The ELM Survey. VIII. Ninety-eight Double White Dwarf Binaries

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OUTLINE

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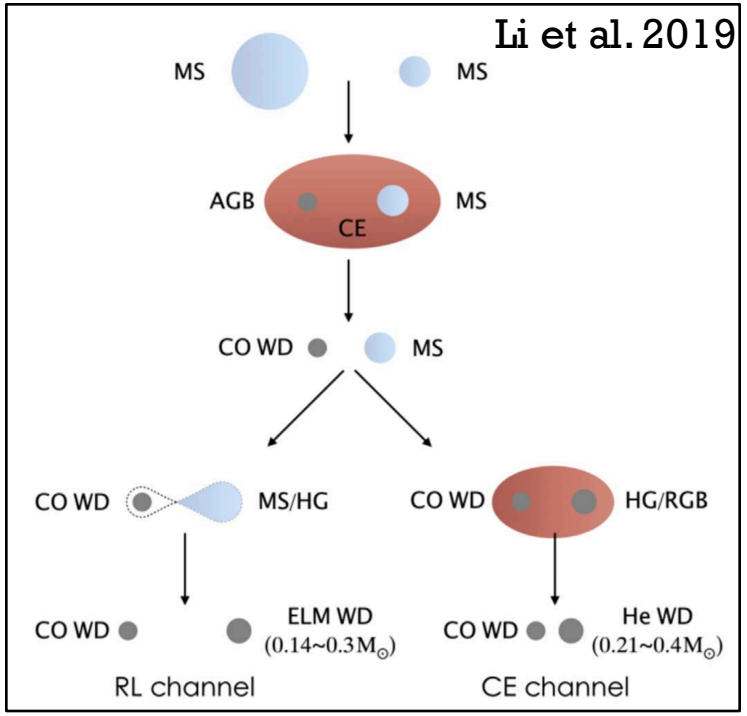
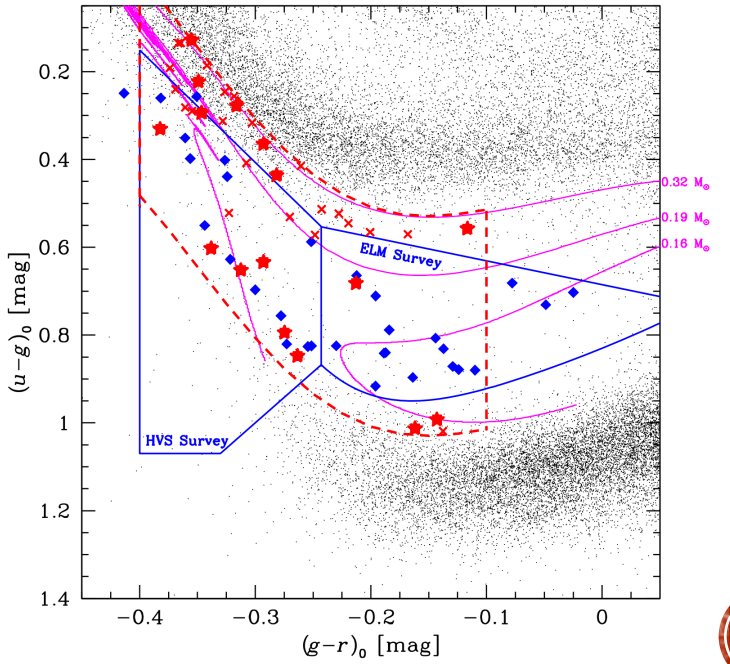
1 Background

- $\mathcal{O}(10^8)$ double degenerate white dwarf binaries in the Milky Way (Han 1998; Nelemans et al. 2001).
- Ultracompact WD binaries, with orbital periods from minutes to hours, are strong mHz gravitational-wave sources. (AM CVn systems; supernovae; single massive white dwarf; R CrB stars, and so on (Webbink 1984).
- Theoretical models have long predicted that most ultra-compact WD binaries contain low-mass, He-core WDs (e.g., Iben 1990).
- Observational: 1 Marsh et al. (1995) found 5 in 7 lowest mass WDs are in binaries; 2 The ESO Supernovae type Ia Progenitor Survey (SPY) found 39 in 643 normal hydrogen-atmosphere WDs are the lowest mass WDs in binary systems.



- The completed ELM Survey; targeting extremely low mass (ELM) $<0.3\ M_\odot$ ($5<\log g<7$) WDs in the Sloan Digital Sky Survey (SDSS) footprint (Kilic et al. 2010, 2011a; Brown et al. 2010, 2012b); containing over half of the known detached double WDs in the Galaxy (Marsh 2019).
- The contamination is mainly from metal-poor subdwarf A-type stars (field blue stragglers).



