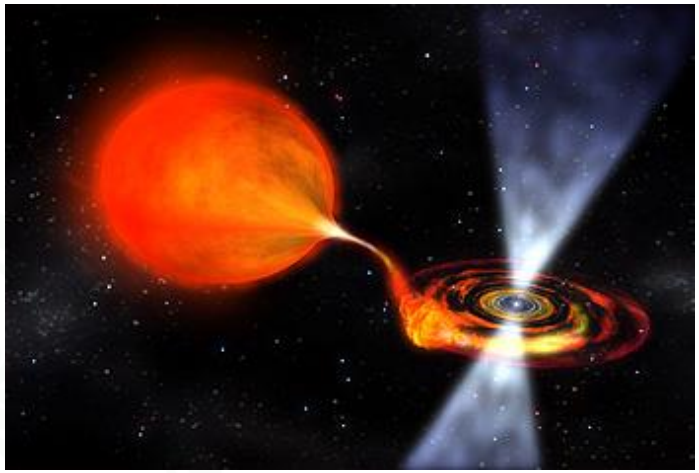
A multi-wavelength search for new pulsar candidates in compact binaries



P. H. Thomas Tam

Materials mostly based on the PhD thesis of Dr. Wenjun Huang and Dr. Chun-Yan Lu

Liangliang Ren, Jiamao Lin

FAST/Future Pulsar Symposium
2025/7/6

Searching for MSPs in binaries

- Companion starlight distorted by the suspected NS ->**optical photometry**
- Focusing on two kinds of such binaries:

1. Compact MSP binaries, or spiders *(emit γ-rays, part 1, Lu, C. Y., et al. 2025, ApJ, 978, 106)*

2. Extremely low-mass WDs, or ELM WDs *(must have a companion, part 2, Huang W. J., et al. 2025, ApJ, 980, 46)*

The formation of millisecond pulsars

- They have been rejuvenated by a "spin-up process" involving the accumulation of matter from a companion star (e.g., Alpar+1982)
- Transfer of angular momentum
- Spider systems (redbacks + black widows) may be related to the final stage of MSP formation

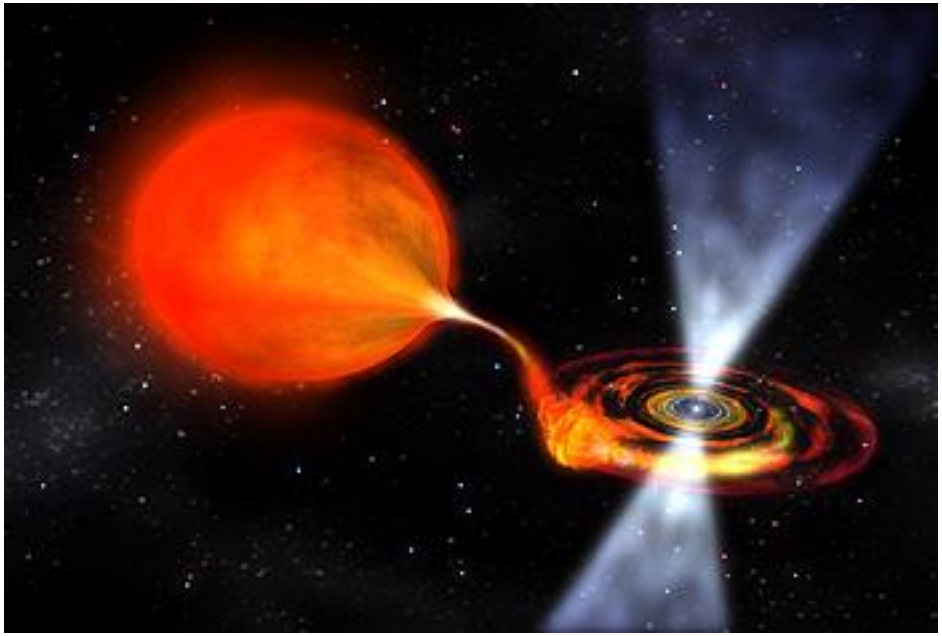
letters to nature

Nature **300**, 728 - 730 (23 December 1982); doi:10.1038/300728a0

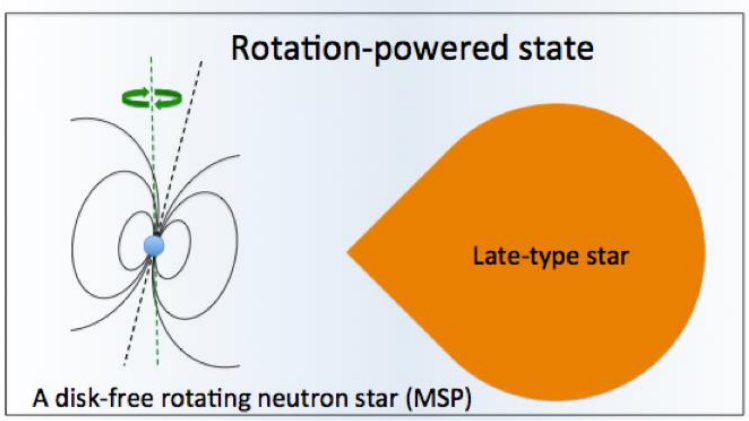
A new class of radio pulsars

M. A. ALPAR*, A. F. CHENG†, M. A. RUDERMAN* & J. SHAHAM*‡

*Departments of Physics and Astronomy, Columbia Astrophysics Laboratory, 538 W. 120
†Department of Physics and Astronomy, Rutgers University, Frelinghuysen Rd, Piscataway
‡Permanent address: Racah Institute of Physics, Hebrew University, Jerusalem, Israel.



Redback pulsars



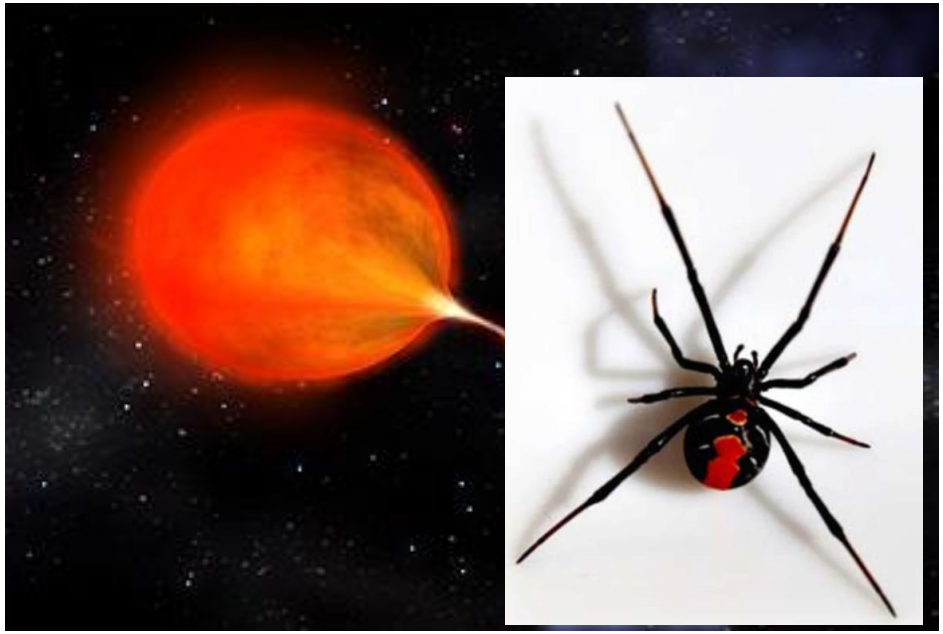
0.1 M_{sun} <M<1.0 M_{sun}: redbacks (non-degenerate companion)



Redback pulsars are heavy

- Long-term "spin-up process", accumulating up to 0.27M_{sun} matter from a companion star (e.g., Li 2021)
- Transfer of angular momentum & mass



