Observing and Modeling Ultracompact Binaries Detectable by LISA

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Smith College 2020
LIGO SURF 2019
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Image credit: Caltech/IPAC

Outline

- Multi-messenger astrophysics
- LISA
- Ultracompact binaries
  - White dwarf binaries
  - Low-mass X-ray binaries
- Simulations
- Observations
- Future work

Multi-messenger Astrophysics

- **EM**
  - Orbital period
  - Inclination
  - Relative radii
  - Mass ratio
- **GW**
  - Chirp mass
  - GW frequency
- **EM + GW**
  - Distance from EM breaks degeneracy

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Multi-messenger Astrophysics

- **EM**
  - Orbital period
  - Inclination
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  - Mass ratio
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  - Chirp mass
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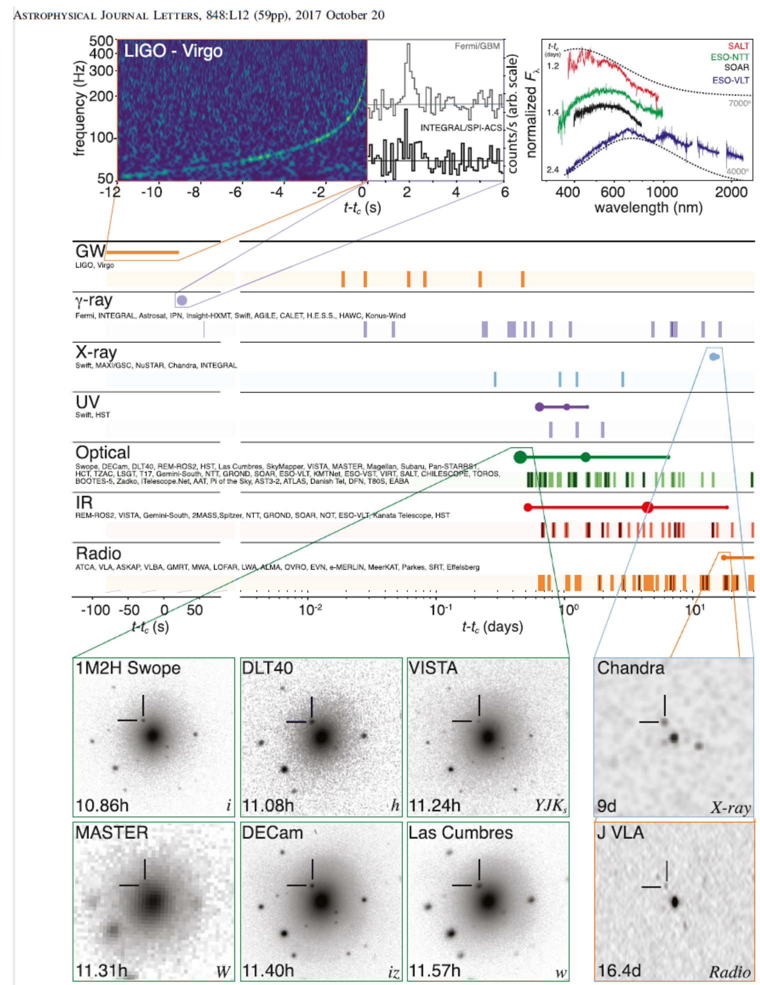
GW170817



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LISA

- 3 test masses, 6 laser links
- 2.5 million km arms
- Earth trailing heliocentric orbit

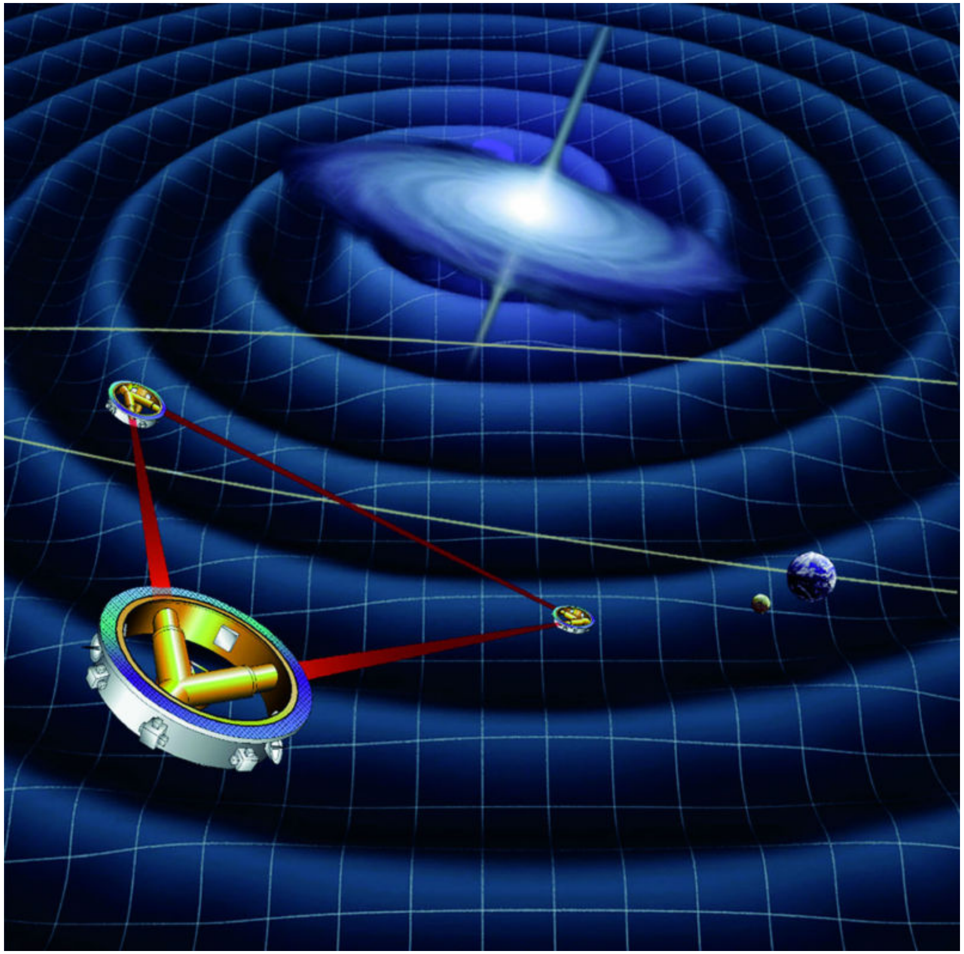

Image credit: ESA

LISA

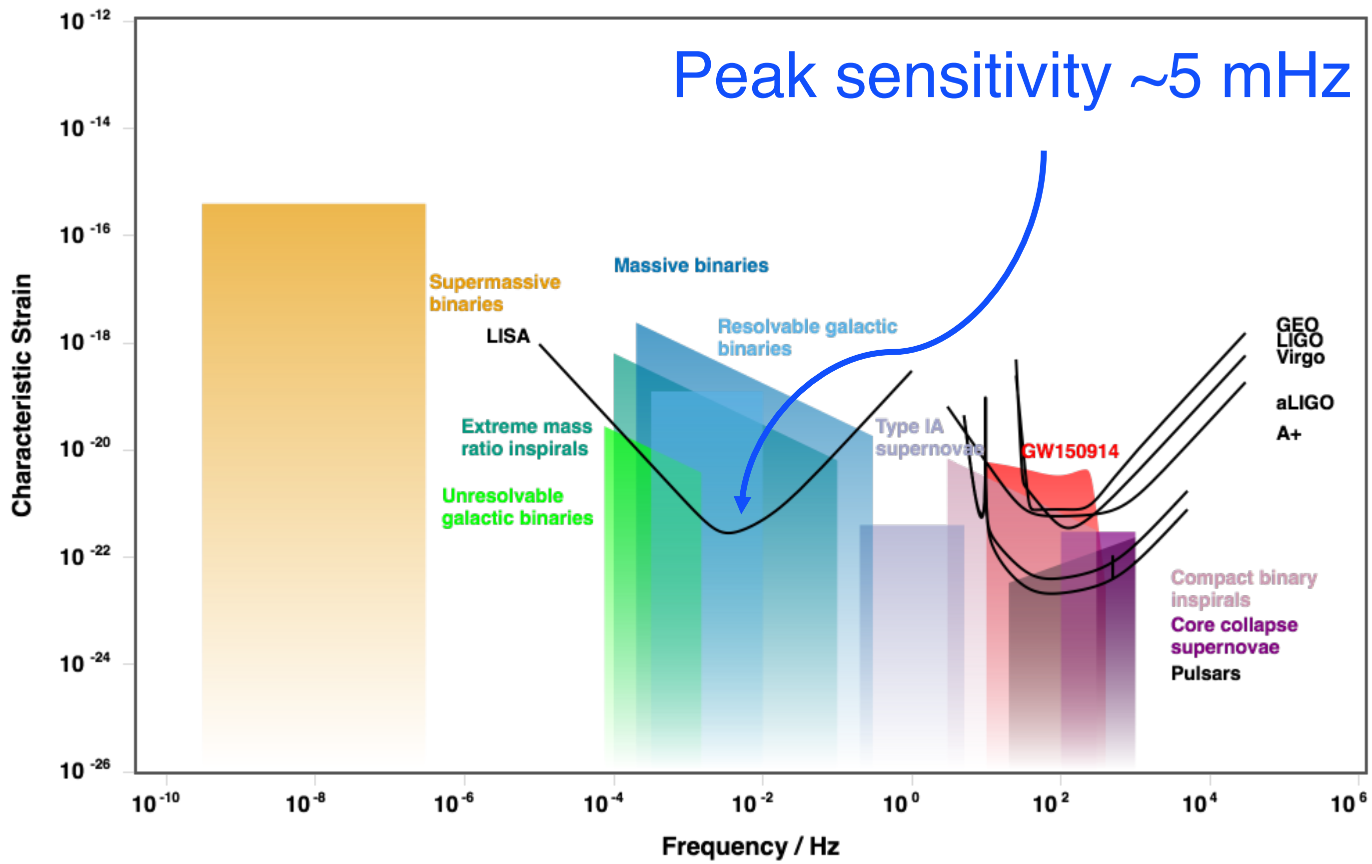

Image credit: Moore, Cole, Berry 2014 (**arXiv:1408.0740)**

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LISA Verification Binaries

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Figure credit:
Burdge+ 2019

LISA Verification Binaries

- Identify LISA sources in EM
  - » P ~ minutes - hours
- Predict GW waveform
  - » monochromatic
- Calibrate LISA GW signal