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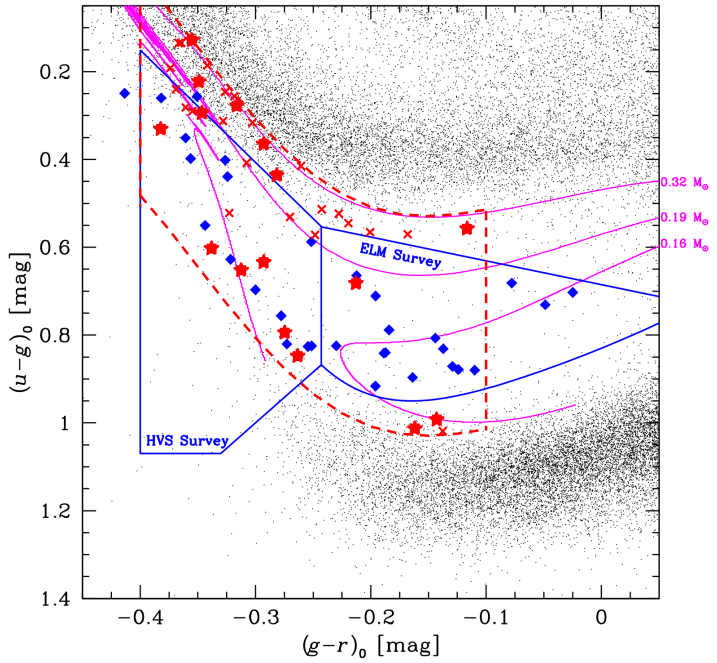
2 Data

- Target selection
  - Based on the dereddened broad band magnitudes and colors of SDSS photometry.
  - $(u-g)_0$ spans the Balmer decrement and provides a sensitive measure of surface gravity.
  - $(v-r)_0$ is used to measure the effective temperature.
  - $(r-i)_0$ is uses to exclude sources with nonstellar colors.



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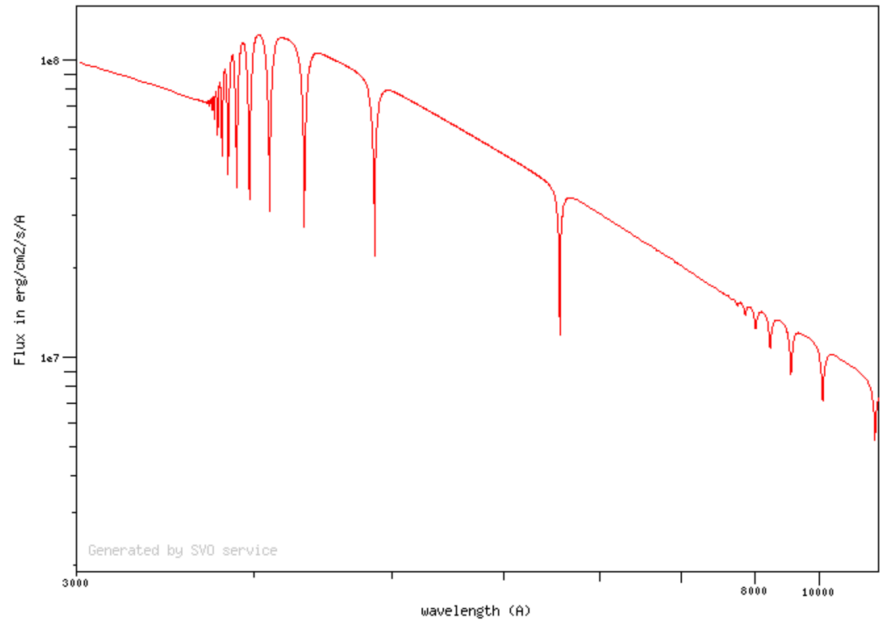
- Survey design and Spectroscopy observations
  - Acquired a single spectrum for every candidate and determined its nature using stellar atmosphere fits.
  - Acquired multi-epoch spectroscopy for candidates that appear to be 5<log g<7 WDs.
  - A total of 230 candidates with >3 epochs of observations.
  - High-order Balmer lines are sensitive to surface gravity (Tremblay & Bergeron 2009) and provide a good measure of radial velocity.



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Telescope	spectrograph	resolution	S/R requirement
the 6.5m MMT telescope	Blue Channel spectrograph; the 8321 mm^{-1} grating in second order; a 1″ or 1.25″ slit	1.0 or 1.2 Å spectral resolution over 3550<λ<4500 Å	~7 per pixel; ~12 per resolution element, per exposure
the 1.5 m FLWO telescope	FAST spectrograph; the 6001 mm^{-1} grating in second order; a 1.5″ slit	1.7 Å spectral resolution over 3550<λ<5500 Å	~15 per pixel; ~23 per resolution element, per exposure
the 4.1 m SOAR telescope	the Goodman High Throughput spectrograph; the 9301 mm^{-1} grating; a 1.03″ slit	2.2 Å spectral resolution over 3550<λ<5250 Å	
the 8 m Gemini telescopes	the Gemini Multi Object Spectrograph; the B600 grating; a 0.5″ slit	2.1 Å spectral resolution over 3600<λ<6600 Å	
the 4 m Mayall telescope	the Kitt Peak Ohio State Multi-Object Spectrograph; the Blue VPH grating; a 1.5″ slit	2.0 Å spectral resolution over 3500<λ<6200 Å	