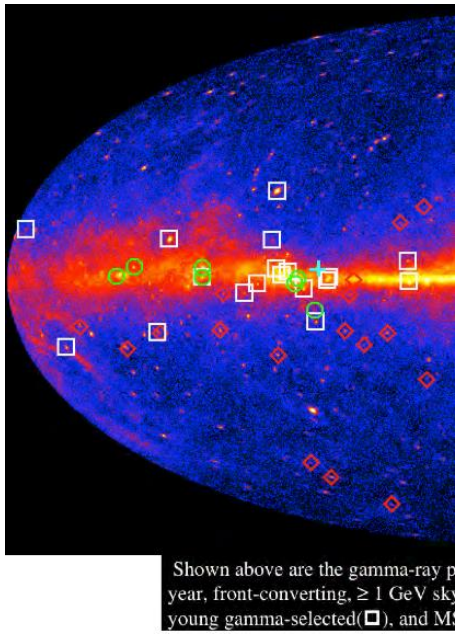


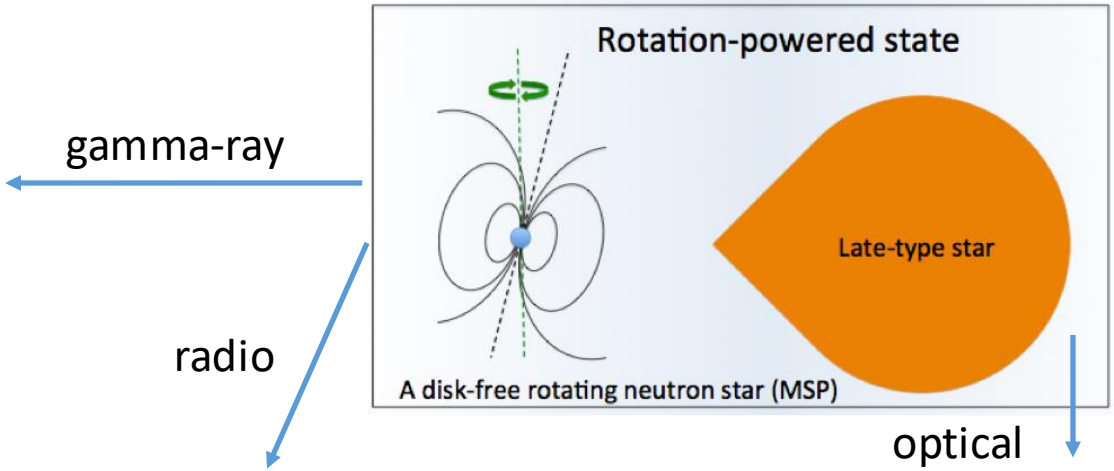
mass, hydrogen-rich companions are discussed in the context of the 14 confirmed and 10 candidate field redbacks. We find that the neutron stars in redbacks have a median mass of 1.78 ± 0.09 $M_\odot$ with a dispersion of $\sigma = 0.21 \pm 0.09$. Neutron stars with masses in excess of 2 $M_\odot$ are consistent with, but not firmly demanded by,

How to detect more redbacks?

1) detecting the pulsar - radio, gamma-ray surveys

2) detecting the companion - **optical**

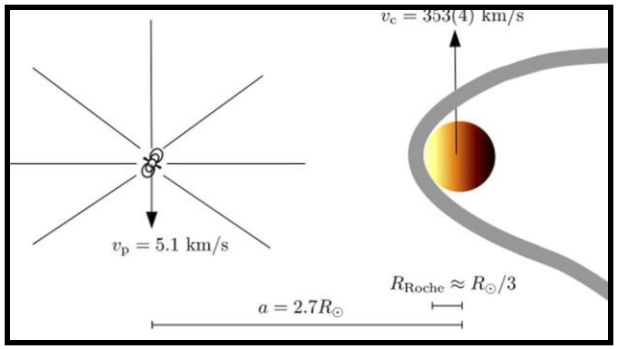


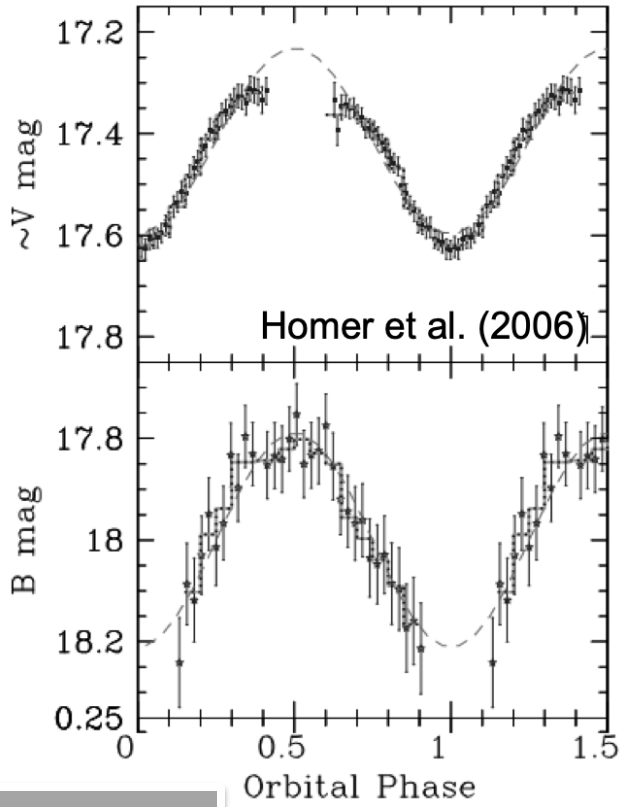






Orbital modulation in *optical*:
1. pulsar irradiation





PSR J1023+0038

2. ellipsoidal variation (EV)

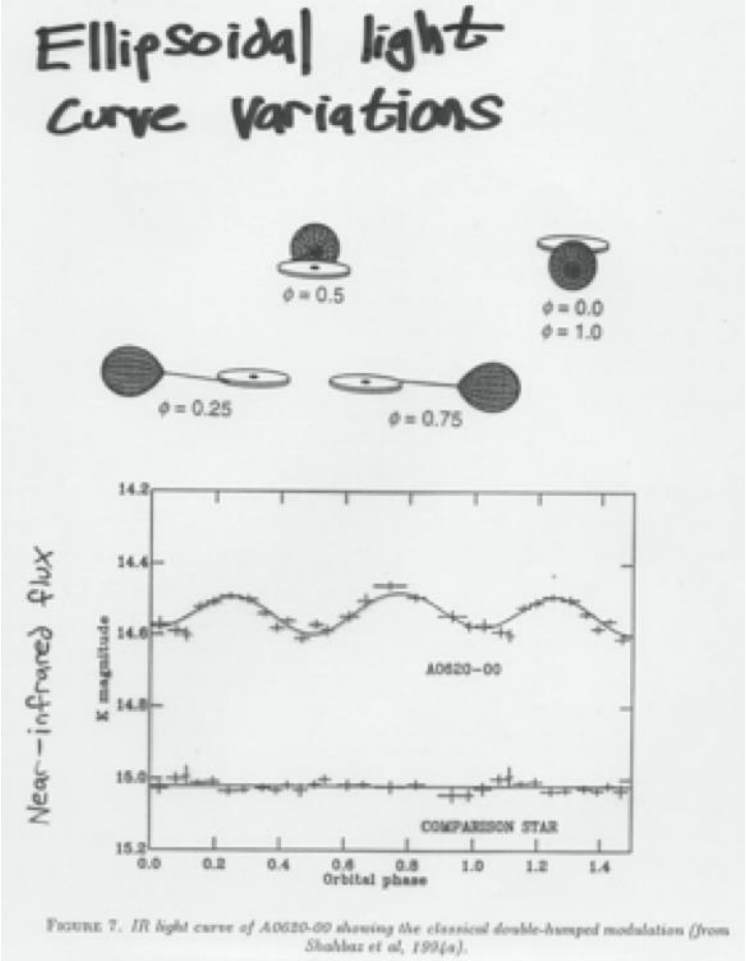
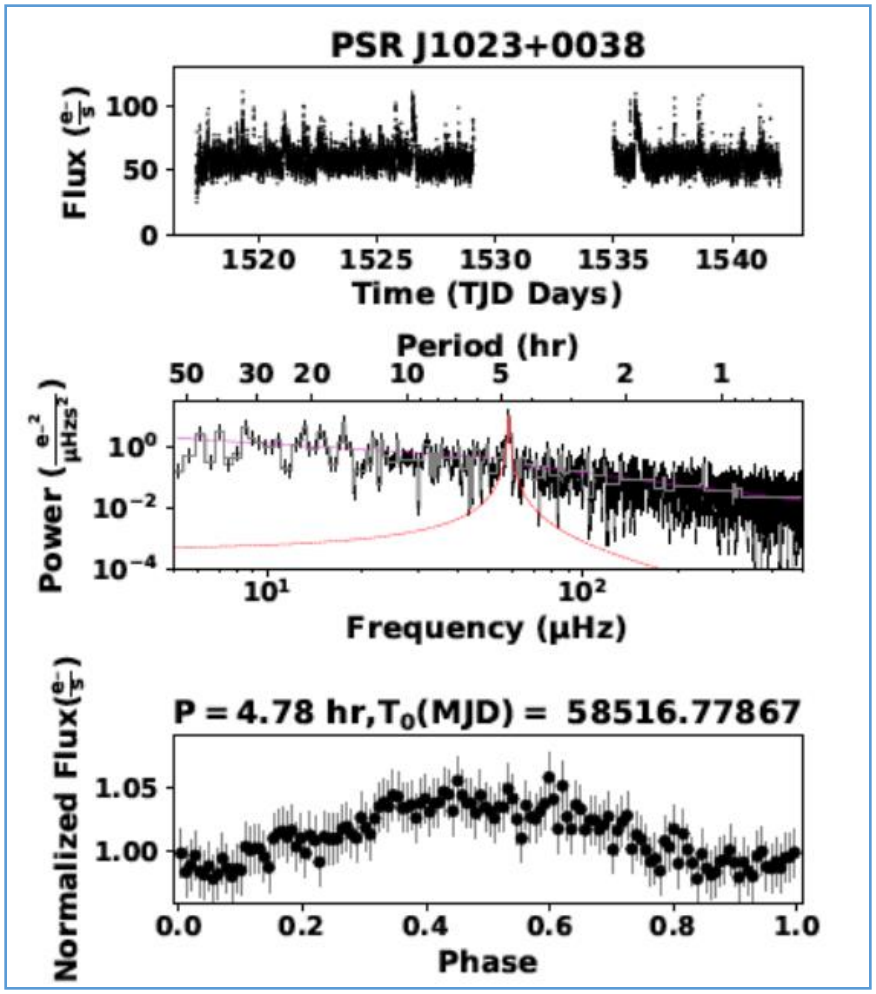


FIGURE 7. IR light curve of A0620-00 showing the classical double-humped modulation (from Shahbaz et al, 1994a).