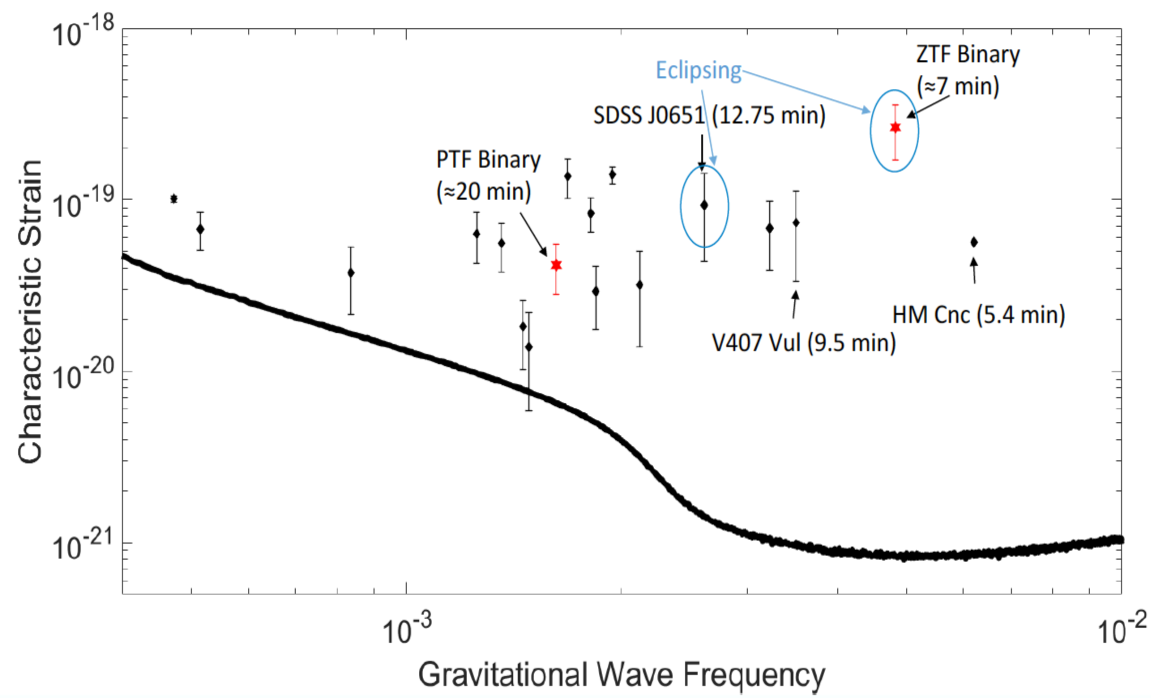

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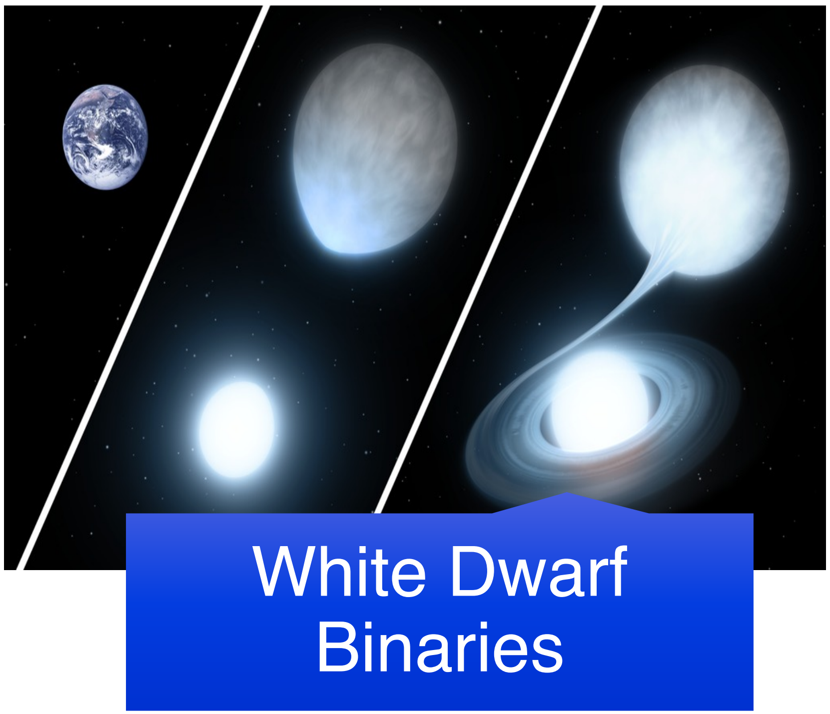
Figure credit: Burdge+ 2019

LISA Verification Binaries



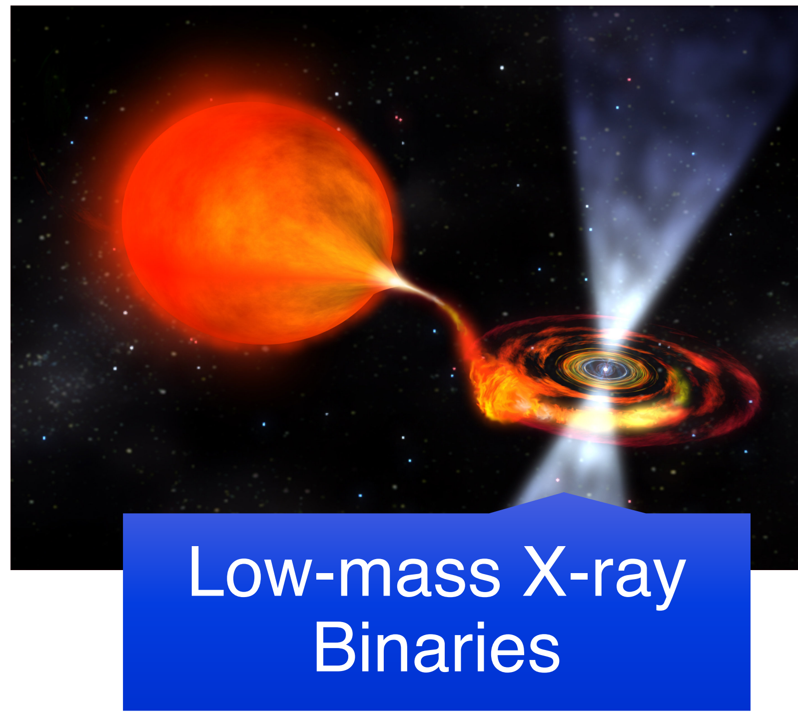
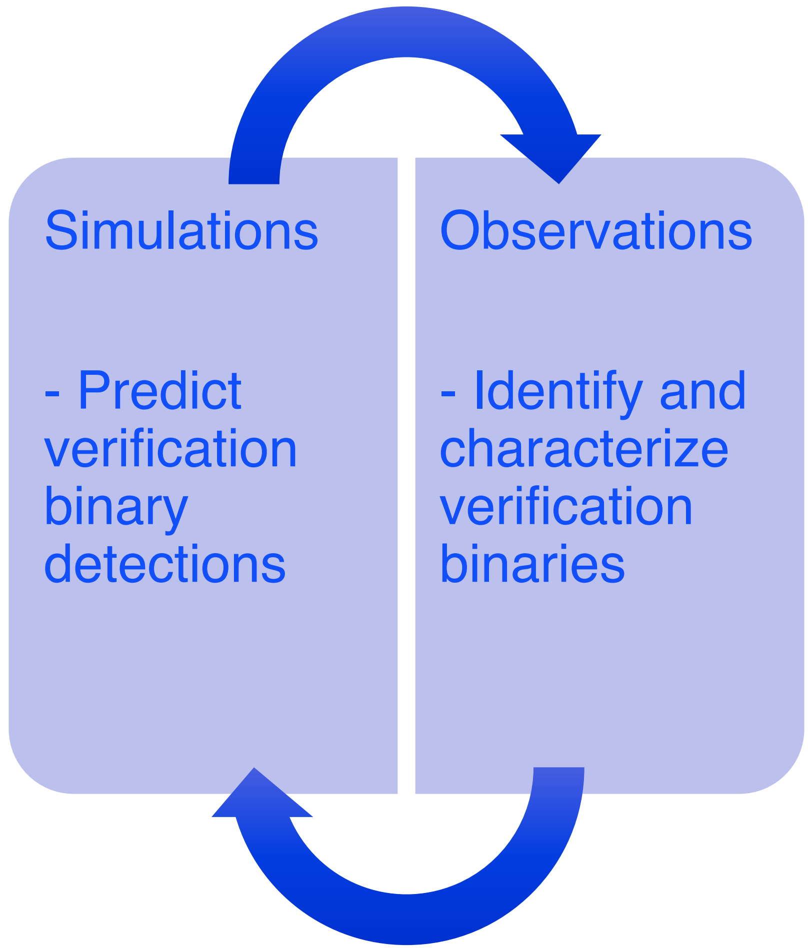
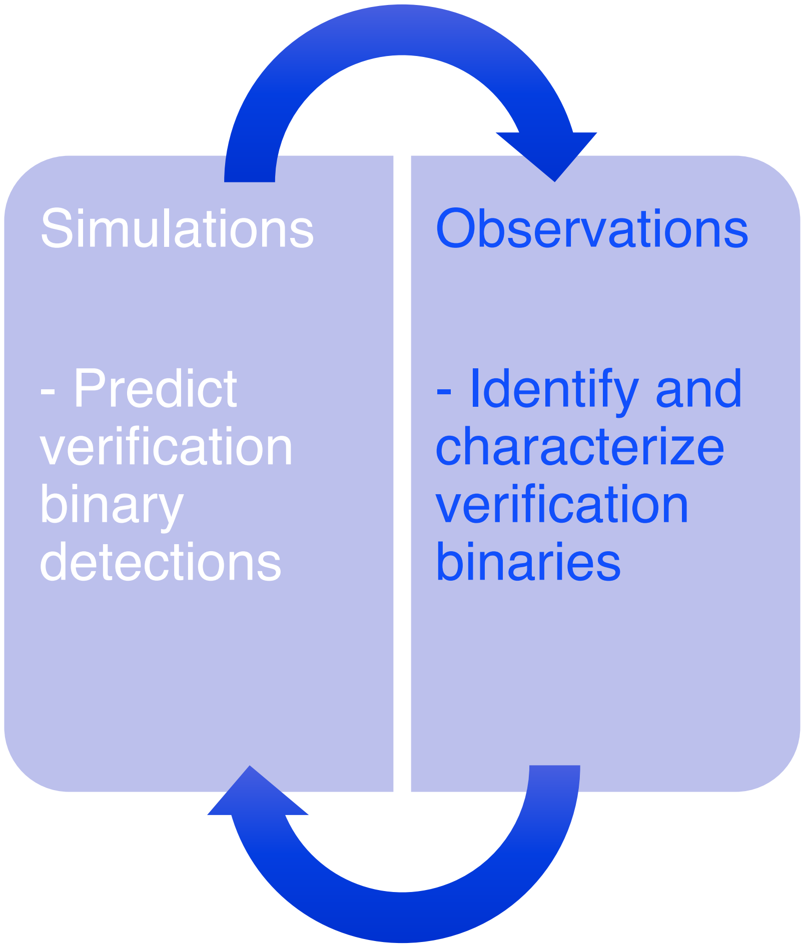


Image credit: Caltech (L); Dana Berry/NASA Goddard Space Flight Center (R)