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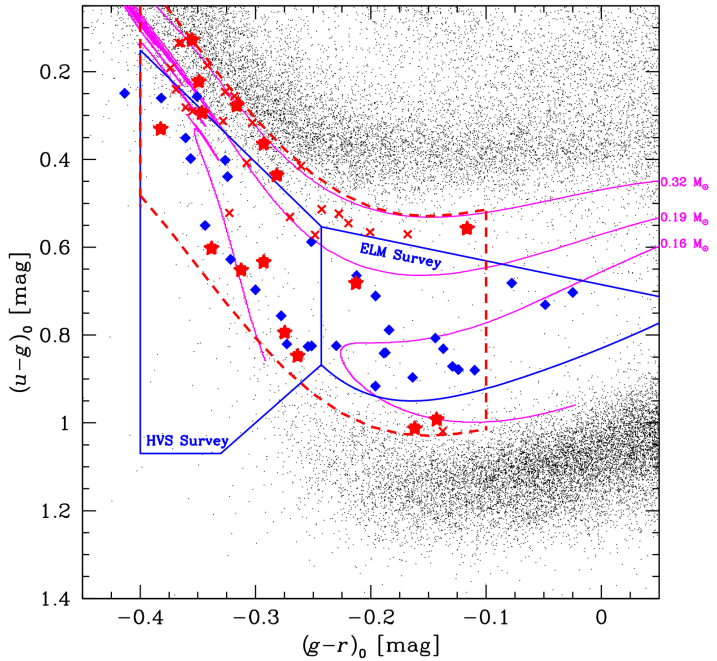

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➢ Survey design and Spectroscopy observations

- Acquired a single spectrum for every candidate and determined its nature using stellar atmosphere fits.
- Acquired multi-epoch spectroscopy for candidates that appear to be 5<log g<7 WDs.
- A total of 230 candidates with >3 epochs of observations.

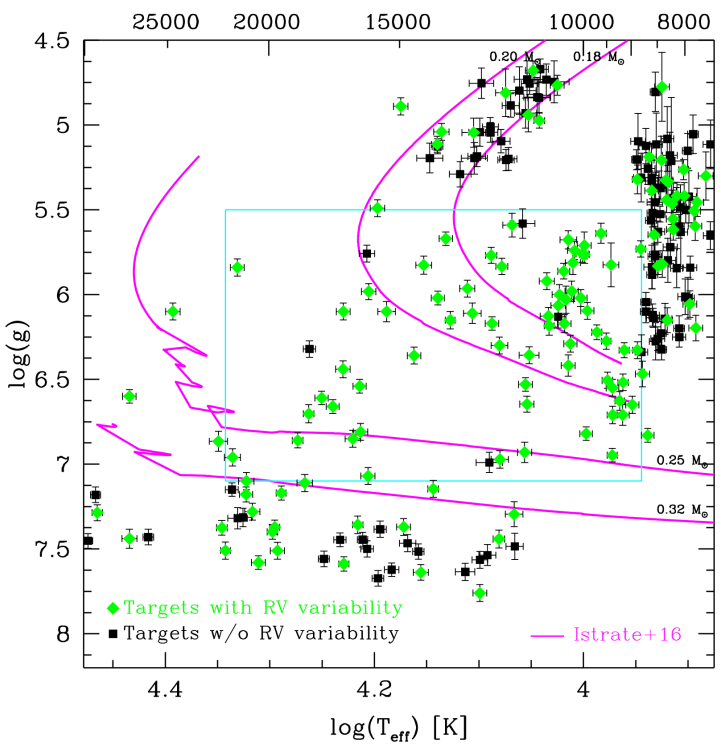
- High-order Balmer lines are sensitive to surface gravity (Tremblay & Bergeron 2009) and provide a good measure of radial velocity.

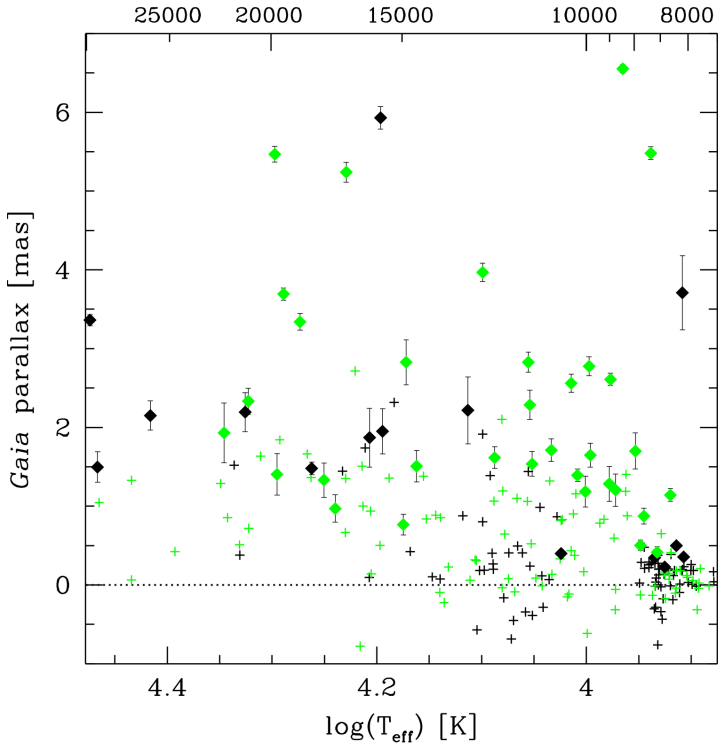
- Measured radial velocities using full wavelength range of the spectra with the cross-correlation package RVSAO (Kurtz & Mink 1998).
- 4338 radial velocity measurements for 230 low-mass WD candidates with >3 observations.
- 128 of the 230 candidates have statistically significant velocity variability.