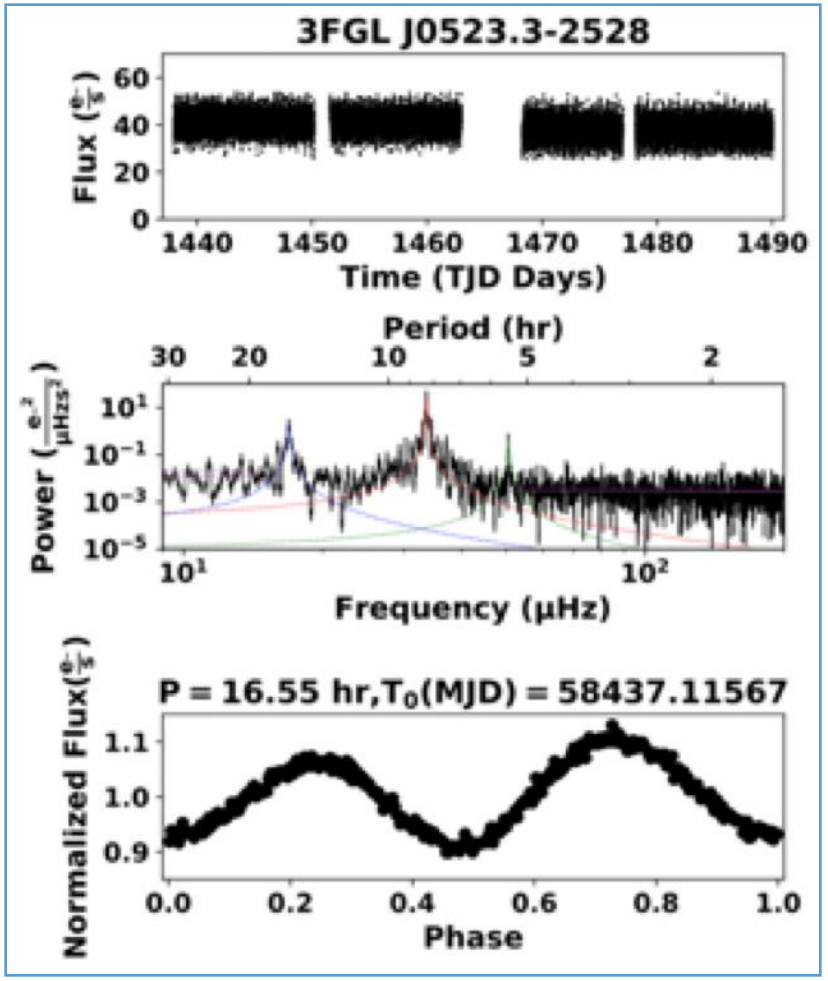
Confirming orbital periods in known redback systems



pulsar irradiation type



EV type



Pal et al. (2020)

Methodology: cross-matching Fermi sources with ZTF sources with periodic signal

- **ZTF DR10 are public database with lots of photometric data in 3 bands：**

- **Fermi-LAT fourth source catalog (4FGL) cross-match with ZTF Data**

(4FGL-DR3 over 2157 gamma-ray sources are without definitive associations at other wavelengths)

In which 751 are covered by ZTF survey (better angular resolution than TESS w/ color info).



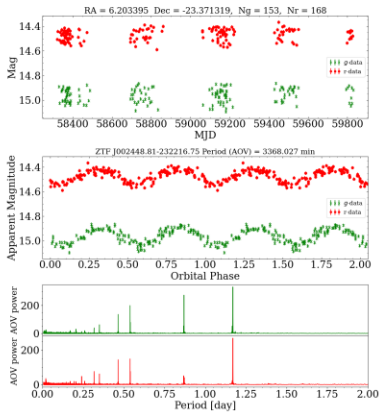
Zwicky Transient Facility (ZTF)

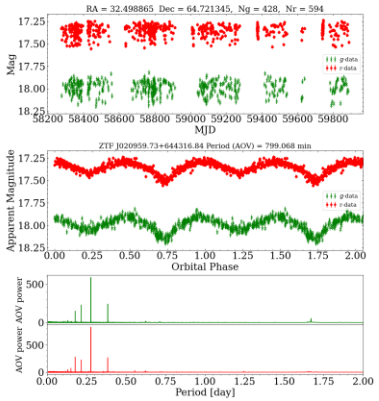
- ✓ $\delta > -28^\circ$
- ✓ 30s exposures
- ✓ scans the entire Northern sky every two days.
- ✓ multi-filter
  - 20.8 Mag in g-band
  - 20.6 Mag in r-band
  - 20.2 Mag in i-band

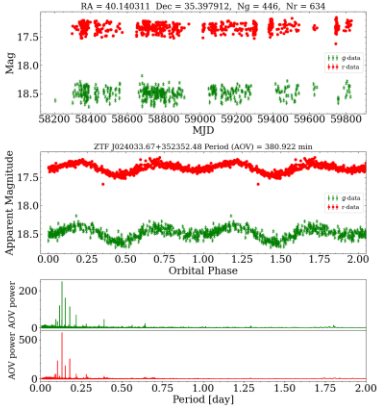
https://www.ztf.caltech.edu/

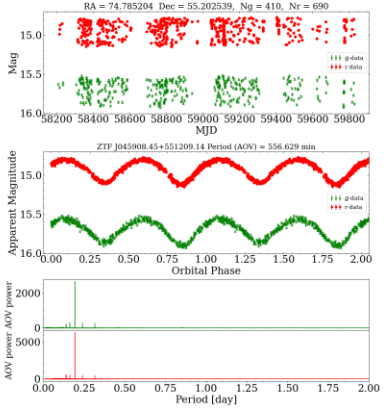
48 inch Samuel Oschin Schmidt telescope at Palomar Observatory

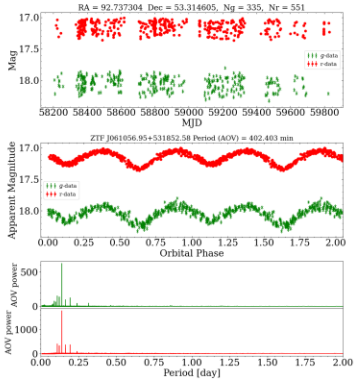
☐ Within 6’ from that 751 4FGL positions, we found 194 EV-type binaries, examples are shown below:

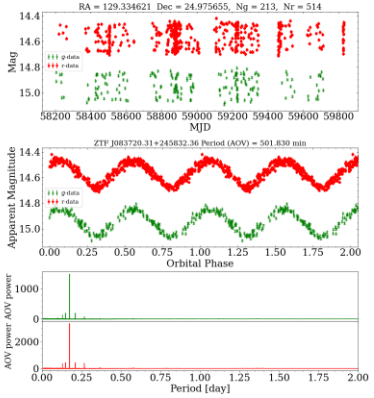


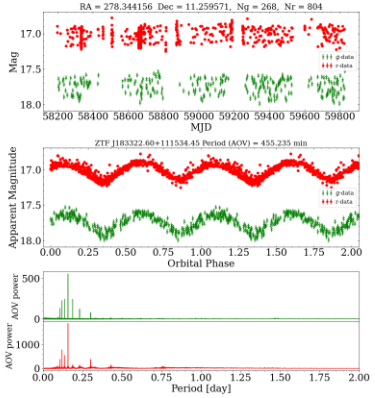


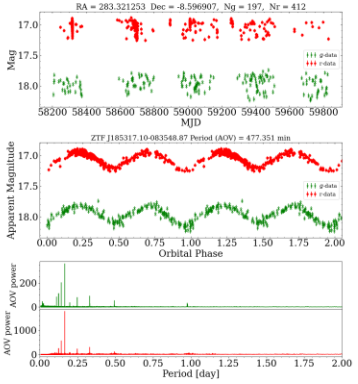








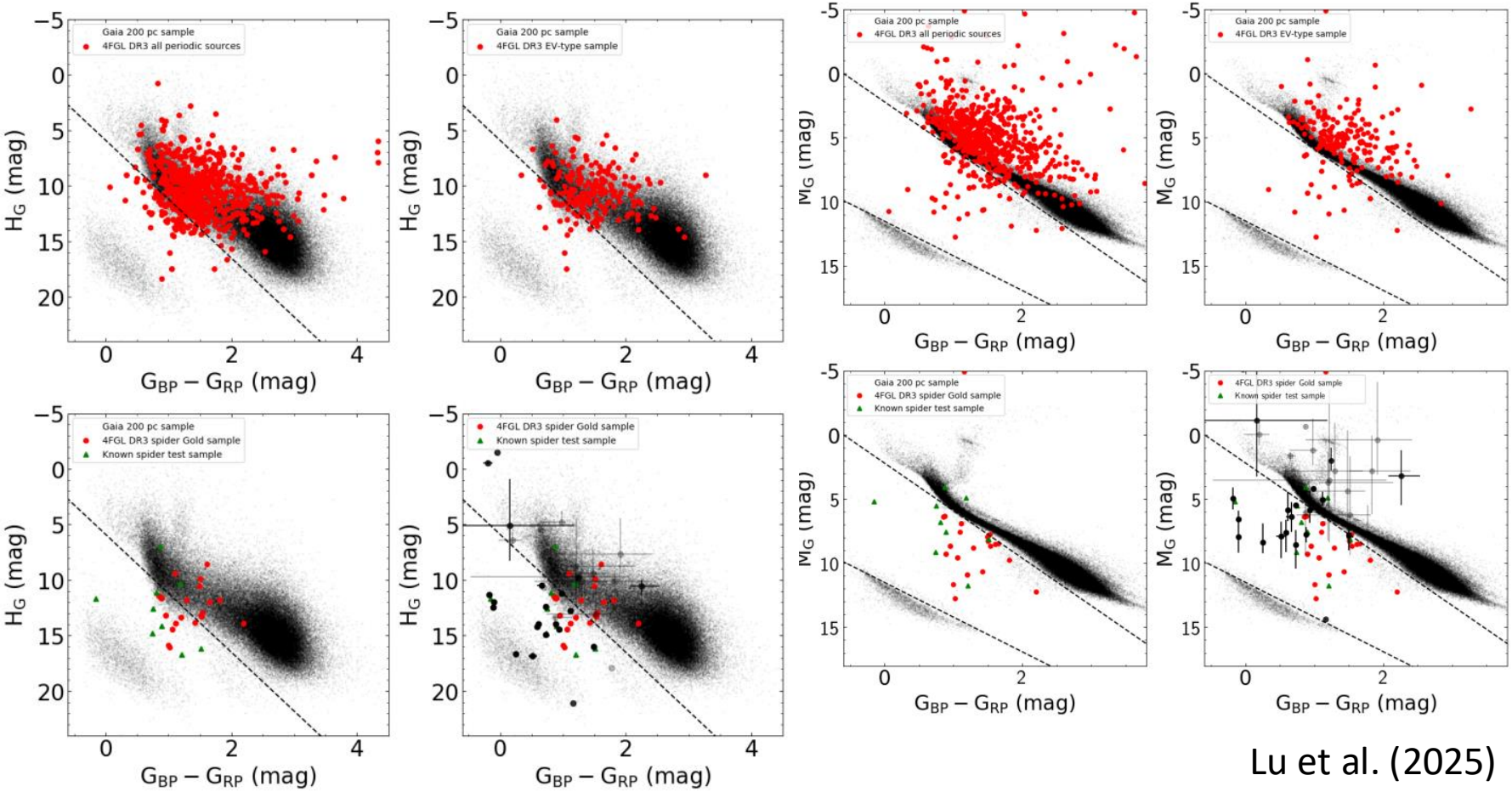




Lu et al. (2025)

GAIA colors

- **Imposing their anticipated positions in Gaia Hertzsprung-Russell diagram, we got 24 candidates**



Lu et al. (2025)

List of candidates (24)

We proposed FAST observations of some of the above in 2025

FAST Proposal Coverpage

NO: SQB-2025-0173

Proposal Title:

A Radio Search for Spider Pulsar Candidates with Optical Ellipsoidal Variations Associated with Unidentified Fermi Sources

Source_Name	Observing_Mode	Int_Time(s)	Repeats	RA/Start_DEC/TargetNumber	DEC/End_DEC	Freq.
J1813+2820	Tracking	1200	2	18:13:26.28	+28:20:07.9	
J1853-0842	Tracking	1200	2	18:53:17.08	-08:42:44.4	
J1901-0716	Tracking	1200	2	19:01:56.11	-07:16:51.0	
J2032-0717	Tracking	1200	2	20:32:08.23	-07:17:15.5	
J1934+1040	Tracking	1200	2	19:34:03.35	+10:40:02.2	
J2118+3727	Tracking	1200	2	21:18:10.17	+37:27:25.7	
J2117+3726	Tracking	1200	2	21:17:56.34	+37:26:44.8	

4FGL J2032.3-0720	ZTF J2032-0717	6907532096123807104	308.034276	-7.287635	2.9681	16.914207	0.89426	506.917
4FGL J2144.2+7709	ZTF J2144+7714	2283760245882786560	326.211604	77.243606	15.65	18.33	0.81	324.686
4FGL J0336.0+7502[a]	ZTF J0336+7503	544927450310303104	54.042790	75.054776	0.8516	20.615477	1.0510998	223.091
4FGL J1838.2+3223[b]	ZTF J1838+3224	2090923983890463104	279.570111	32.4031872	1.6056	20.60957	0.9992714	241.493

Lu et al. (2025)

Summary:

- We search for optical sources in circles of 6’ in 4FGL unknown sources, with ellipsoidal variables or Irradiation-type characteristics, and found 194.
- Imposing their positions in Gaia H-R diagram, 24 remains.
- 19 are within 4FGL 95% c.l. error ellipses
- Further imposing positions in Gaia color-reduced proper motion diagram, we finally got 9 ‘gold sample’ candidates

To do’s:

- SED fitting, light curve fitting can tell us more about the binary parameters
- Use X-rays, radio, and optical (e.g., radial velocity) measurements will reveal their true nature

A Search for Radio Millisecond Pulsar Companions around Extremely Low-mass White Dwarfs with Ellipsoidal Variability

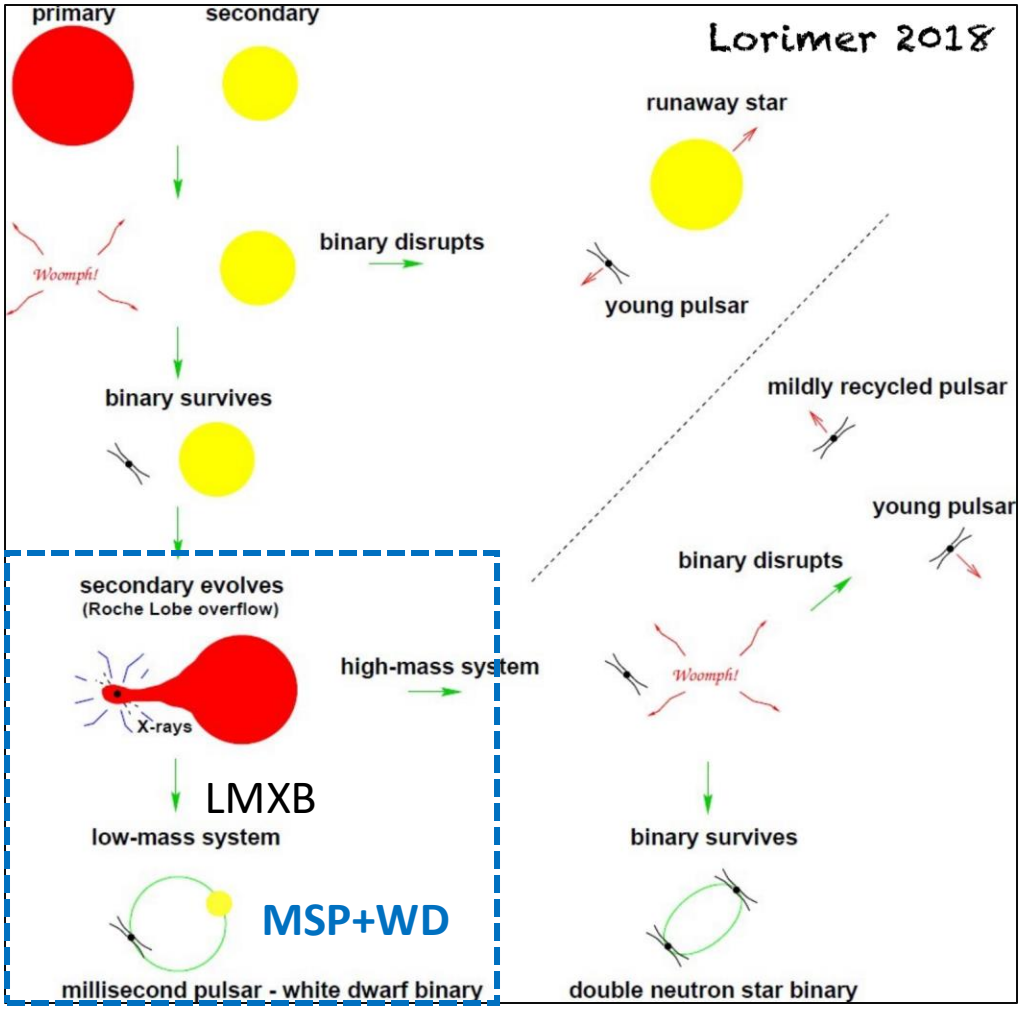
Wenjun Huang
黄文俊

Huang W. J., et al. 2025, ApJ, 980, 46



Pulsar Binary

- MSPs are recycled pulsars that accrete mass and transfer angular momentum from their companions, while most of the donors eventually become (low-mass He) **WD**s.