LISA Verification Binaries



LISA Verification Binaries



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Orbital Decay

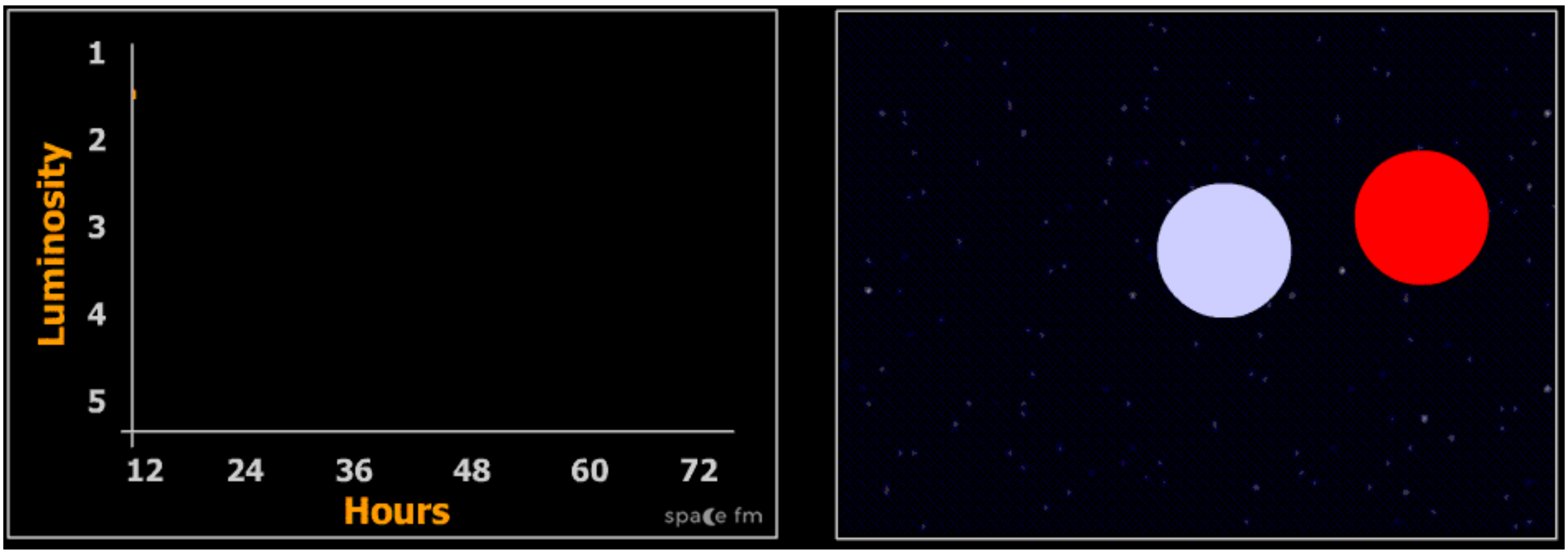
- Objects in binary orbit give off GW
- As energy is lost, period decreases

$$\dot{P} = \frac{-96\pi}{5c^5}(\pi G \mathcal{M} f_{gw})^{\frac{5}{3}}$$

Animation credit: NASA/Dana Berry, Sky Works Digital

Simulated Light Curves

- Construct eclipsing light curve given binary parameters



Animation credit: space.fm

Simulated Light Curves

- Interpolate light curve over time given decay rate
- Eclipse mid points shift over time
- White dwarf binary
  - » -10^{-11} s/s

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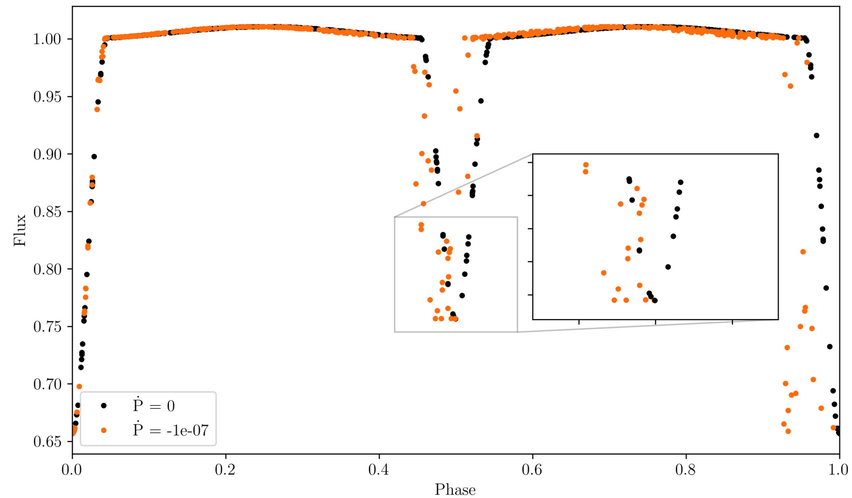
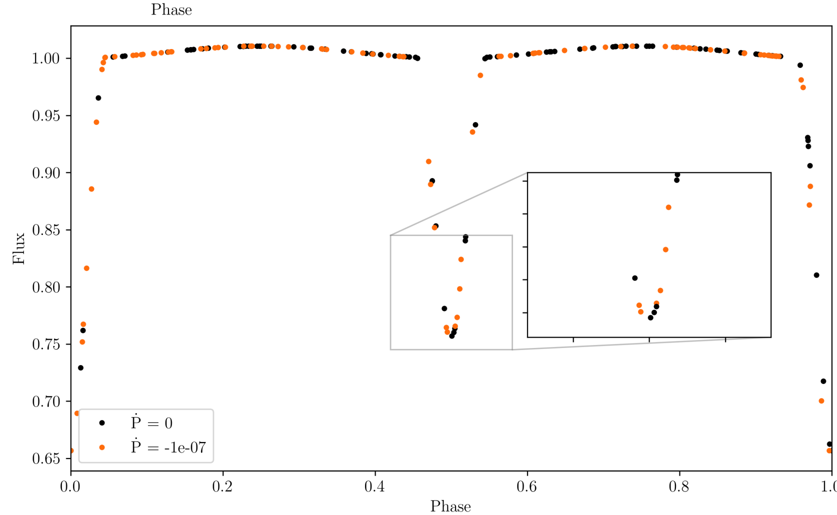


10 years (LSST)

1 year (ZTF)



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DWD Simulations

Galactic Binary Population

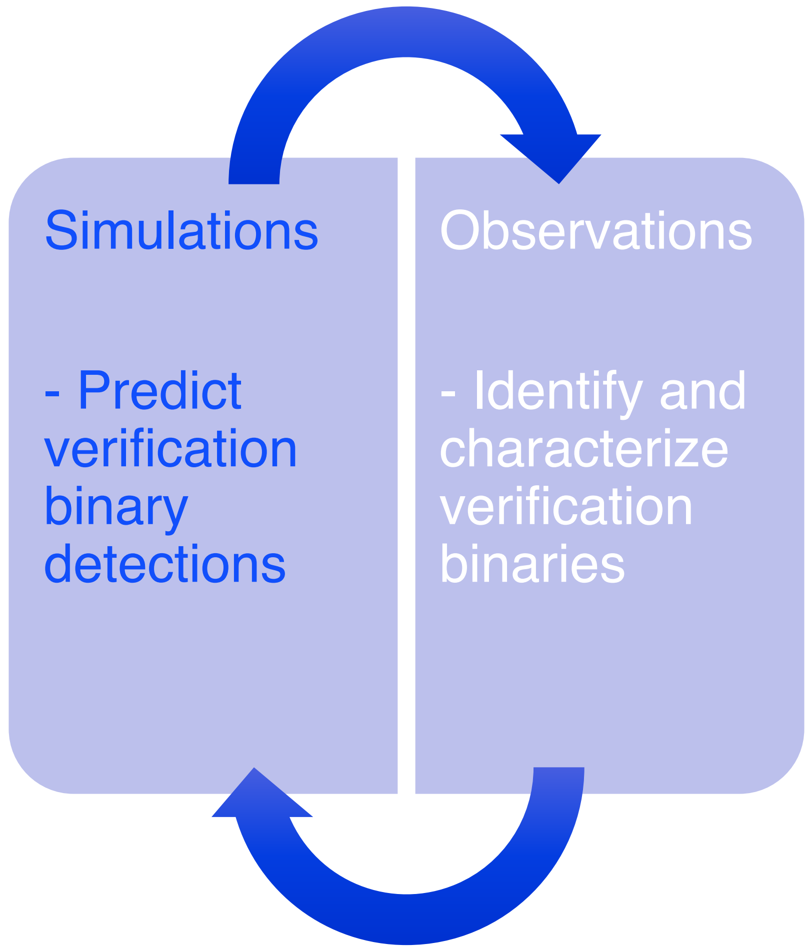
- Gravitational waveform catalog
- Light curve corresponding to each binary system

Orbital Decay Light Curves

- Period search simulated photometry
- Constrain range of inclination and period we can detect

Quantify range of white dwarf binaries we expect to detect in EM and GW

LISA Verification Binaries



EM Follow-up

Wide field surveys (ZTF)

- Cadence ~3 days
- Period search
- HR Diagram (Gaia)

