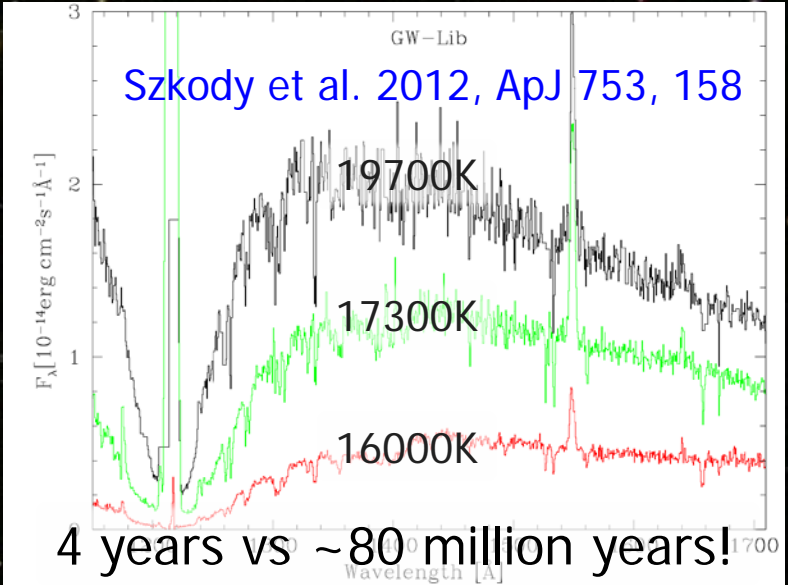
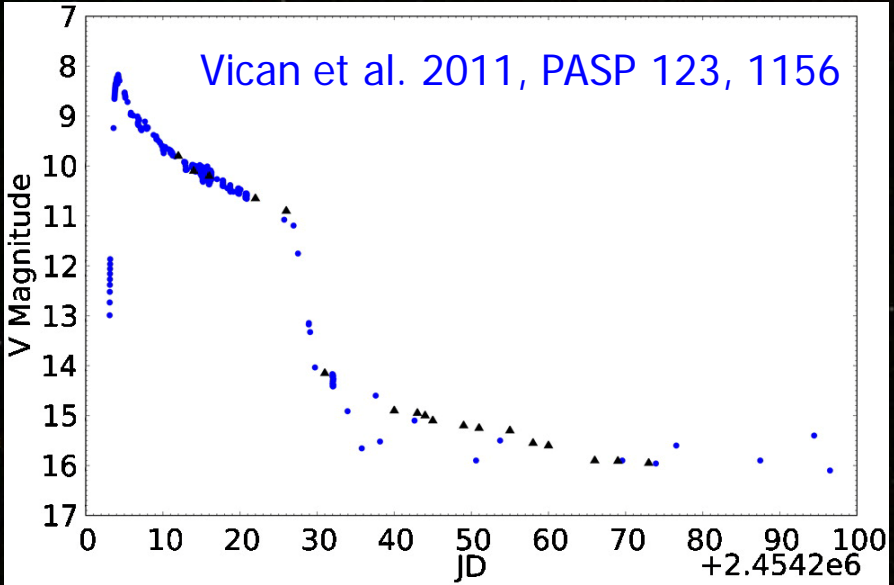
15800 spectra
2sec exposure time
no deadtime

(Bloemen et al. 2013, MNRAS.429.3433)

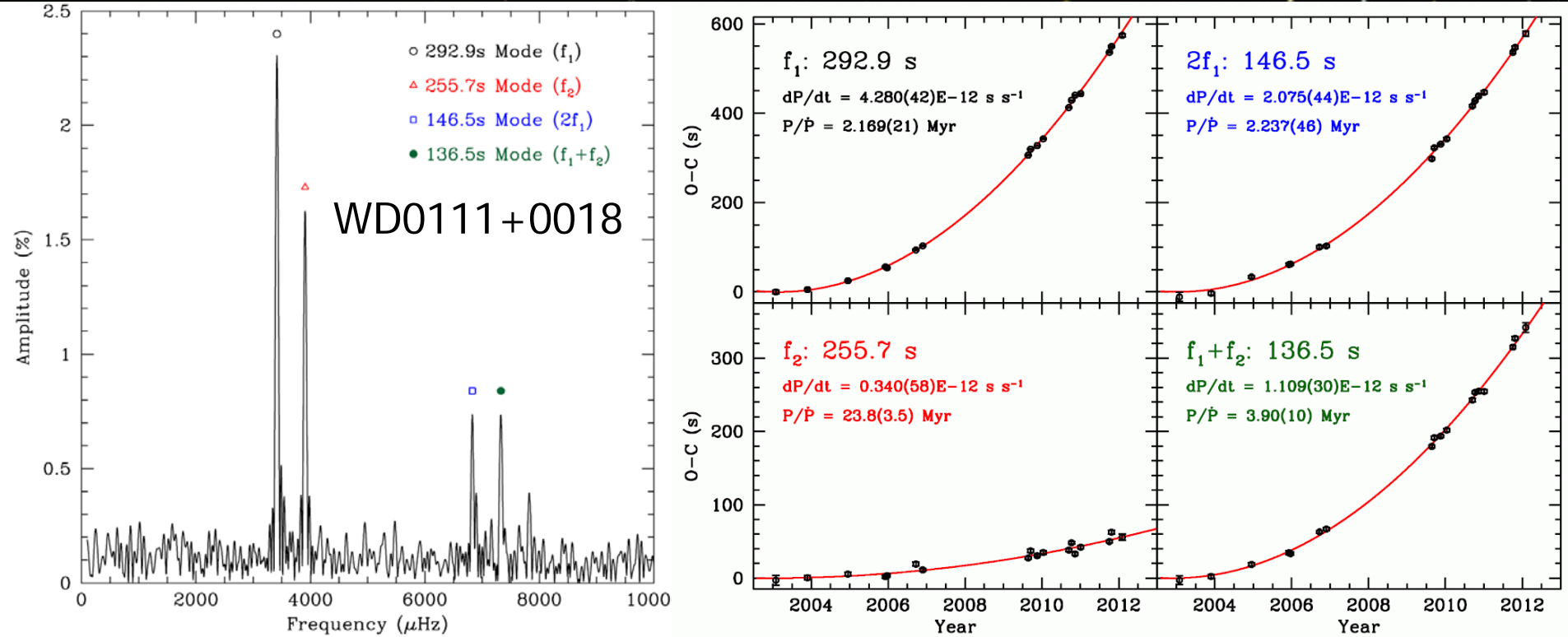
GW Lib – a pulsator that underwent a disc outburst