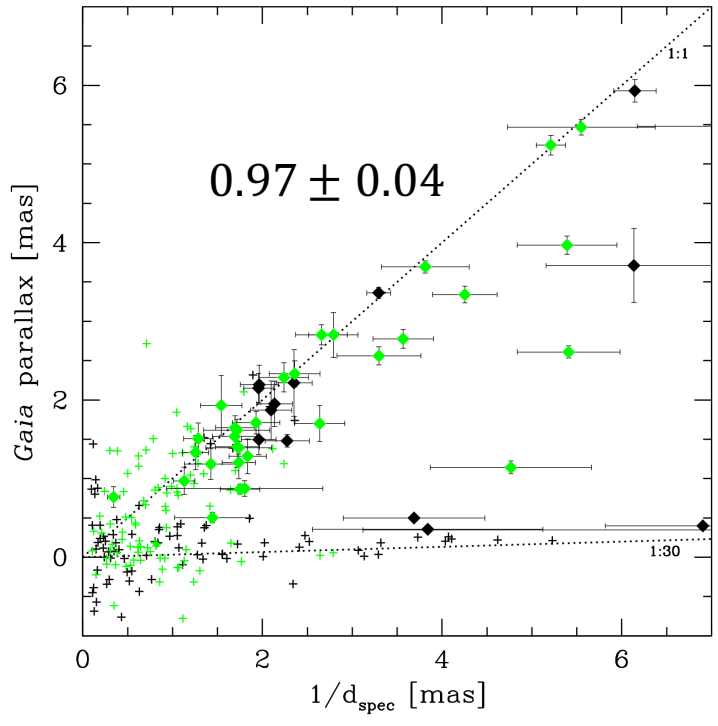
2 Data

➢WD parameters

- Fit the summed rest-frame spectra of each candidate to a grid of pure hydrogen-atmosphere models that span 4000 K < T < 35,000 K and 4.5<log g<9.
- Interpolate Teff and log g measurements through WD evolutionary tracks to estimate its putative WD mass and luminosity.
- Compute heliocentric distances, d, using dereddened apparent SDSS g-band magnitude, g_0, and the absolute magnitude M_g derived from the tracks, $d = 10^{\frac{g_0 - M_g}{5} - 2}$kpc.