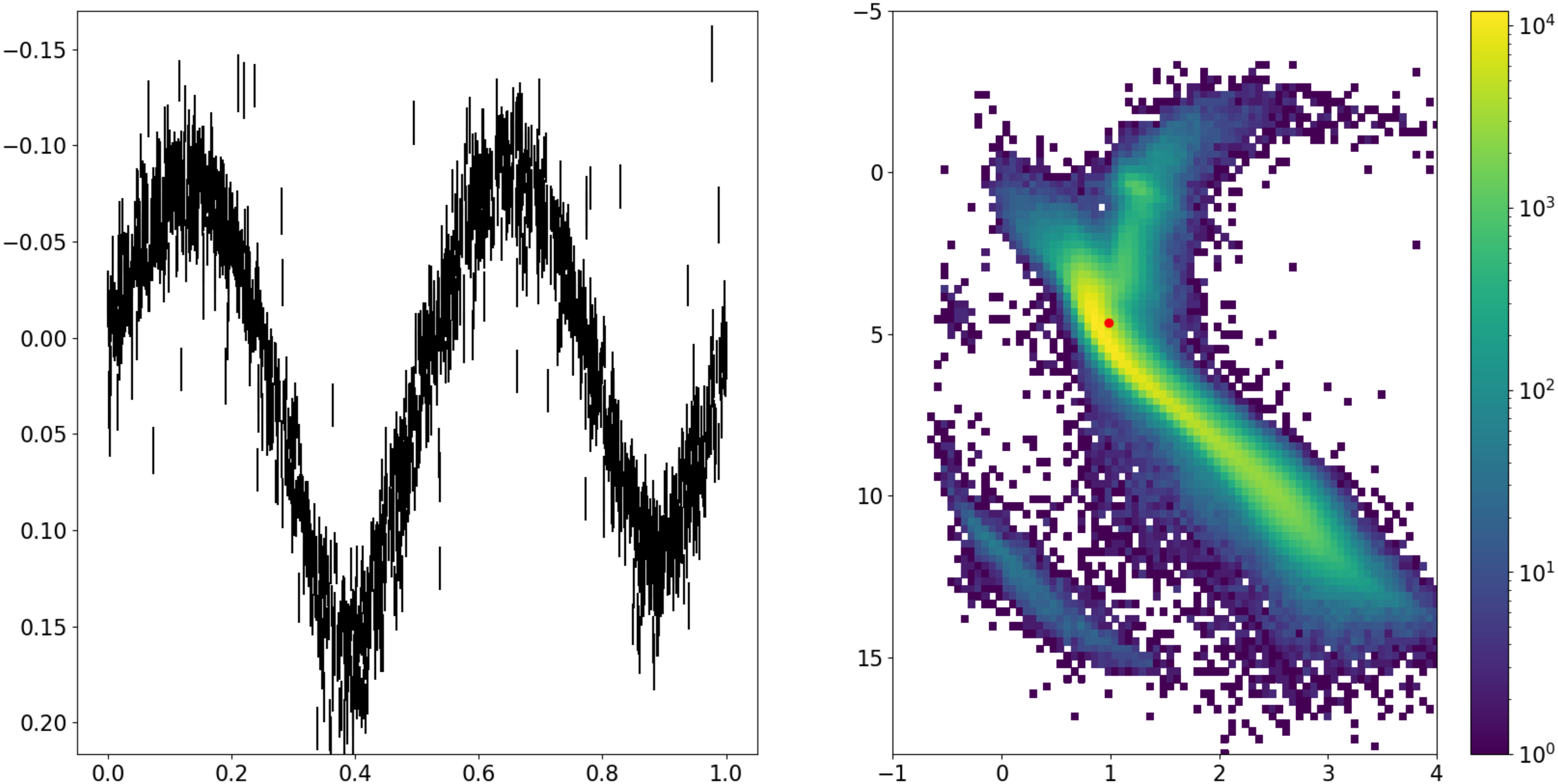
Scan and cross match

- Visually scan light curves
- Cross match with SIMBAD

Follow up

- High cadence photometry
- Spectroscopy

ZTF Light Curves



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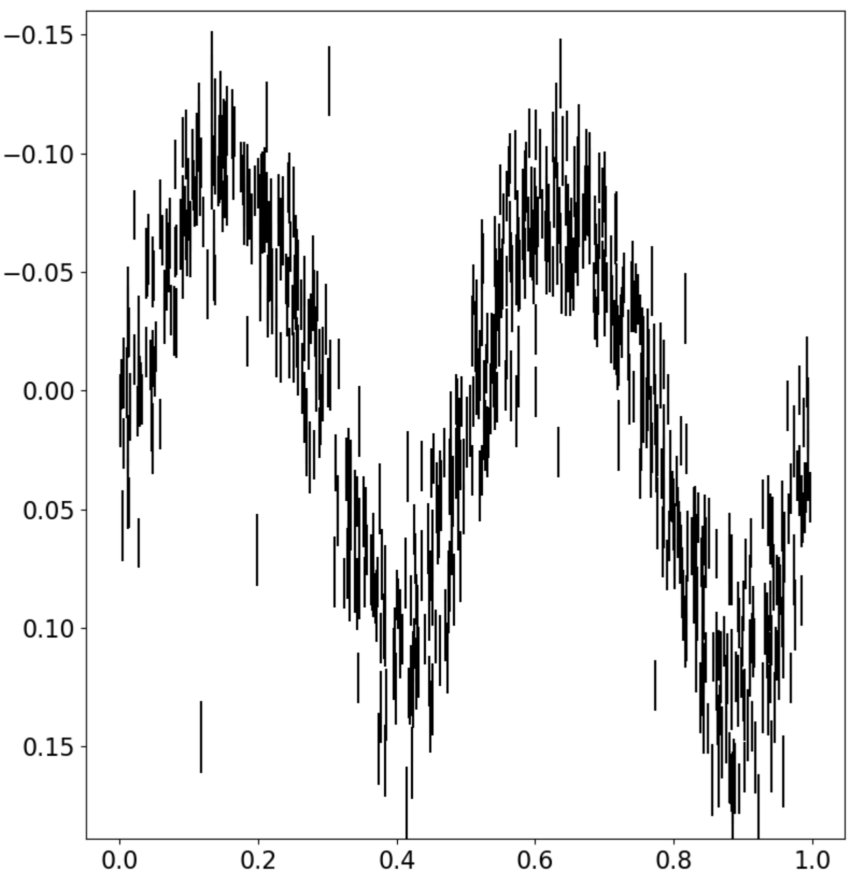
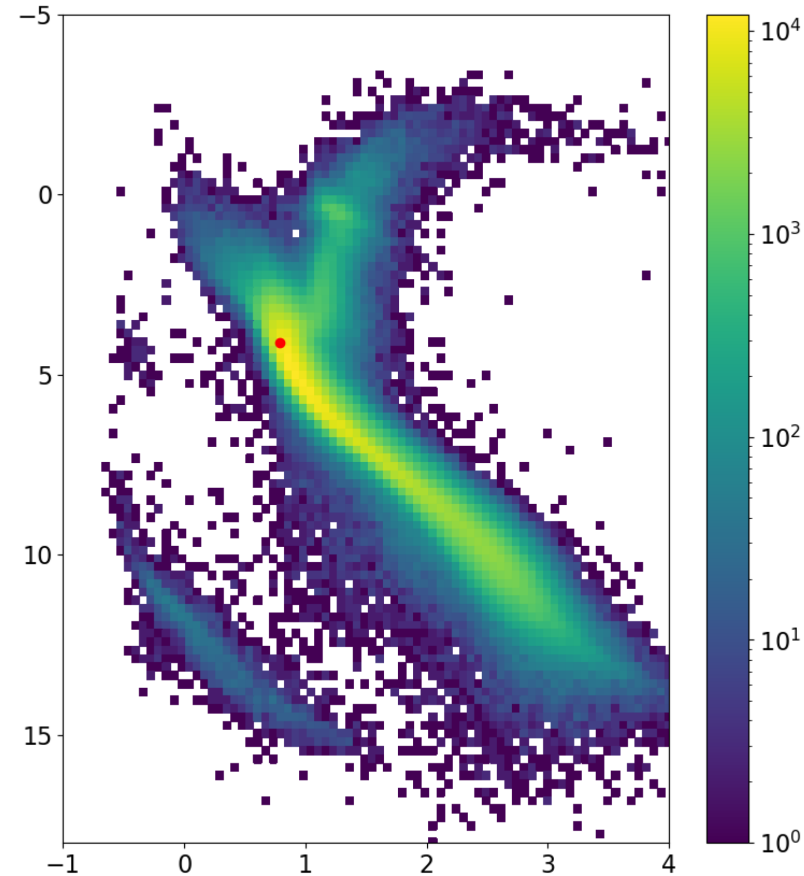
ZTF Light Curves





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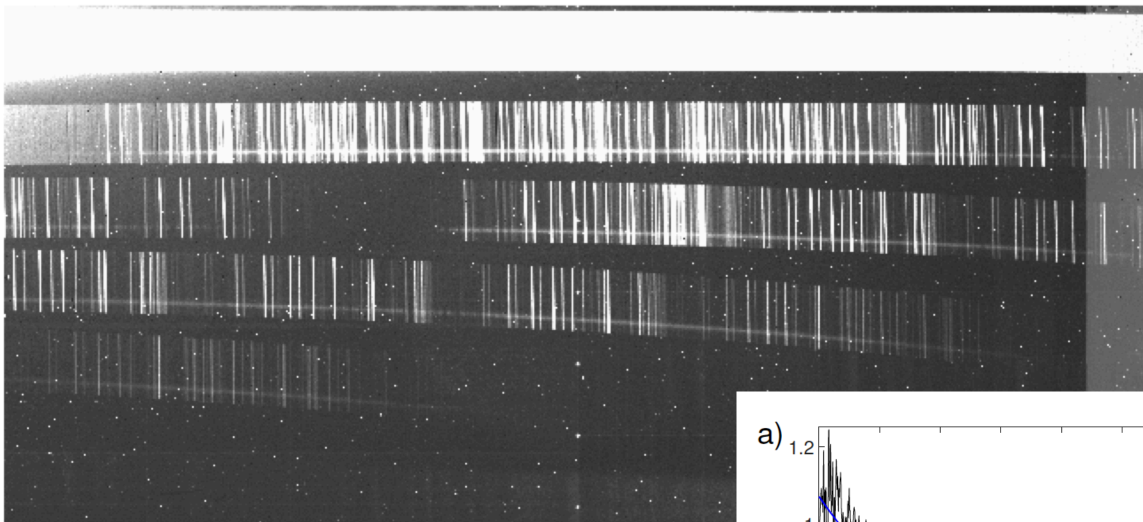
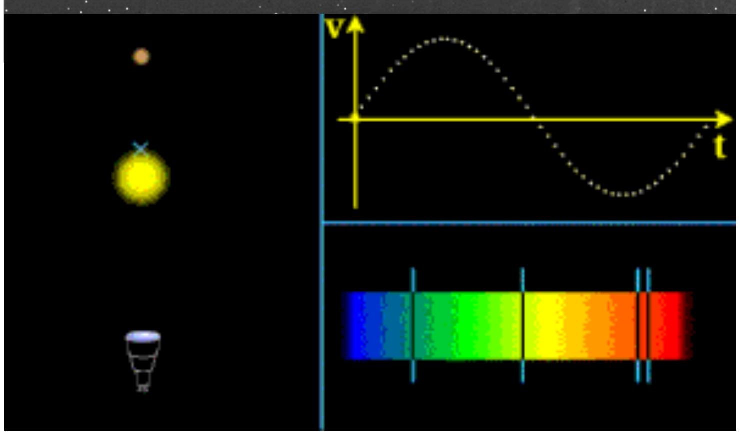
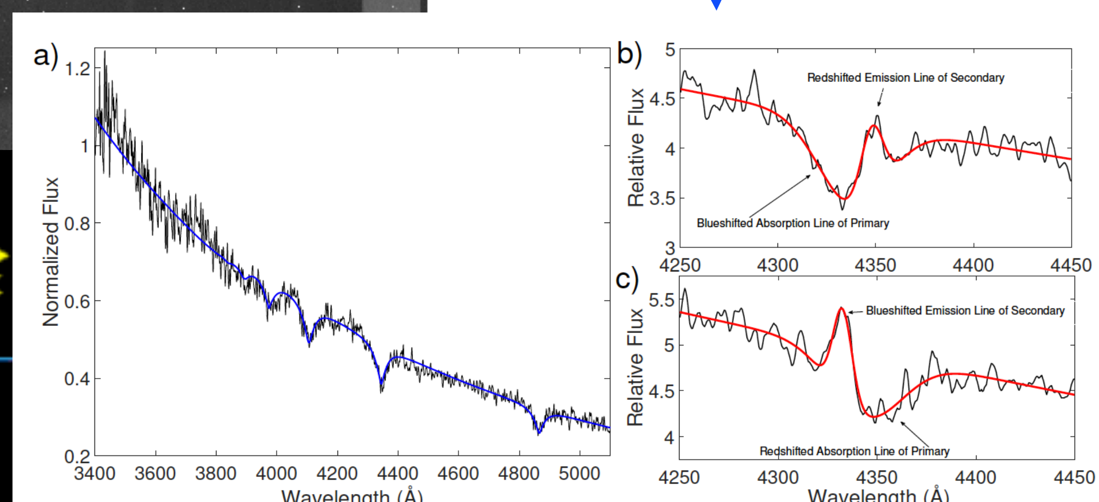
Spectroscopy





Data reduction and analysis



Animation credit: PLATO

Figure credit: Burdge+ 2019 (**arXiv: 1907.11291**)