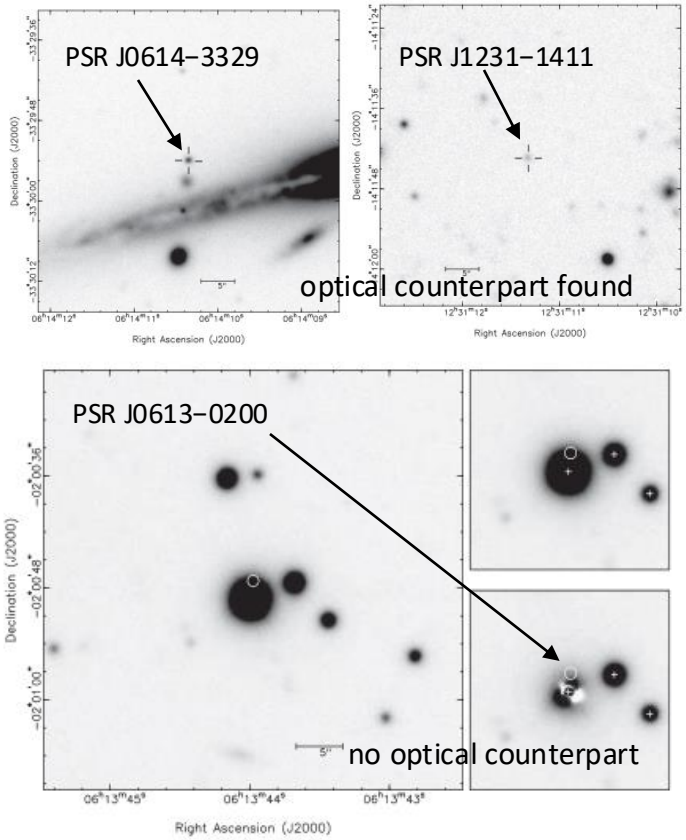


Search for MSP/WD Systems

- 214 MSP/WDs in ATNF Pulsar Catalog, and a few have optically identified companions ;
- Finding optical counterparts of MSP/WDs is important: constrain pulsar mass, age or distance.

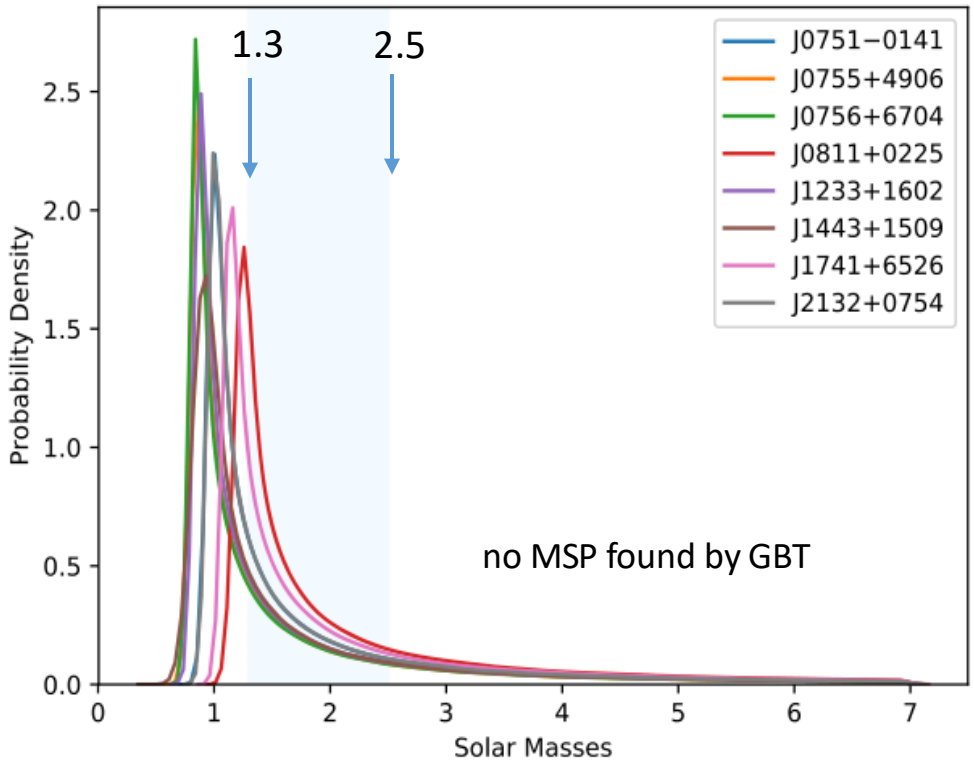
How can we find more optically visible MSP/WD systems?

Search for optical counterparts for known MSPs



(Bassa et al. 2016)

Search for MSP around low-mass WDs



PDF for the companion mass

(Athanasiadis et al. 2021)

Extremely Low-Mass (ELM) WDs

- **Extremely Low Mass White Dwarfs** (ELM WDs, He-core white dwarfs < 0.3 $M_{\odot}$)
  - ELM WDs can only be formed within close binary system:
    - Common Envelope ejection (CE)
    - stable Roche Lobe overflow (RL)
  - ELM survey discovered about 150 low mass WDs (Kosakowski et al. 2023);
  - Short-period WD binaries (<1 h) may emit detectable GW at mHz frequencies.

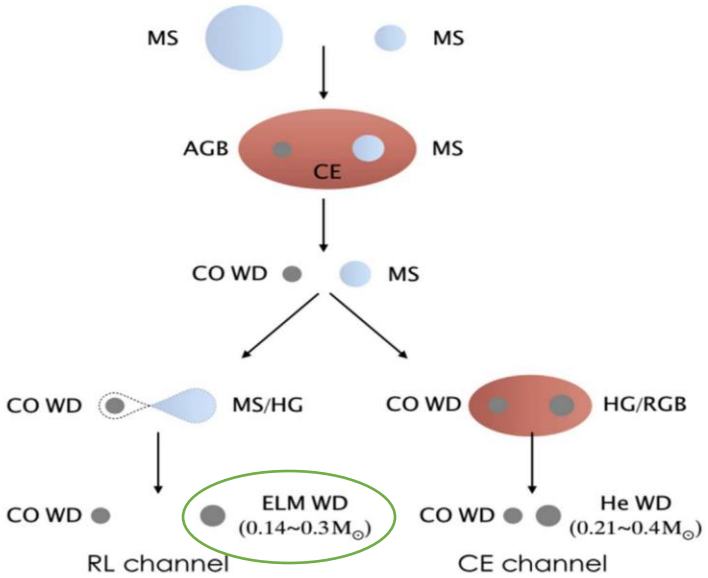
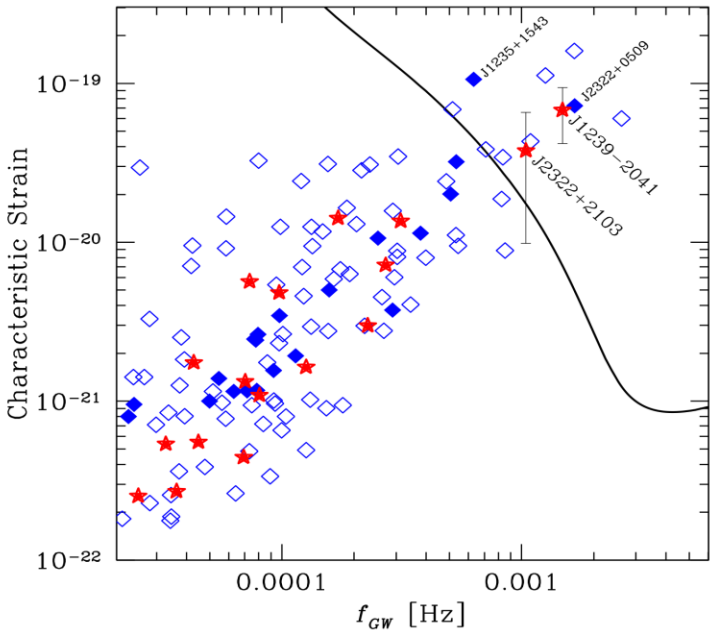


Figure 2. Sketch map for the formation of DDs with ELM WDs. MS—main sequence, AGB—asymptotic giant branch, CE—common envelope, HG—Hertzsprung gap, RGB—red giant branch.