2 Data

- Clean ELM WD Sample
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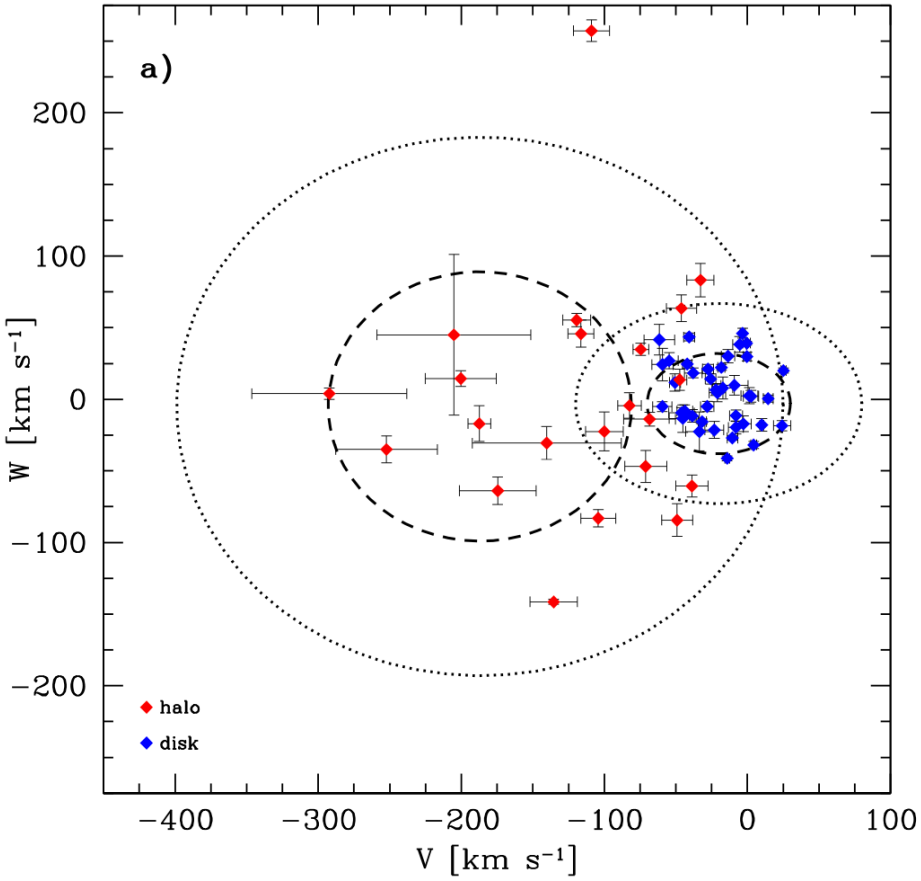
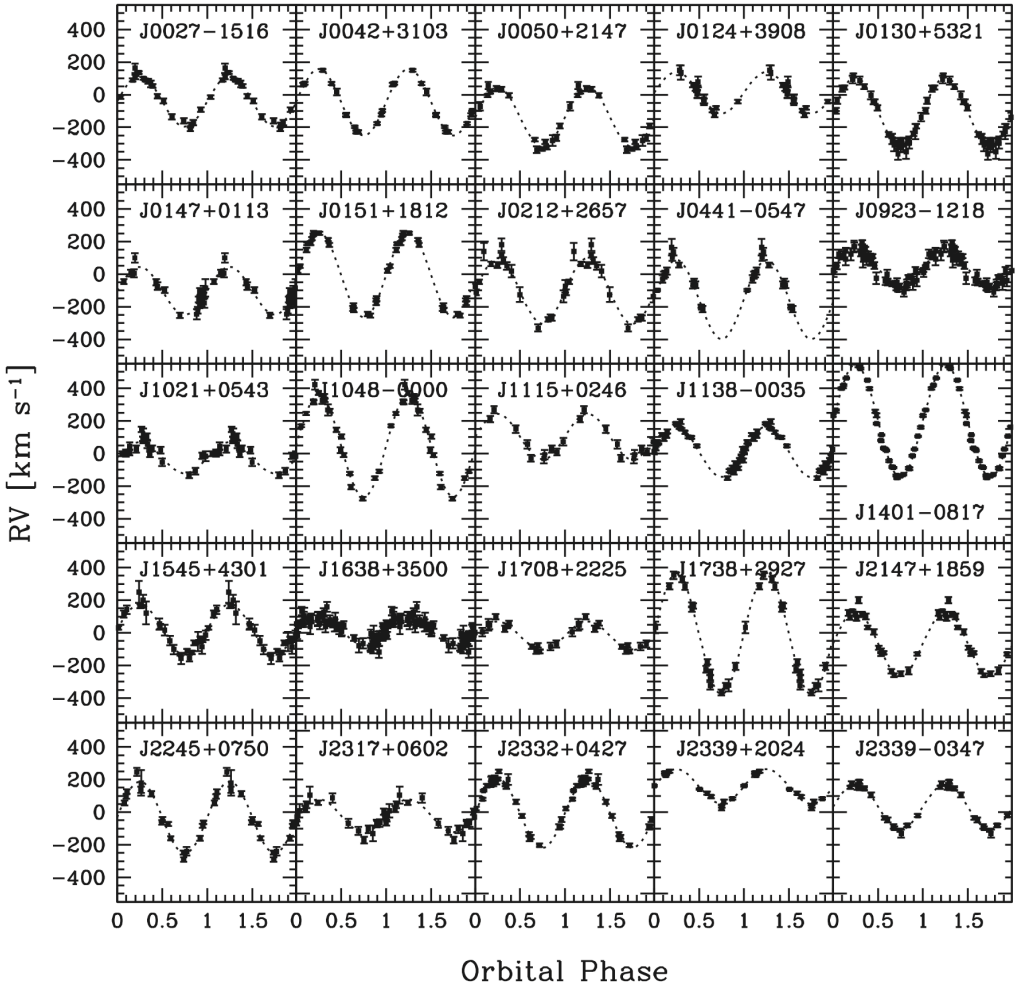
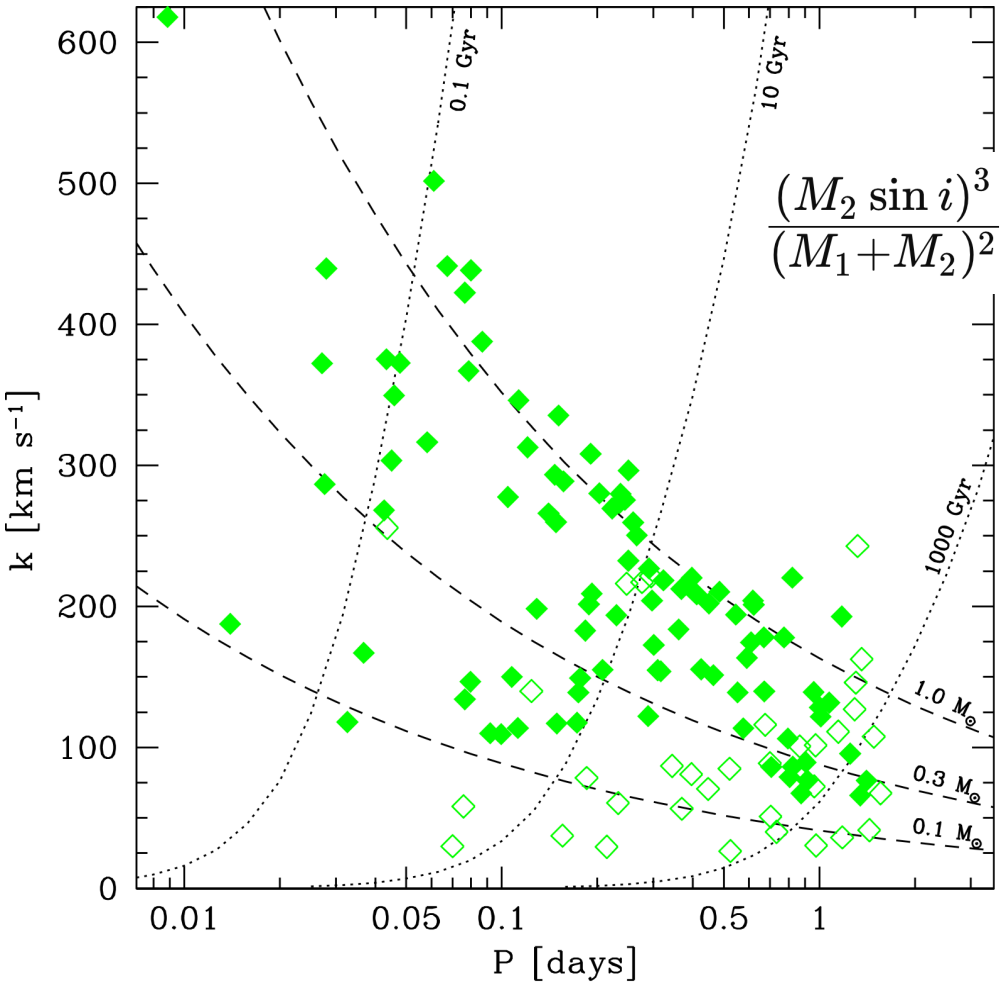
    - π/σ_π>5, Teff>9000K, log g>5.5; 115 sources.
    - Remove one sdB star and four candidates with $\frac{\pi}{\sigma_\pi} > 5$ and distance estimates that differ by more than 3×; 110 sources.
    - Add six candidate WDs with Teff<9000 K or log g<5.5 on the basis of parallax and binary orbital period; 116 sources.
    - Add six candidates with significant K > 100 km s^{-1} orbital motion and short P < 0.27 day periods; 122 sources.
  - ELM WD sample
    - M < 0.3 $M_\odot$; 79 sources.
  - Clean ELM WD sample
    - ELM WDs in the dereddened magnitude range 15< g_0 <20, located in the SDSS footprint, with 8800K<Teff< 22000K and 5.5<log g<7.1; 62 sources.
    - 35% (22/62) halo objects and 65% (40/62) disk objects; statistically identical distributions in the Teff and log g space.