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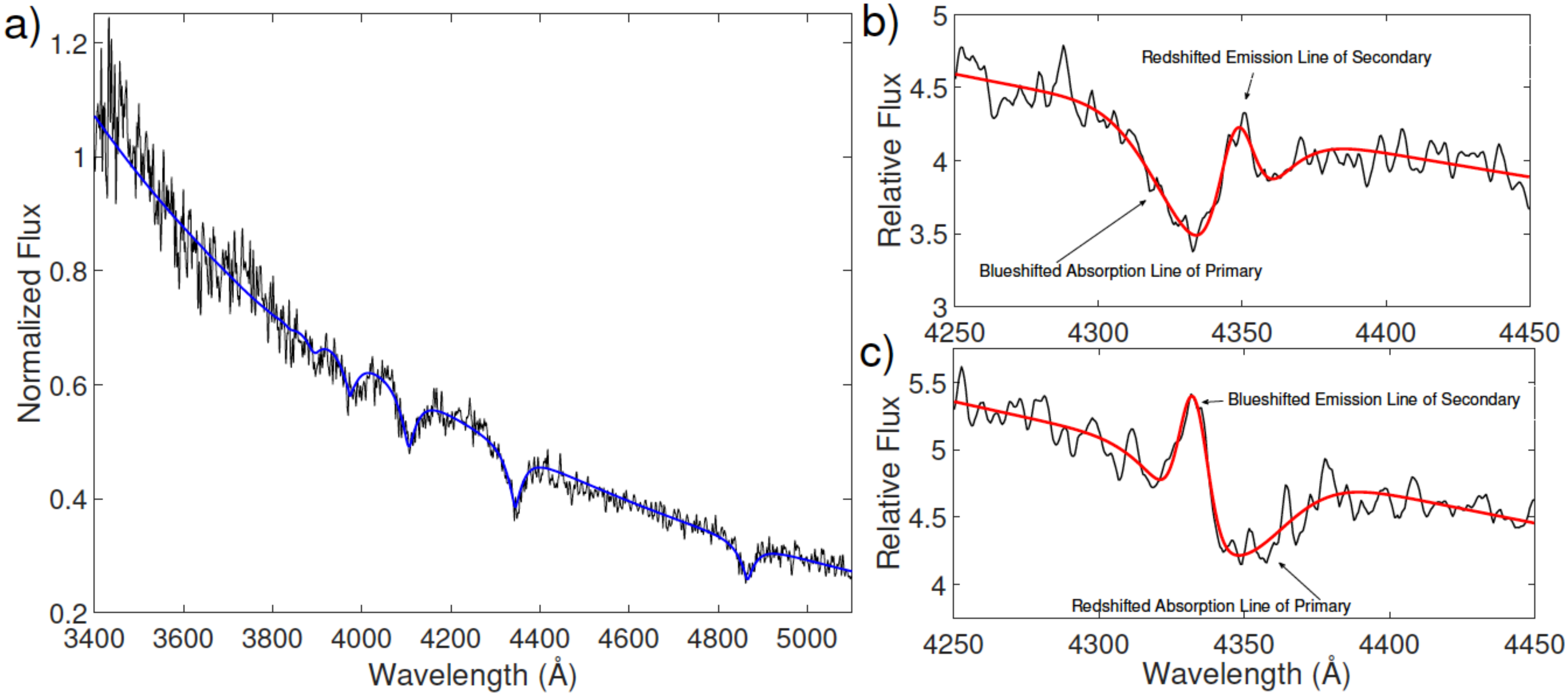
Spectroscopy



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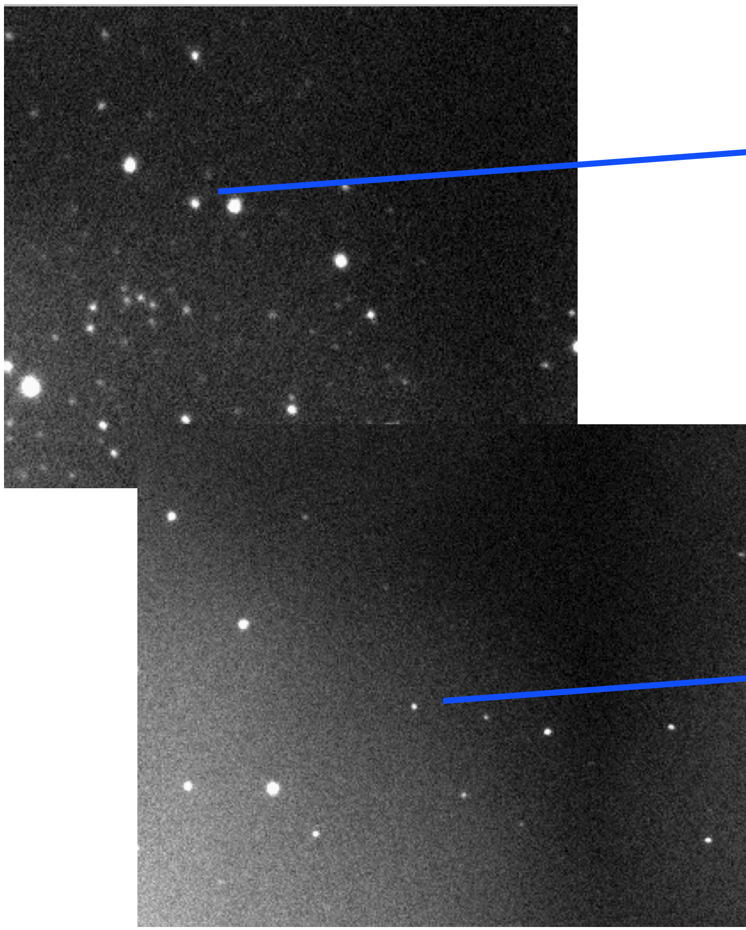
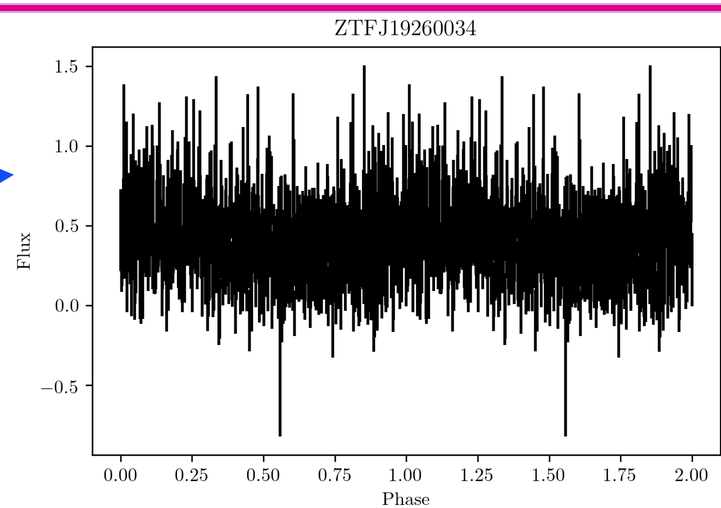
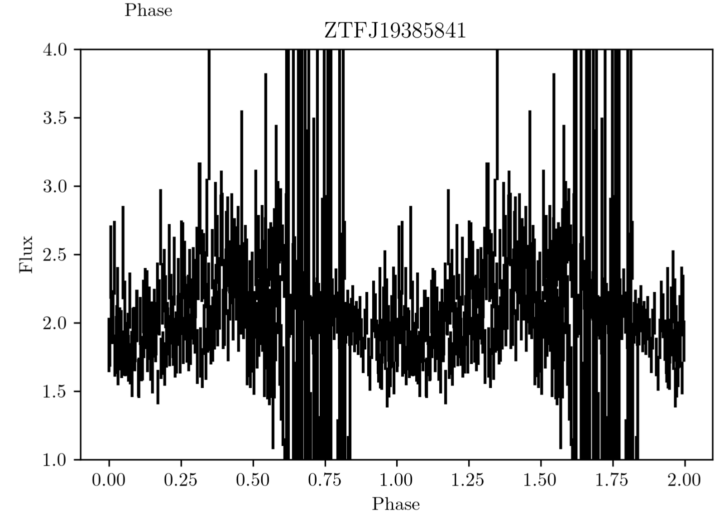
KPED Light Curves







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KPED Light Curves

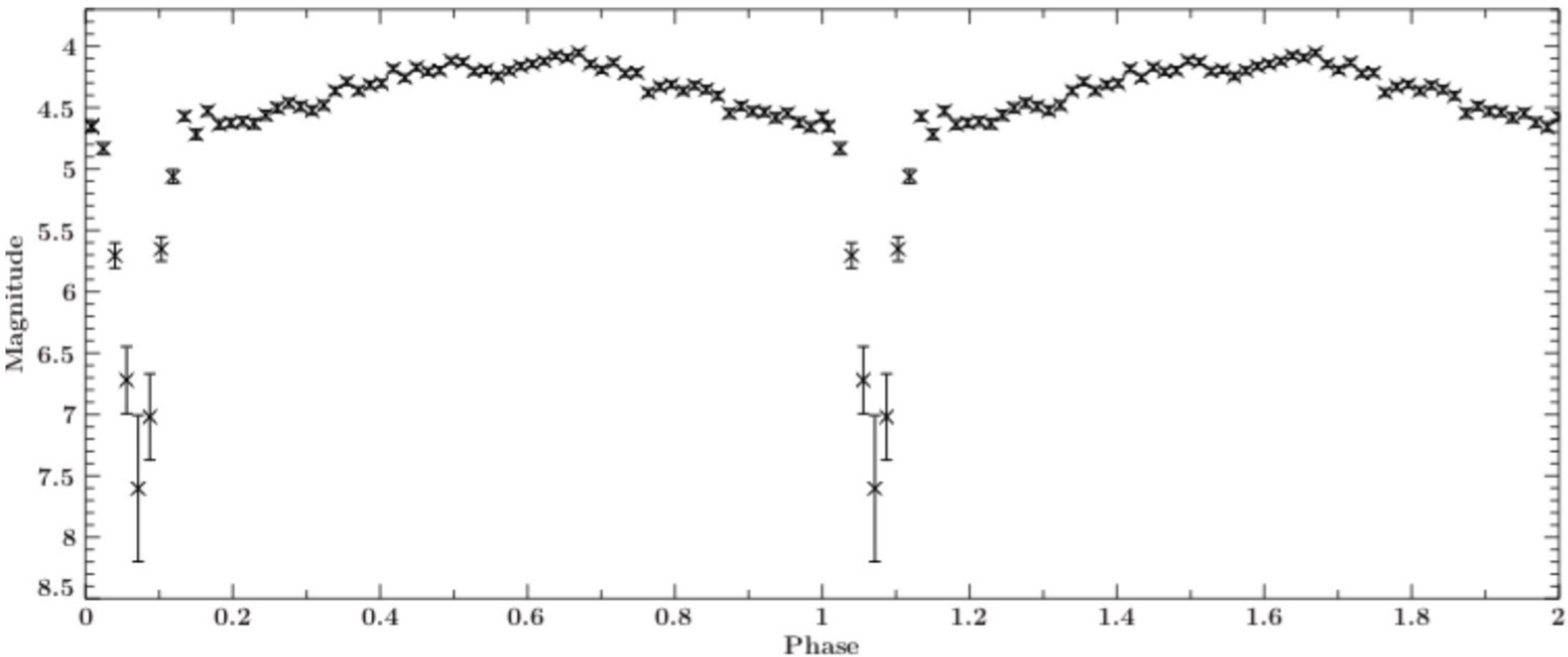

Image credit: Burdge+ 2019

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Conclusions and Next Steps

- Multi-messenger astronomy allows us to further constrain a source’s astrophysical parameters
- Ultracompact binaries are needed to verify and calibrate LISA
  - Simulate Galactic Binary population waveforms and photometry
  - Follow up of wide field sky surveys with high cadence photometry and spectroscopy