GW Lib – a pulsator that underwent a disc outburst



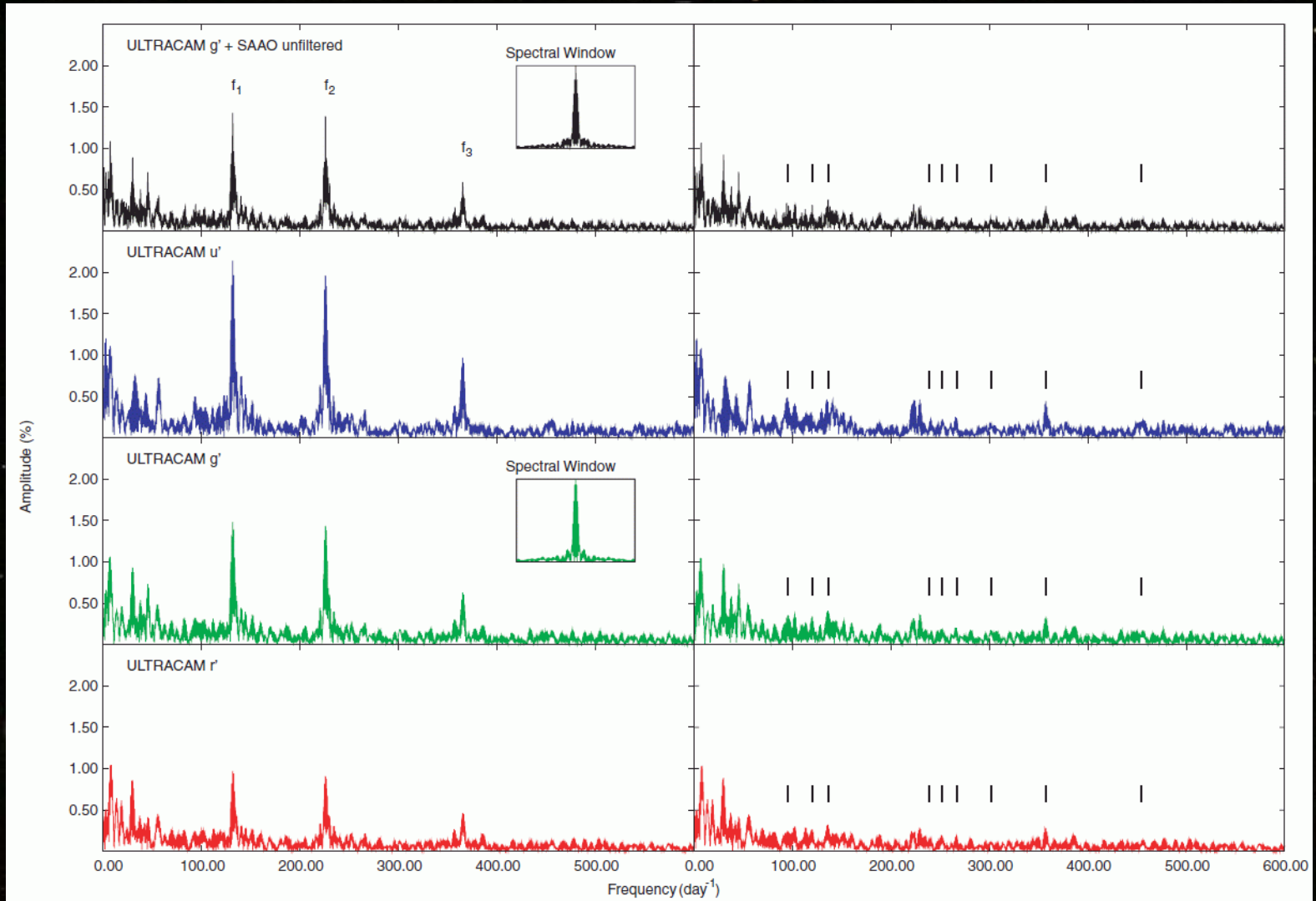
Pulsation period evolution in single WDs