3 Binaries

- 128 binaries in the completed ELM Survey and 98 detached double WD binaries (a circular orbit fit).





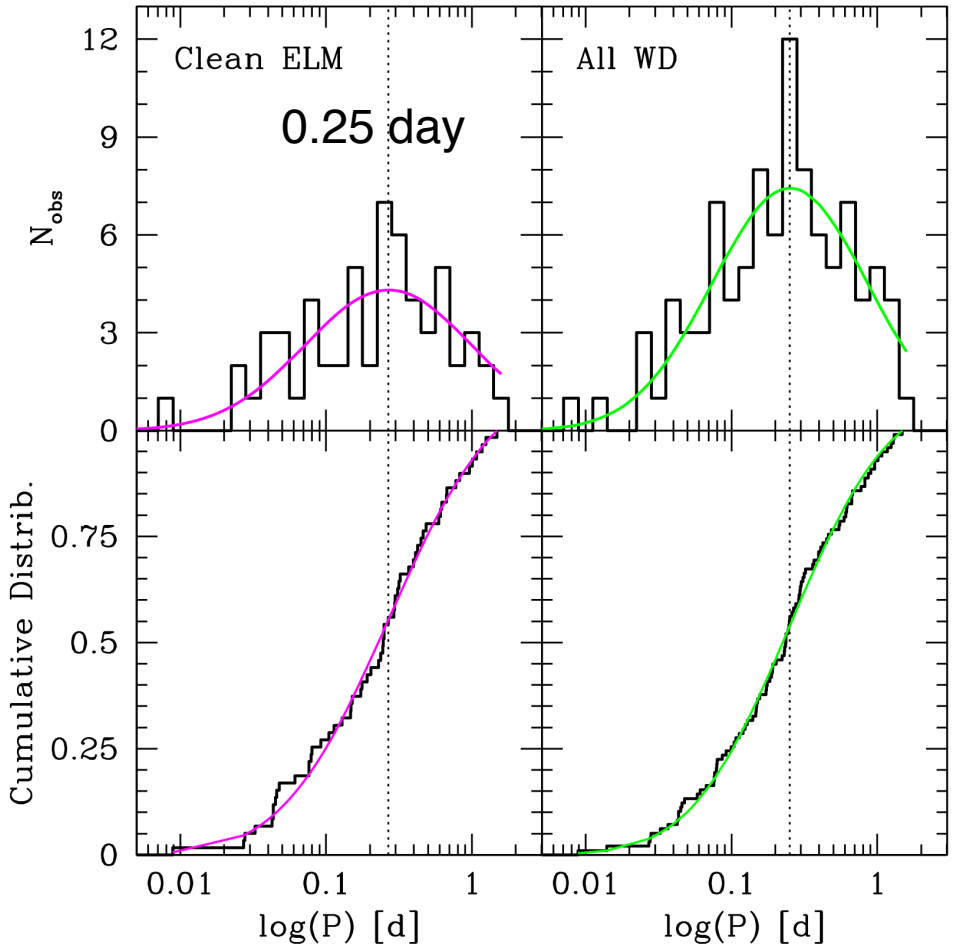
$$\frac{(M_2 \sin i)^3}{(M_1+M_2)^2} = \frac{PK_1^3}{2\pi G}$$

- Using X-ray (Chandra X-ray Observatory) and radio (the Robert C. Byrd Green Bank Telescope) observations to place constraints on the presence of millisecond pulsar companions.
- No neutron star counterparts; The unseen companions are likely WDs.