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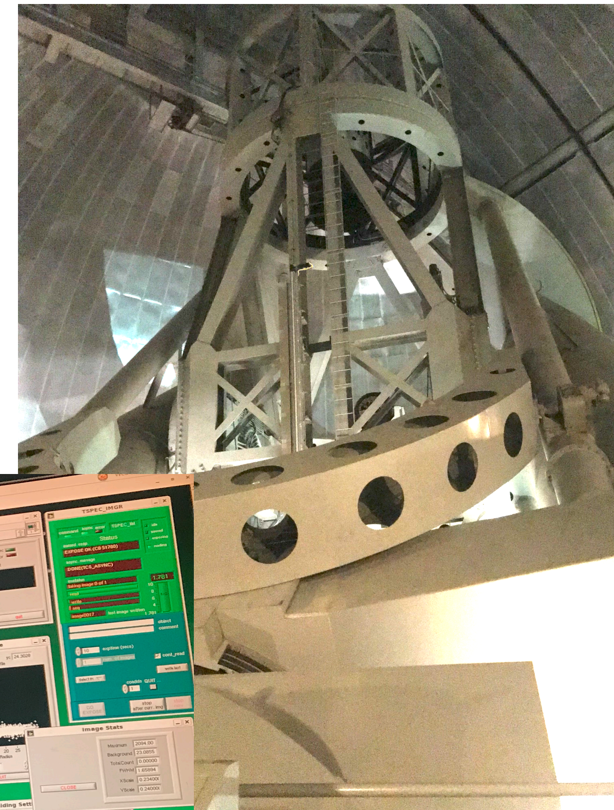
Acknowledgements

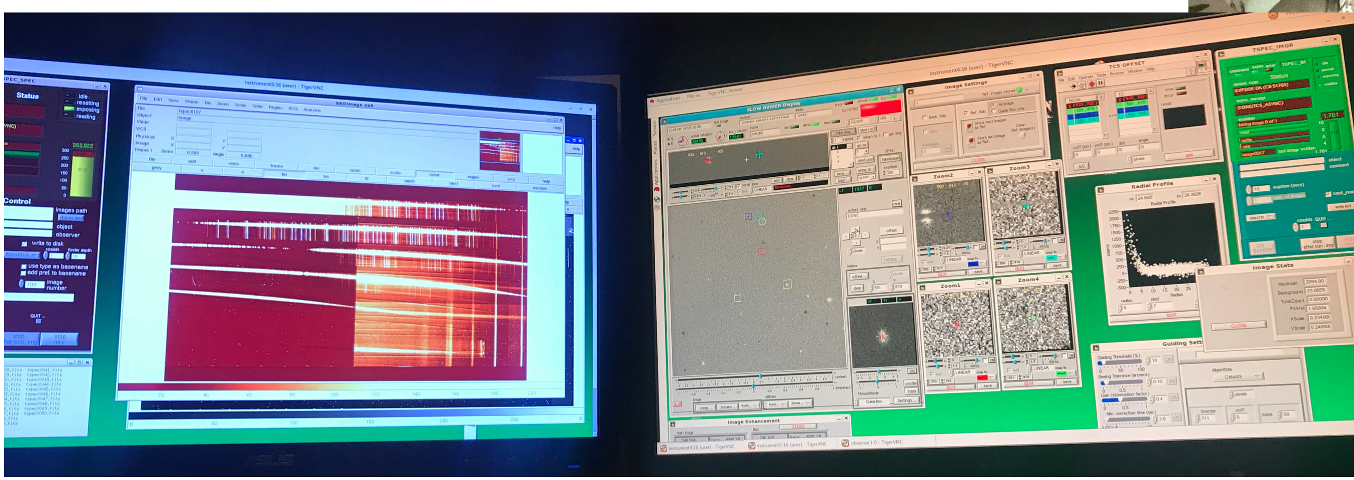
- Michael Coughlin
- Shreya Anand
- Kevin Burdge
- Kishalay De
- Alan Weinstein
- LIGO Lab
- LIGO SURF
- Caltech SFP

Additional Slides

TSpec

- Palomar 200" Hale telescope
- Triple Spec NIR spectrograph
  - » 1.0 – 2.4 μm
- 2 hours of observing
- 1 × 30 arcsecond slit





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KPED

- WIYN 2.1 m
- EMCCD
- High cadence photometry
- frame rates > 1 Hz (readout time)
- FOV 4.4’ x 4.4’

J1539: 7 min binary

- 6.91 min period
- GW freq 4.8 mHz
  - LISA SNR ~ 139 in 4 years
- Surface brightness ratio 0.036
- Quasi-sinusoidal modulation
  - primary star irradiates one side of secondary
- $\dot{P} =$ -2.365*10^{-11} s/s

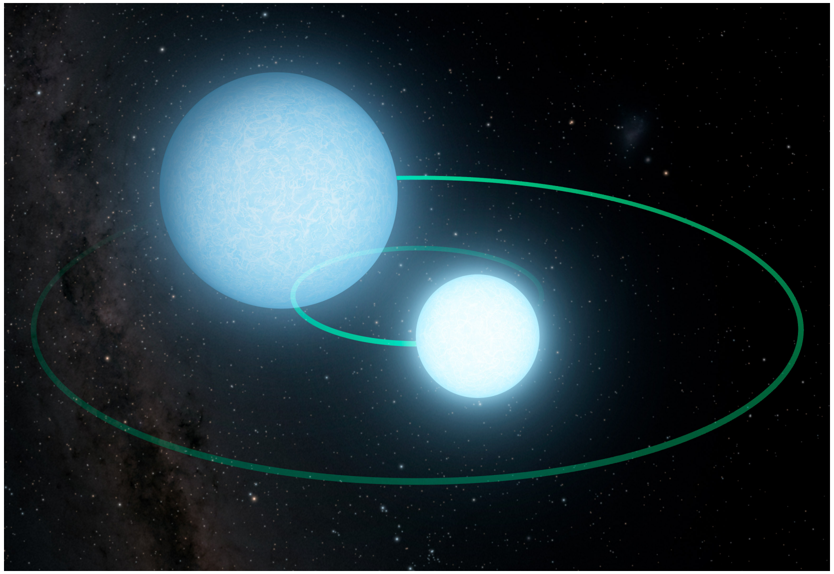

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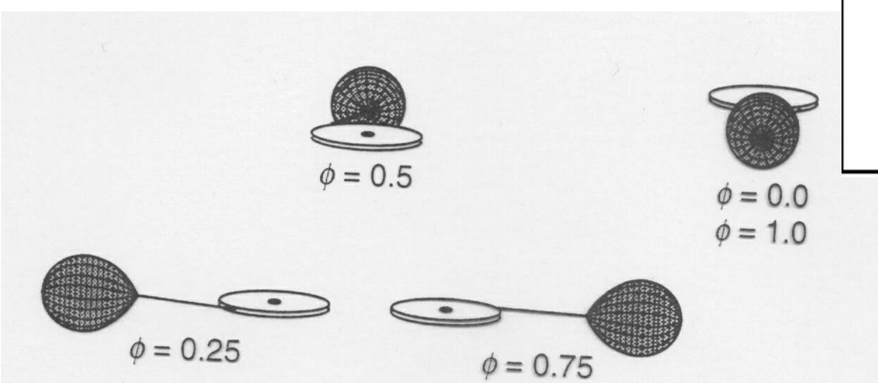
Image credit: Caltech/IPAC

Ellipsoidal Modulation

- Ellipsoidal modulation
- Tidal bulges change projected area of star



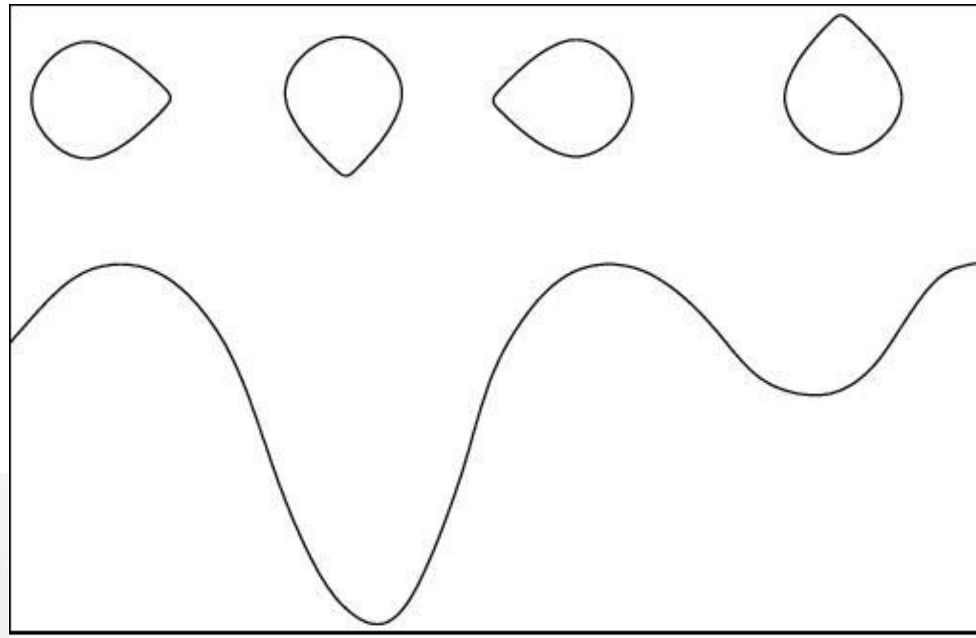
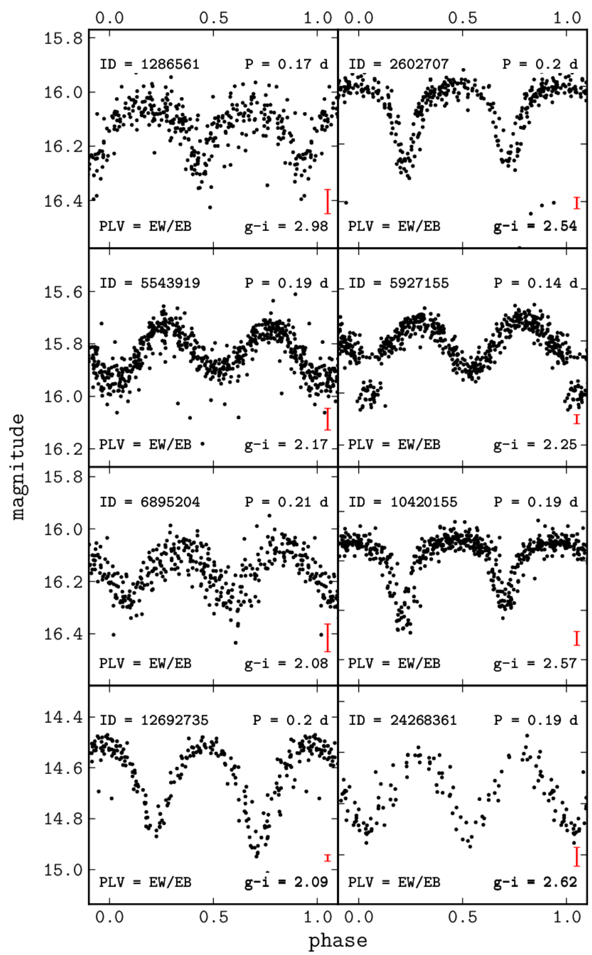


Image credit: Niel Brandt, PSU (L); Reed+ 2011 (**arXiv: 1011.0387**) (R)