(Li et al. 2019)

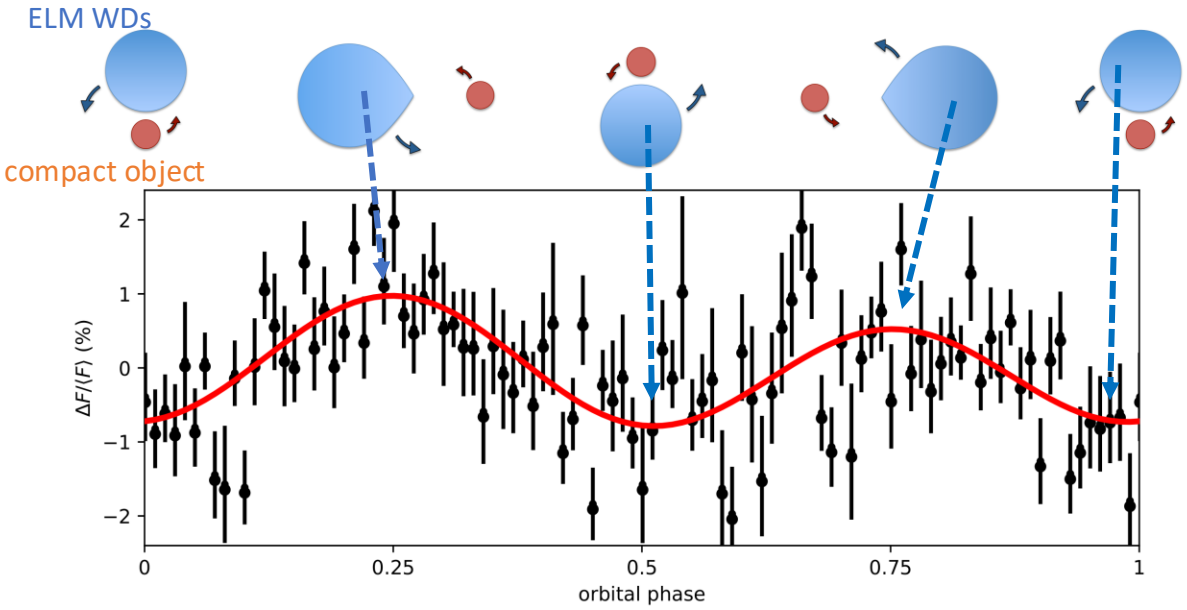


(Brown et al. 2022)

Ellipsoidal (ELL) Lightcurve of ELM WDs

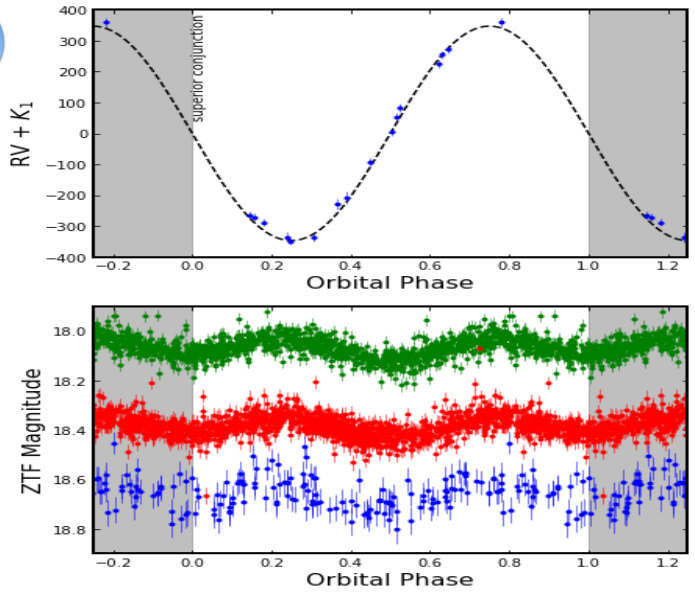
- Why select ELM WDs to search for MSPs:
  - ELM WDs are larger and brighter than typical WDs. → optically visible;
  - Low-mass white dwarfs in tight binaries can be tidally distorted by their more massive companions, either MSPs or CO WDs. → ELL-type lightcurve.

Motivation: searching for ELM WDs with ellipsoidal variability can provide one of clues for finding potential MSPs.



Ellipsoidal (ELL-type) lightcurve

PSR J1816+4510/proto-ELM WD



(Huang et al. in prep.)

Target Selection

- Select targets:
  - 6823 ELM WD candidates from Gaia EDR3 (Gentile Fusillo et al. 2021);
    mass_H < 0.3 & mass_He < 0.3 & mass_mixed < 0.3 & Pwd > 0.75
  - 5762 ELM WD candidates based on Gaia DR2 (Pelisoli & Vos 2019);
  - 119 known ELM WDs from ELM Survey.
- Query lightcurve data from ZTF-DR15 for the above ~12,000 ELM WDs or their candidates;
- Using LS algorithm to search for period between 5 min—1 day;



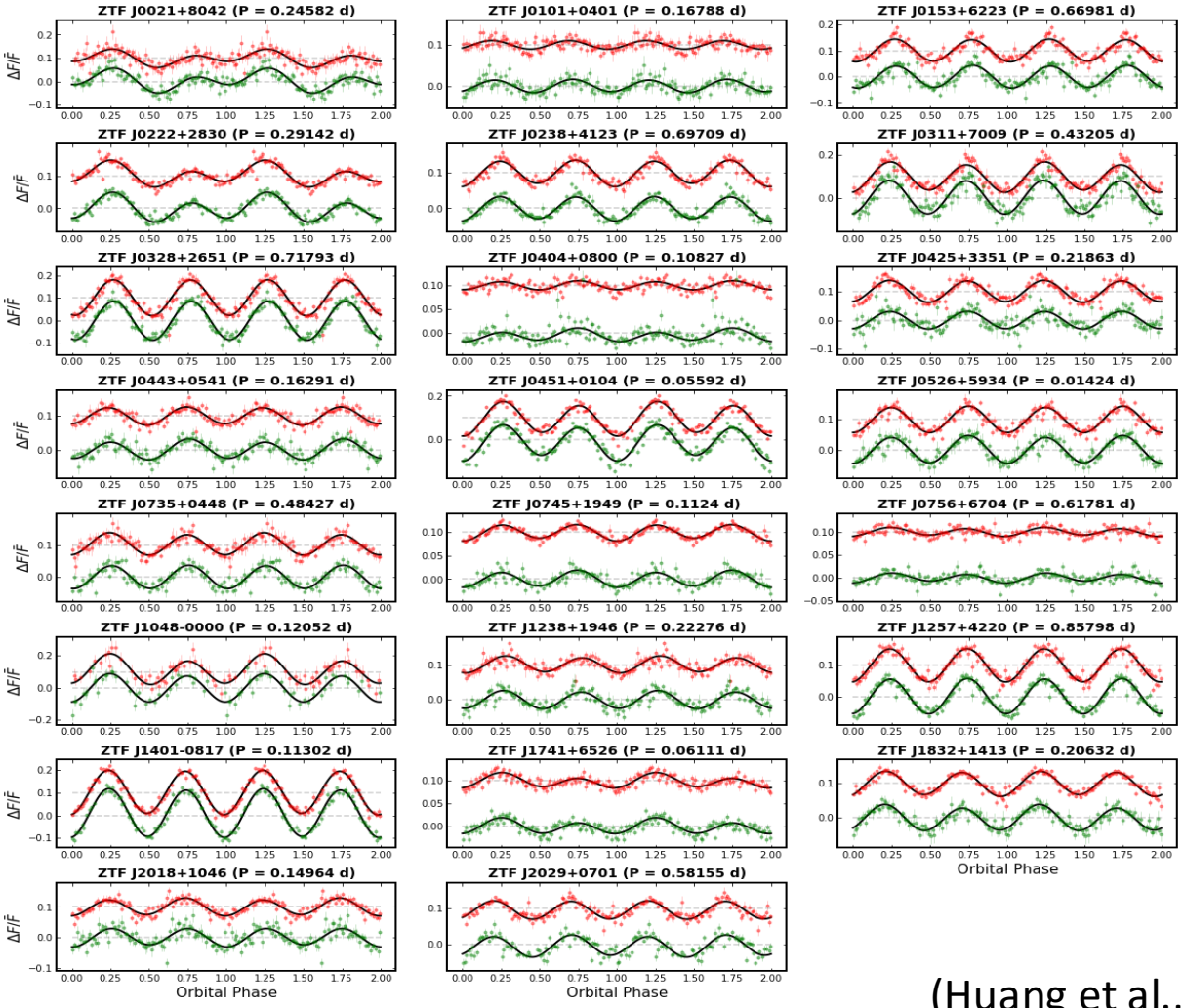
Zwicky Transient Facility (ZTF)

- ✓ $\delta > -28^{\circ}$
- ✓ 30s exposures
- ✓ scans the entire Northern sky every two days.
- ✓ multi-filter
  - 20.8 Mag in g-band
  - 20.6 Mag in r-band
  - 20.2 Mag in i-band