3 Binaries

➢Orbital Period Distribution

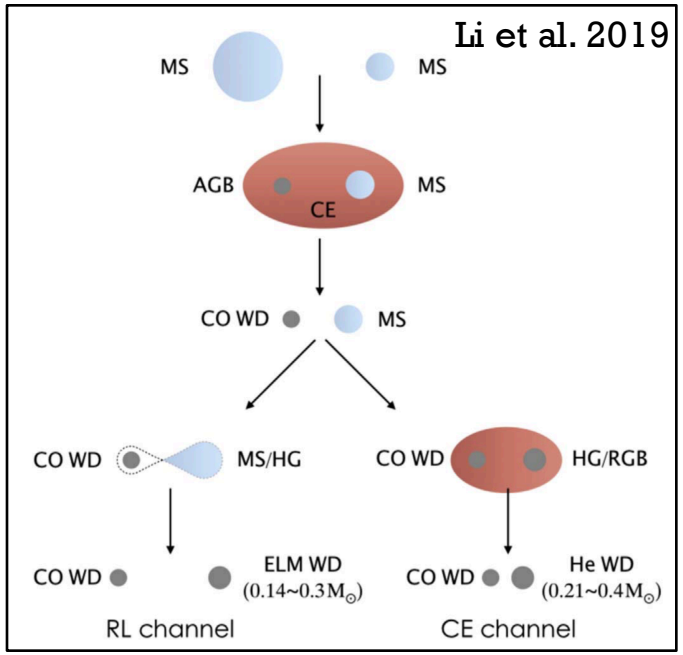
- The observed orbital periods of the ELM Survey range from 0.0089< P<1.5 day and are well described by a lognormal distribution.

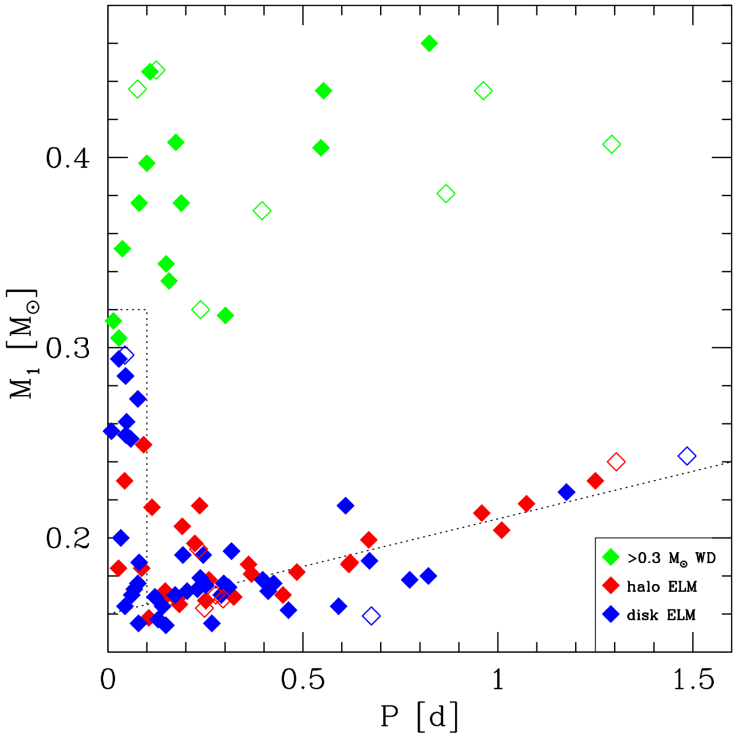


➢ELM WD Binary Fraction

- 95% (59/62) of the clean ELM WD sample are binaries with significant radial velocity orbital motion.
- Higher mass WDs have a much lower binary fraction (Brown et al. 2011a).
- In the SPY survey, the multiplicity of M > 0.45 $M_\odot$ WDs is 4% (23/567) (Napiwotzki et al. 2019), or about 25× lower than the M < 0.3 $M_\odot$ WDs observed here.