The Variable Sky



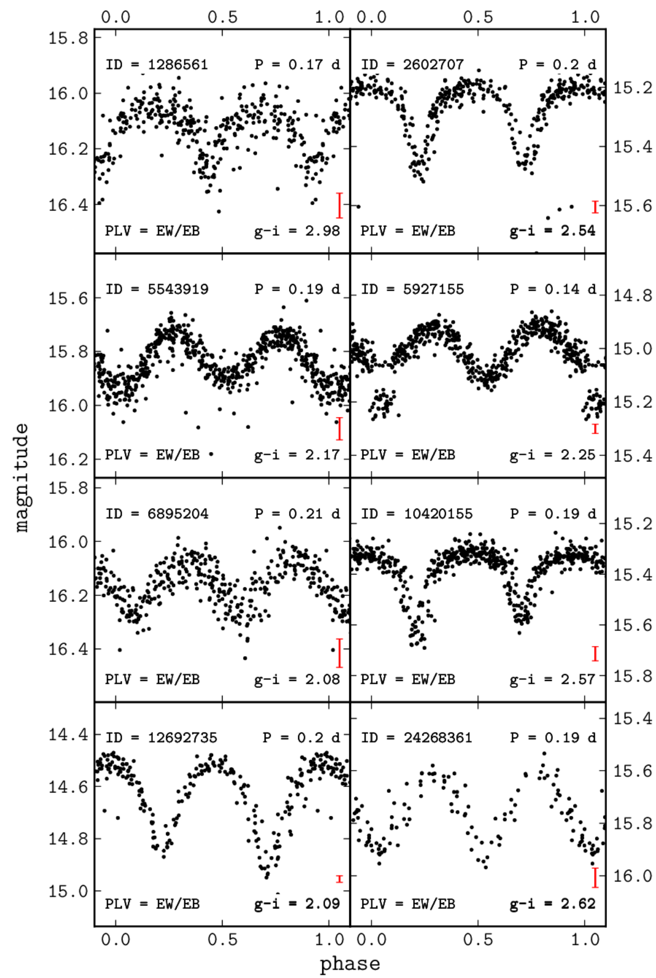
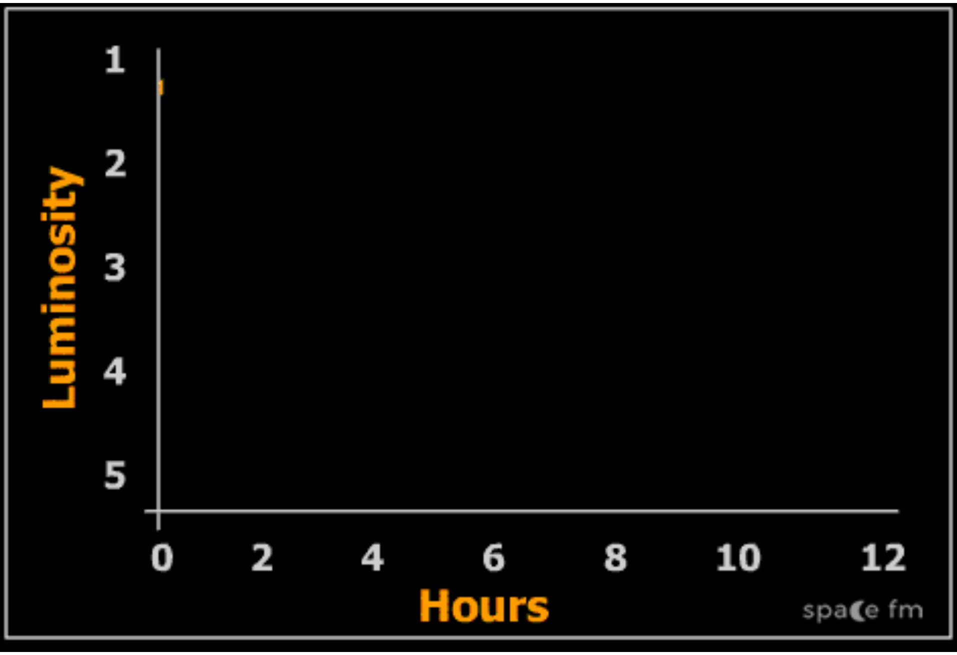
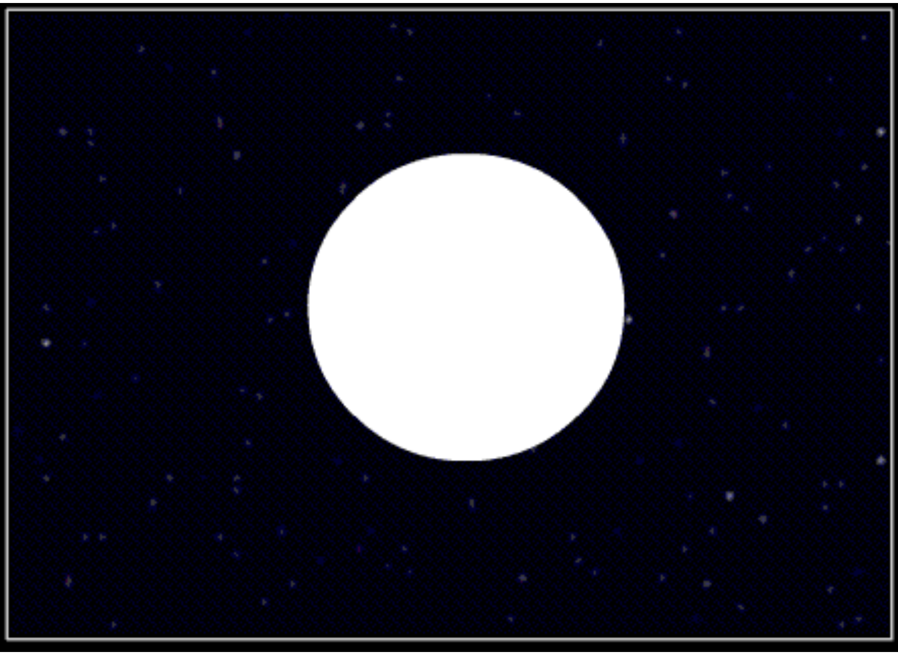


Image credit: Palaversa+ 2013 (**arXiv:1308.0357**)

Pulsating White Dwarfs





Animation credit: space.fm

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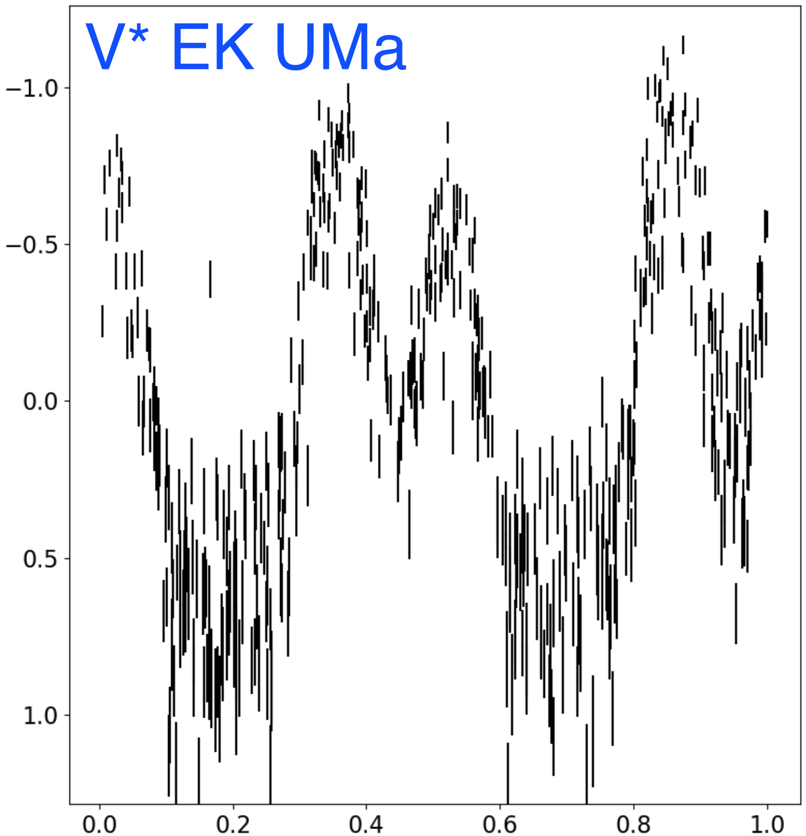
More ZTF Light Curves



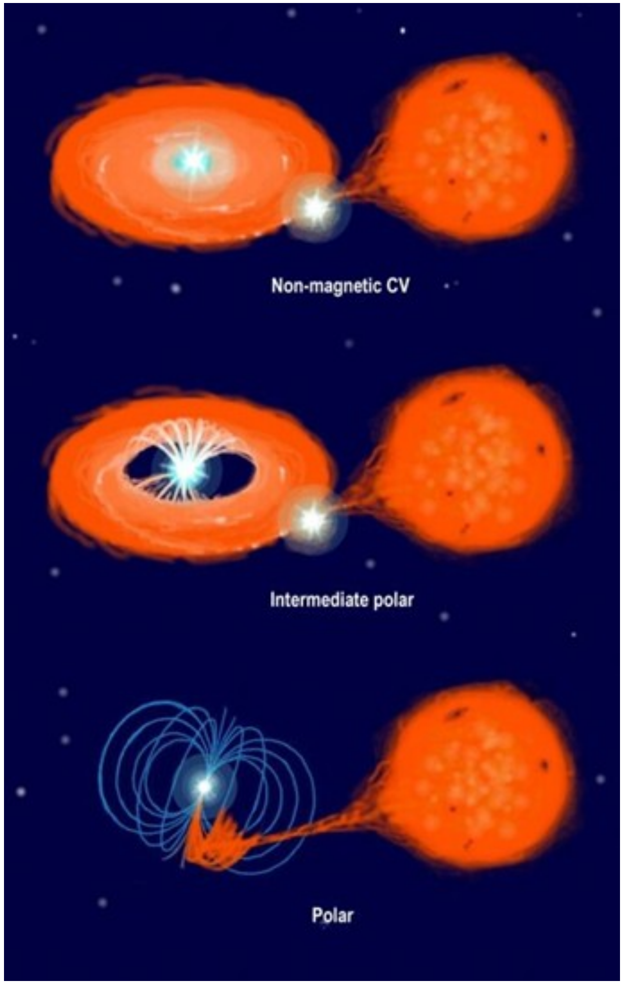


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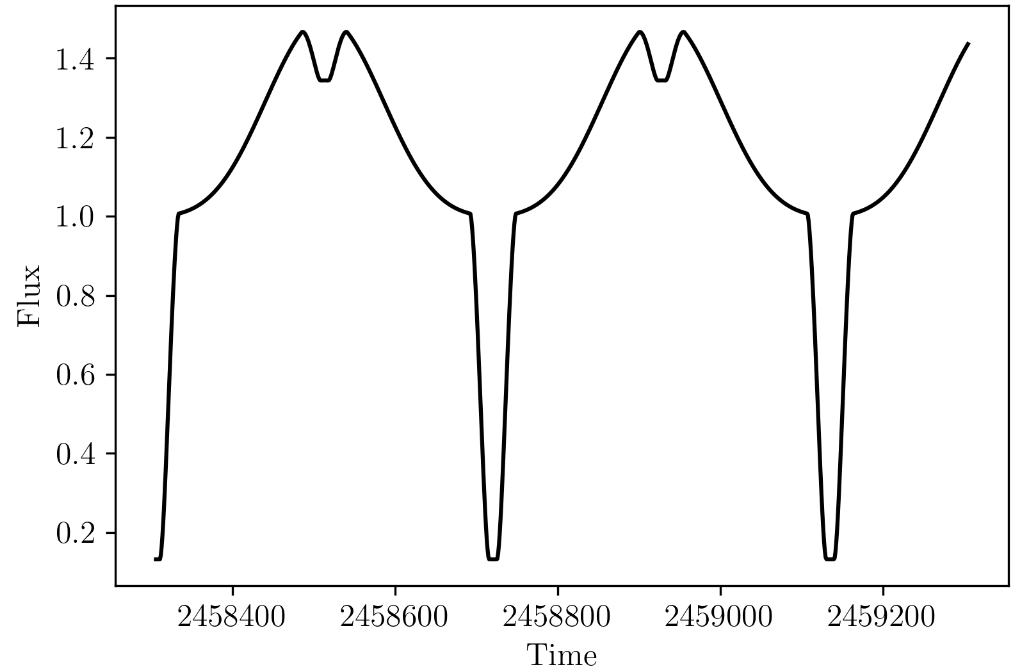
Image credit: Ivan L. Andronov