48 inch Samuel Oschin Schmidt telescope at Palomar Observatory

Light curves of ellipsoidal (ELL) -type

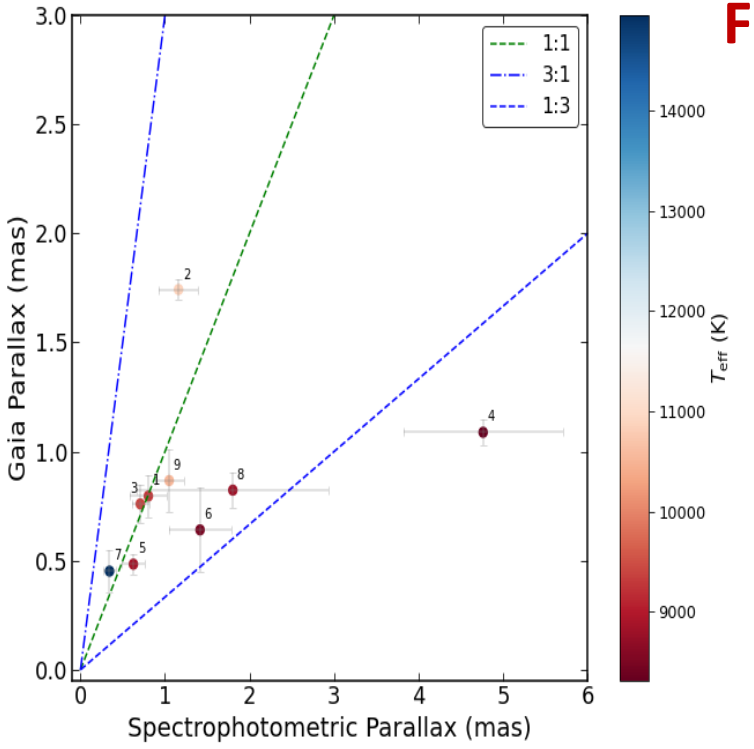
- ELL-type binaries: similar peak-to-peak amplitude in ZTF g-band and r-band lightcurves.
- We obtained 23 ELL-type ELM WDs or candidates, and 17 of them are newly discovered.



(Huang et al., 2025)

High-priority ELM WDs

- Select High priority ELM WDs:
  - $8000\ \mathrm{K} < T_{\mathrm{eff}} < 25000\ \mathrm{K}, 5 < \log g < 7 \Rightarrow M_{WD} < 0.3\ M_{\odot}$
  - Spectrophotometric parallax (π_{spec}) estimates agreed with Gaia parallax within a factor of three.



Finally we obtain 9 high-priority ELM WDs.

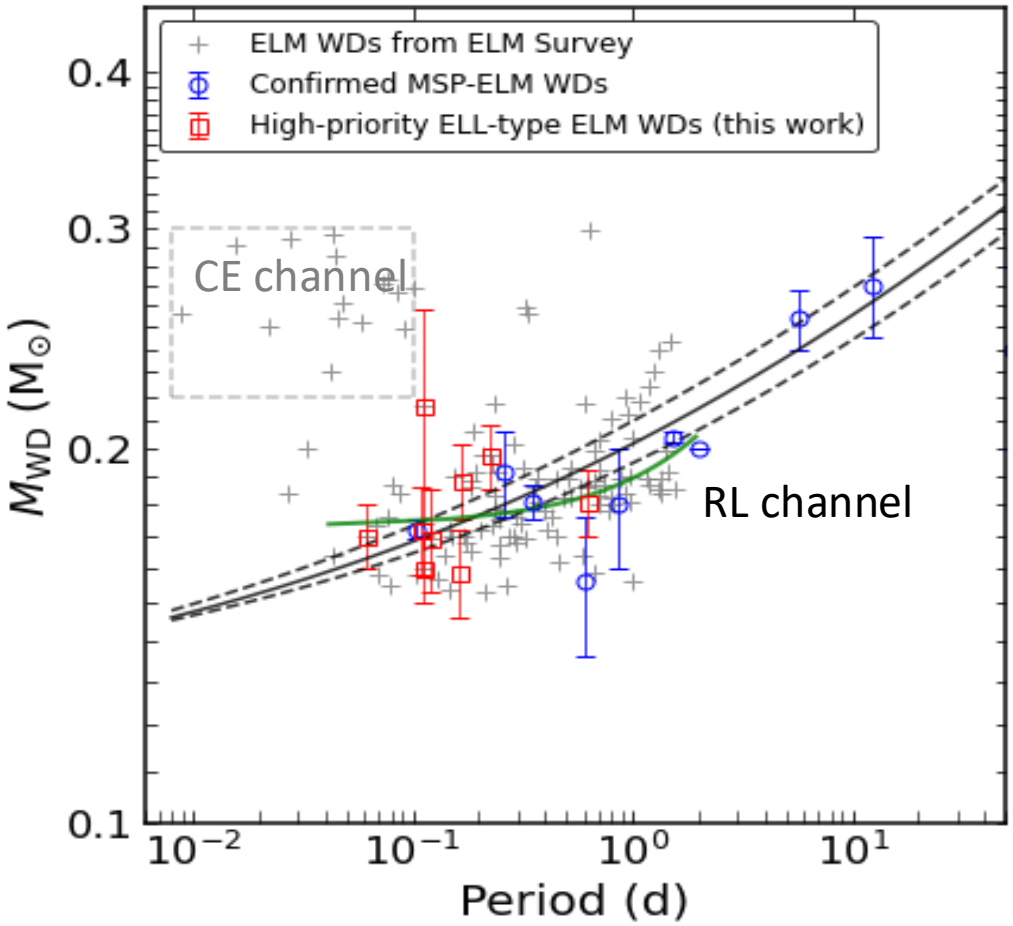
Table 2. The Measured and Derived Parameters of the 9 High-priority ELM WDs

	Name	RA (hh:mm:ss.ss)	DEC (dd:mm:ss.s)	T_{eff} (K)	$\log g_1$ (cm s^{-2})	M_1 ($M_{\odot}$)	$\mathrm{Parallax_{Gaia}}$ (mas)	$\mathrm{Parallax_{spec}}$ (mas)	$\mathrm{Distance_{spec}}$ (kpc)
1	ZTF J0101+0401	01:01:28.69	+04:01:59.0	9284^{+120}_{-120}	$5.229^{+0.089}_{-0.089}$	0.188 ± 0.013	0.796±0.098	0.803±0.222	1.245±0.321
2	ZTF J0404+0800	04:04:18.39	+08:00:02.9	10860^{+120}_{-120}	$4.985^{+0.121}_{-0.121}$	0.172 ± 0.014	1.742±0.044	1.160±0.229	0.862±0.177
3	ZTF J0443+0541	04:43:02.66	+05:41:17.0	9390^{+140}_{-140}	$4.998^{+0.097}_{-0.097}$	0.159 ± 0.013	0.760±0.085	0.708±0.104	1.413±0.211
4	ZTF J0745+1949	07:45:11.56	+19:49:26.6	8313^{+100}_{-100}	$6.151^{+0.074}_{-0.074}$	0.160 ± 0.010	1.088±0.059	4.762±0.941	0.210±0.040
5	ZTF J0756+6704	07:56:10.73	+67:04:24.4	11640^{+250}_{-250}	$4.90^{+0.14}_{-0.14}$	0.181 ± 0.011	0.484±0.046	0.626±0.141	1.597±0.343
6	ZTF J1048-0000	10:48:26.86	-00:00:56.8	8484^{+90}_{-90}	$5.831^{+0.051}_{-0.051}$	0.169 ± 0.016	0.641±0.195	1.414±0.373	0.707±0.175
7	ZTF J1238+1946	12:38:00.08	+19:46:31.1	14950^{+420}_{-420}	$4.890^{+0.050}_{-0.050}$	0.197 ± 0.012	0.452±0.099	0.344±0.072	2.908±0.583
8	ZTF J1401-0817	14:01:18.80	-08:17:23.5	8813^{+90}_{-90}	$5.731^{+0.048}_{-0.048}$	0.216 ± 0.042	0.823±0.079	1.802±1.135	0.555±0.268
9	ZTF J1741+6526	17:41:40.49	+65:26:38.6	10540^{+170}_{-170}	$6.000^{+0.060}_{-0.060}$	0.170 ± 0.010	0.867±0.143	1.049±0.171	0.953±0.151

(Huang et al., 2025)

$M_{WD} - P$ diagram

- The mass-period diagram provides a clear reflection of the formation channel (RL or CE);
- ELM WDs with MSPs are formed via the RL channel;
- Our 9 high-priority ELM WDs follow the RL channel.