$$dP/dt = 3 \times 10^{-5} \text{ s/yr}$$

Hermes et al. 2013, ApJ 766, 43

60 days after the outburst

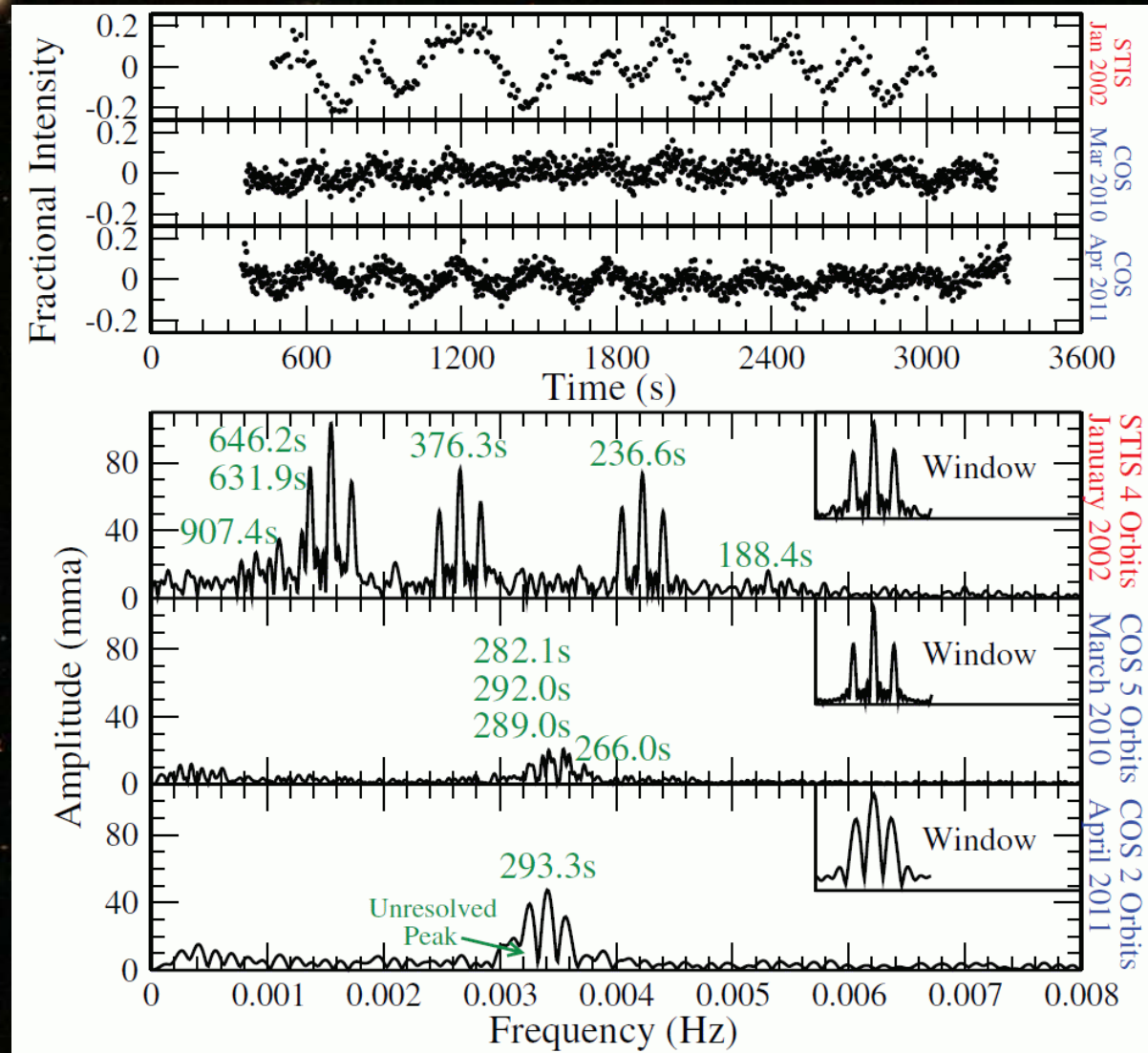


COS time-tag data: 3 & 4 years after the outburst

quiescence \Rightarrow

3yrs \Rightarrow

4yrs \Rightarrow



quiescence \Rightarrow

3yrs \Rightarrow

4yrs \Rightarrow

Conclusions

- High-speed observations of white dwarfs provide substantial insight into fundamental (astro)physics.
- The current and future large area surveys provide an extremely rich sample of targets for such studies, we have merely begun to scratch the surface.