➢Mass–Period Distribution: Link to Formation





3 Binaries

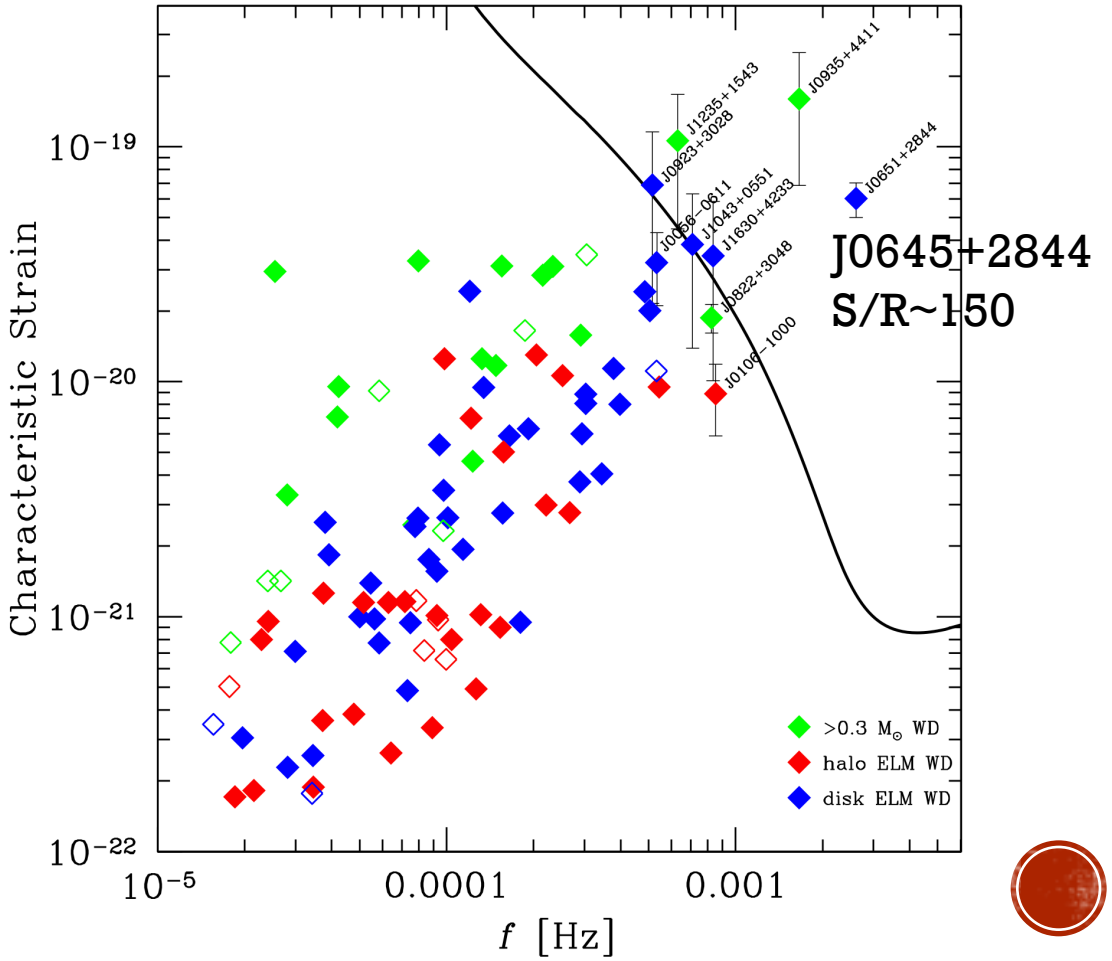
➢He+CO Merger Rate: Link to Outcomes

- ELM WDs are He-core WDs. Their unseen companions are typically 0.75 $M_\odot$ objects at 1.6 $R_\odot$ orbital separations thus CO-core WDs (He + CO WD; mass ratios of about 1:4).
- A 1:4 mass ratio suggests that most binaries will evolve into stable helium mass-transfer systems, so-called AM CVn stars (Marsh et al. 2004).
- The updated merger rate for ELM WD binaries in the disk of the Milky Way is 2×10^{-3} yr^{-1}.
- The merger rate of observed ELM WD binaries exceeds the formation rate of stable mass-transfer AM CVn binaries in the Milky Way (Roelofs et al. 2007b; Carter et al. 2013) by a factor of at least 25.
- The ELM Survey observations thus require unstable mass transfer outcomes and support models in which most He+CO WDs merge (Shen 2015).

➢Gravitational Wave Sources

- White dwarf binaries with P <1 hr emit gravitational waves at millihertz frequencies and are potentially multi-messenger sources.

$$h_c = 3.4 \times 10^{-23}\sqrt{\cos^4(i) + 6\cos^2(i) + 1}\,\mathcal{M}^{5/3}P^{-2/3}d^{-1}$$



4 Conclusions

- The ELM Survey is a major observational program that targeted low-mass, He-core WDs on the basis of magnitude and color in the SDSS footprint.
- 230 sources have 4338 radial velocity measurements, 230 stellar atmosphere fits and 128 radial velocity orbital solutions.
- The ELM Survey contains a total of 98 WD+WD binaries, more than half of the known detached double WD binaries in the Milky Way.
- 35% of the binaries are halo objects on the basis of 3D space motions.
- Their orbital periods span $0.0089 < P < 1.5$ day and are correlated with He WD mass, providing evidence for both stable Roche-lobe and unstable common-envelope formation channels.
- The merger rate is 25 times higher than the formation rate of stable mass-transfer AM CVn binaries, thus our observations require unstable mass-transfer outcomes for He+CO WD binary mergers (Shen 2015; Brown et al. 2016b).
- The observed binaries notably emit gravitational waves at mHz frequencies. Two ELM Survey discoveries, J0651+2844 and J0935+4411, will be detected at high S/N by the future LISA mission.

THANKS