Black lines: theoretical relationship between WD mass and orbital period for MSP/WDs:

$$\frac{M_{\rm WD}}{M_\odot} = \left(\frac{P_{\rm orb}}{b}\right)^{1/a} + c$$

$$(a,b,c) = \begin{cases} 4.50 & 1.2\times10^{5} & 0.120 & \text{Pop.I} \\ 4.75 & 1.1\times10^{5} & 0.115 & \text{Pop.I+II} \\ 5.00 & 1.0\times10^{5} & 0.110 & \text{Pop.II} \end{cases}$$

(Tauris & Savonije 1999)

Estimate M_2 from Ellipsoidal Amplitude

- Extract the ellipsoidal amplitude from lightcurve fitting by using five-parameters model:

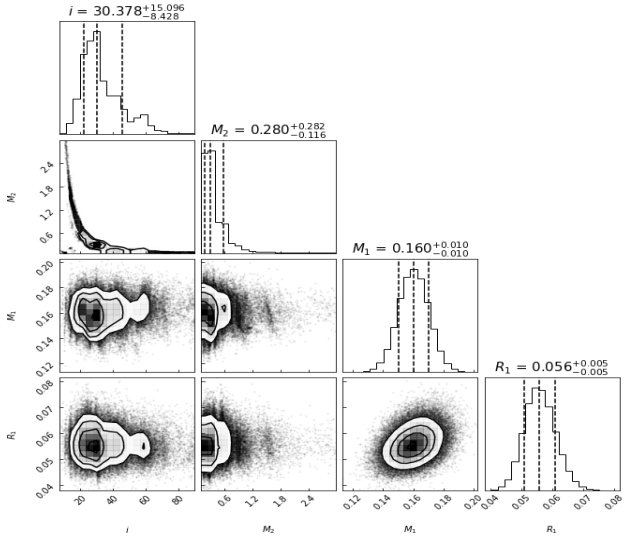
$$\Delta F/F = A_{\rm EV}\cos 2\phi + A_{\rm DB}\sin\phi + A_{\rm REF}\cos\phi + B\sin 2\phi + C$$

Ellipsoidal Doppler beaming Reflection/ irradiation

$$A_{\rm EV} = \frac{3\pi^2(15+u_1)(1+\tau_1)M_2R_1^3\sin^2 i}{5P_{\rm orb}^2(3-u_1)GM_1(M_1+M_2)}$$

$$f_1(M_2) = \frac{P_{\rm orb}K_1^3}{2\pi G} = \frac{M_2^3\sin^3 i}{(M_1+M_2)^2}$$

two unknowns:
- companion mass M_2
- inclination angle i.



MC results of J0745+1949.

4 candidates have $M_2 > 1M_\odot$

Jname	M_1 $(M_\odot)$	R_1 $(R_\odot)$	M_2 $(M_\odot)$	i $(^\circ)$	$A_{\rm EV}$ (%)
ZTF J0101+0401	$0.193^{+0.011}_{-0.011}$	$0.191^{+0.013}_{-0.014}$	$0.635^{+0.987}_{-0.233}$	$47.049^{+23.971}_{-17.740}$	1.32(16)
ZTF J0404+0800	$0.172^{+0.014}_{-0.014}$	$0.222^{+0.034}_{-0.030}$	$0.027^{+0.044}_{-0.013}$	$61.829^{+19.544}_{-24.274}$	1.11(09)
ZTF J0443+0541	$0.160^{+0.013}_{-0.013}$	$0.224^{+0.023}_{-0.018}$	$0.421^{+0.697}_{-0.227}$	$74.819^{+10.491}_{-13.938}$	2.69(16)
ZTF J0745+1949	$0.160^{+0.010}_{-0.010}$	$0.056^{+0.005}_{-0.005}$	$0.280^{+0.282}_{-0.116}$	$30.378^{+15.096}_{-8.428}$	1.61(09)
ZTF J0756+6704	$0.181^{+0.011}_{-0.008}$	$0.321^{+0.036}_{-0.096}$	$1.326^{+1.190}_{-0.437}$	$54.169^{+27.036}_{-15.451}$	0.90(08)
ZTF J1048-0000	$0.191^{+0.010}_{-0.020}$	$0.087^{+0.007}_{-0.007}$	$0.679^{+0.179}_{-0.032}$	$76.152^{+9.840}_{-16.545}$	8.42(78)
ZTF J1238+1946	$0.195^{+0.012}_{-0.012}$	$0.260^{+0.020}_{-0.014}$	$1.327^{+0.695}_{-0.330}$	$50.050^{+9.887}_{-9.870}$	2.44(14)
ZTF J1401-0817	$0.269^{+0.009}_{-0.005}$	$0.117^{+0.008}_{-0.010}$	$1.167^{+0.902}_{-0.297}$	$58.778^{+20.141}_{-17.158}$	10.37(16)
ZTF J1741+6526	$0.174^{+0.003}_{-0.002}$	$0.064^{+0.004}_{-0.003}$	$1.150^{+0.190}_{-0.049}$	$78.113^{+9.248}_{-12.204}$	1.42(11)

Radio Observation by FAST



- We performed radio observations for 6 targets by using FAST to search for potential pulse signals. Each target was carried out a 15-min L-band tracking observation.

- No convincing radio pulse signal was found among these targets. The sensitivity can be estimated by radiometer equation:

$$S_{\rm mean} = \frac{\eta\beta T_{\rm sys}}{G\sqrt{N_{\rm p}\Delta\nu T_{\rm int}}}\sqrt{\frac{W}{P-W}} \quad \sim 8\ \mu\text{Jy}$$

$$L_{1400\,\rm MHz} = S_{\rm mean}\, d_{\rm spec}^2$$

sampling efficiency: $\beta = 1$
duty cycle: $W/P \sim 0.1$
integration time: $T_{\rm int} = 14$ min
number of polarization: $N_{\rm p} = 2$
bandwidth: $\Delta\nu = 400$ MHz
antenna gain: $G = 16\ K\ {\rm Jy}^{-1}$
S/N threshold: $\eta = 7$
system temperature: $T_{\rm sys} = 25$ K

Jname	M_1 ($M_\odot$)	R_1 ($R_\odot$)	M_2 ($M_\odot$)	i (°)	$A_{\rm EV}$ (%)	$T_{0,\rm sup_conj}$ (MJD)	μ	τ	$f_1(M_2)$ ($M_\odot$)	Radio	$L_{1400\ \rm MHz}$ (mJy kpc^2)
ZTF J0101+0401	$0.193^{+0.011}_{-0.011}$	$0.191^{+0.013}_{-0.014}$	$0.635^{+0.987}_{-0.233}$	$47.049^{+23.971}_{-17.740}$	1.32(16)	58281.49558	0.53	0.27	0.151(19)	FAST	< 0.0139
ZTF J0404+0800	$0.172^{+0.014}_{-0.014}$	$0.222^{+0.034}_{-0.030}$	$0.027^{+0.044}_{-0.013}$	$61.829^{+19.544}_{-24.274}$	1.11(09)	58206.17723	0.51	0.74	-	FAST	< 0.0058
ZTF J0443+0541	$0.160^{+0.013}_{-0.013}$	$0.224^{+0.023}_{-0.018}$	$0.421^{+0.697}_{-0.227}$	$74.819^{+10.491}_{-13.938}$	2.69(16)	58334.53492	0.54	0.27	-	FAST	< 0.0156
ZTF J0745+1949	$0.160^{+0.010}_{-0.010}$	$0.056^{+0.005}_{-0.005}$	$0.280^{+0.282}_{-0.116}$	$30.378^{+15.096}_{-8.428}$	1.61(09)	58205.18216	0.55	0.30	0.017(3)	FAST	< 0.0003
ZTF J0756+6704	$0.181^{+0.011}_{-0.008}$	$0.321^{+0.036}_{-0.096}$	$1.326^{+1.190}_{-0.437}$	$54.169^{+27.036}_{-15.451}$	0.90(08)	58207.49116	0.48	0.70	0.546(33)	GBT	< 0.2550
ZTF J1048-0000	$0.191^{+0.010}_{-0.020}$	$0.087^{+0.007}_{-0.007}$	$0.679^{+0.179}_{-0.032}$	$76.152^{+9.840}_{-16.545}$	8.42(78)	58199.31062	0.55	0.29	0.383(31)	FAST	< 0.0039
ZTF J1238+1946	$0.195^{+0.012}_{-0.012}$	$0.260^{+0.020}_{-0.014}$	$1.327^{+0.695}_{-0.330}$	$50.050^{+9.887}_{-9.870}$	2.44(14)	58202.43981	0.42	0.58	0.453(14)	GBT	< 0.0552
ZTF J1401-0817	$0.269^{+0.009}_{-0.005}$	$0.117^{+0.008}_{-0.010}$	$1.167^{+0.902}_{-0.297}$	$58.778^{+20.141}_{-17.158}$	10.37(16)	58203.46077	0.53	0.28	0.487(12)	FAST	< 0.0024
ZTF J1741+6526	$0.174^{+0.003}_{-0.002}$	$0.064^{+0.004}_{-0.003}$	$1.150^{+0.190}_{-0.049}$	$78.113^{+9.248}_{-12.204}$	1.42(11)	58197.39962	0.50	0.75	0.801(39)	GBT	< 0.0908

Summary

- Using ELM WD catalogs, targeting ZTF public lightcurves exhibiting ellipsoidal-like variations with orbital periods shorter than 1 day, and HR diagram positions.
- We found 9 high-priority ELM WD candidates, four of them may have companion mass exceeding 1 $M_{\odot}$, making them more likely candidates for harboring MSPs.
- So far no convincing pulse signals were detected from FAST observations of 6.

Thanks

中山大学80cm红外望远镜项目 (Sun Yat-sen Univ. 80cm Infrared Telescope)



•0.5”/pix，FoV 3x5.1’x4.1’ (K), 5’x4’ (J)

•Installed at Lenghu in October 2024, currently in commissioning phase.

- Scientific observations have already begun (**Transients**)
- Limiting magnitude: 16.5 (J), 13.8 (K) Vega mag @ 20s
- Limiting magnitude: 18 (J), 15.5 (K) Vega mag @ 1800s

•Expected official operation in September 2025.

- It will operate automatically.

•Welcome for cooperation!