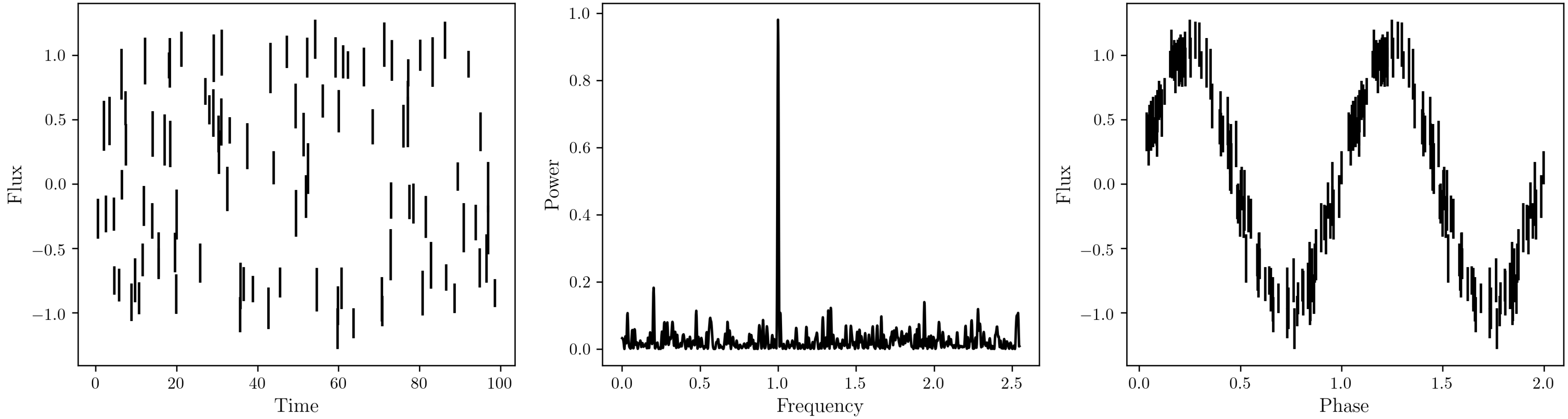
ellc

- Builds eclipsing binary light curves
- Input binary parameters
  - » Relative radii
  - » Inclination
  - » Mass ratio
  - » Star spots
  - » etc
- Pierre Maxted (2016)



Period Search

- **Lomb-Scargle**
  - » **Fourier power versus frequency or period**
- Conditional Entropy
  - » 2D histogram, axes are time and magnitude
  - » Modulate over time bin, minimize scatter



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Period Search

- Lomb-Scargle
  - » Fourier power versus frequency or period
- **Conditional Entropy**
  - » **2D histogram, axes are time and magnitude**
  - » **Modulate over time bin, minimize scatter**

Figure 1. This shows the light curve of a typical type AB RR Lyrae from CRTS (Drake et al. 2013) (a) folded at the trial period which minimizes the entropy (b) and conditional entropy (c).

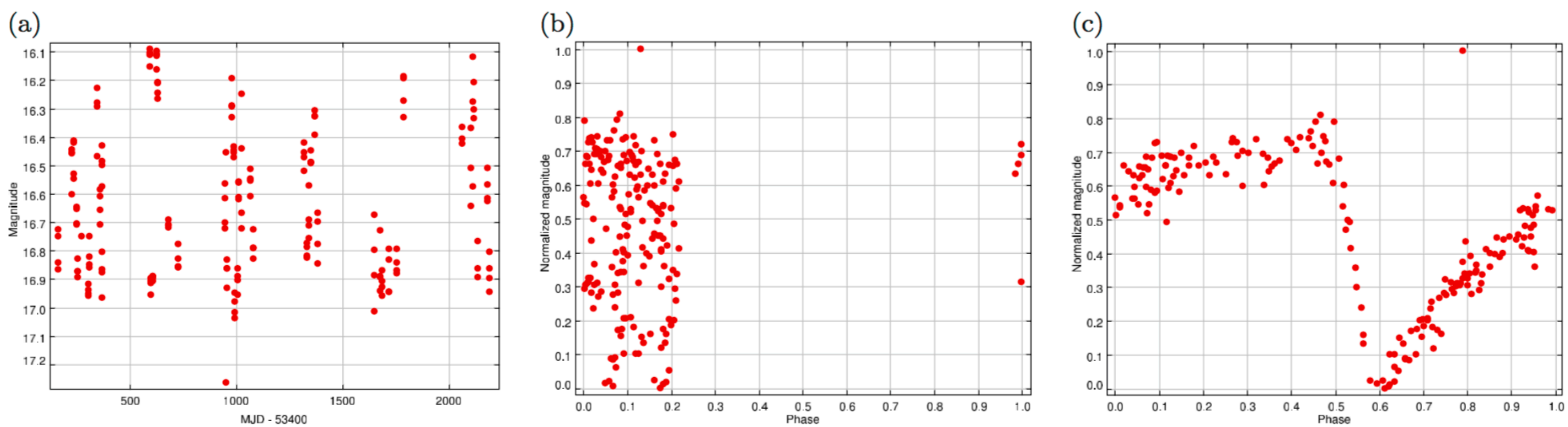

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Figure credit: Graham+ 2013 (**arXiv: 1306.6664**)

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Known Verification Binaries

Table 1. Physical properties of the known verification binaries. Masses and inclination angles in brackets are assumed and based on evolutionary stage and mass ratio estimations

Source	l_{Gal} (deg)	b_{Gal} (deg)	Orbital period (sec)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	ι (deg)	Refs.
AM CVn type							
HM Cnc	206.9246	23.3952	321.529	0.55	0.27	≈38	1,2
V407 Vul	57.7281	6.4006	569.395	[0.8±0.1]	[0.177±0.071]	[60]	3
ES Cet	168.9684	–65.8632	620.21	[0.8±0.1]	[0.161±0.064]	[60]	4
SDSS J135154.46–064309.0	328.5021	53.1240	943.84	[0.8±0.1]	[0.100±0.040]	[60]	5
AM CVn	140.2343	78.9382	1028.73	0.68±0.06	0.125±0.012	43±2	6,7
SDSS J190817.07+394036.4	70.6664	13.9349	1085.7	[0.8±0.1]	[0.085±0.034]	10 - 20	8,9
HP Lib	352.0561	32.5467	1102.70	0.49-0.80	0.048-0.088	26-34	10,11
PTF1 J191905.19+481506.2	79.5945	15.5977	1347.35	[0.8±0.1]	[0.066±0.026]	[60]	12
CXOGBS J175107.6–294037	359.9849	–1.4108	1375.0	[0.8±0.1]	[0.064±0.026]	[60]	13
CR Boo	340.9671	66.4884	1471.3	0.67-1.10	0.044-0.088	30	11,14
V803 Cen	309.3671	20.7262	1596.4	0.78-1.17	0.059-0.109	12 - 15	11,15
Detached white dwarfs							
SDSS J065133.34+284423.4	186.9277	12.6886	765.5	0.247±0.015	0.49±0.02	$86.9^{+1.6}_{-1.0}$	16,17
SDSS J093506.92+441107.0	176.0796	47.3776	1188.0	0.312±0.019	0.75±0.24	[60]	18,19
SDSS J163030.58+423305.7	67.0760	43.3604	2389.8	0.298±0.019	0.76±0.24	[60]	18,20
SDSS J092345.59+302805.0	195.8199	44.7754	3883.7	0.275±0.015	0.76±0.23	[60]	18,21
Hot subdwarf binaries							
CD–30°11223	322.4875	28.9379	4231.8	0.54±0.02	0.79±0.01	82.9±0.4	22

[1]Strohmayer (2005), [2]Roelofs et al. (2010), [3]Ramsay et al. (2002), [4]Espaillat et al. (2005), [5]Green et al. (2018a), [6]Skillman et al. (1999), [7]Roelofs et al. (2006), [8]Fontaine et al. (2011), [9]Kupfer et al. (2015), [10]Patterson et al. (2002) , [11]Roelofs et al. (2007c), [12]Levitan et al. (2014),[13]Wevers et al. (2016), [14]Provencal et al. (1997), [15]Roelofs et al. (2007a), [16]Brown et al. (2011), [17]Hermes et al. (2012), [18]Brown et al. (2016c), [19]Kilic et al. (2014), [20]Kilic et al. (2011), [21](Brown et al. 2010), [22]Geier et al. (2013)

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Table: Kupfer+ 2015 (**arXiv: 1805.00482v2**)

AM CVn

- Cataclysmic variable
- Hot blue binary system
- White dwarf accretes H-poor material from companion

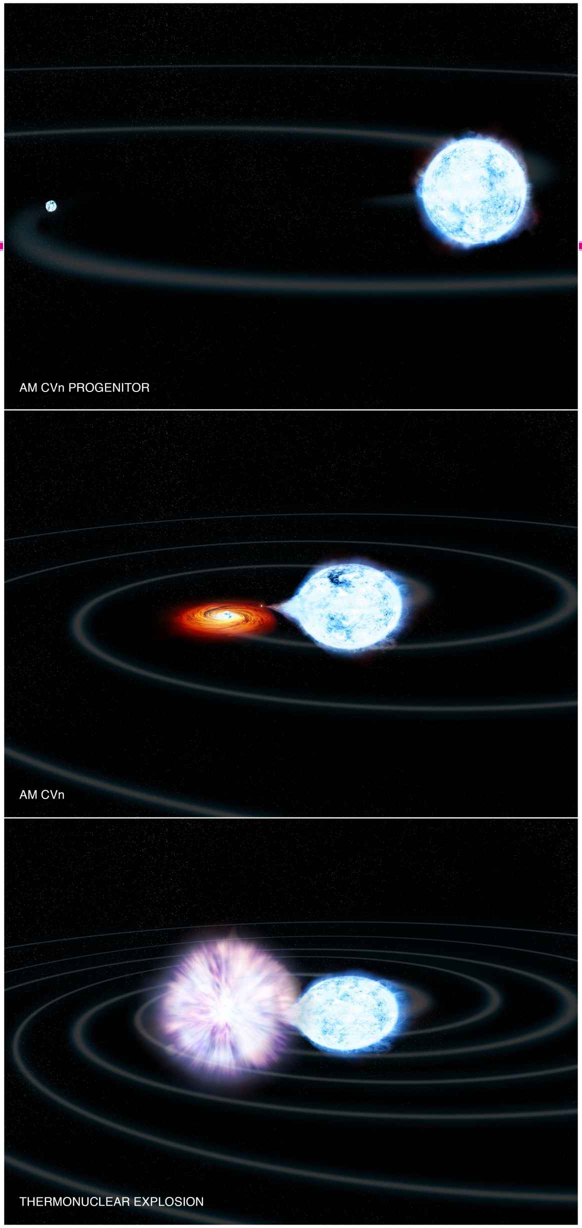
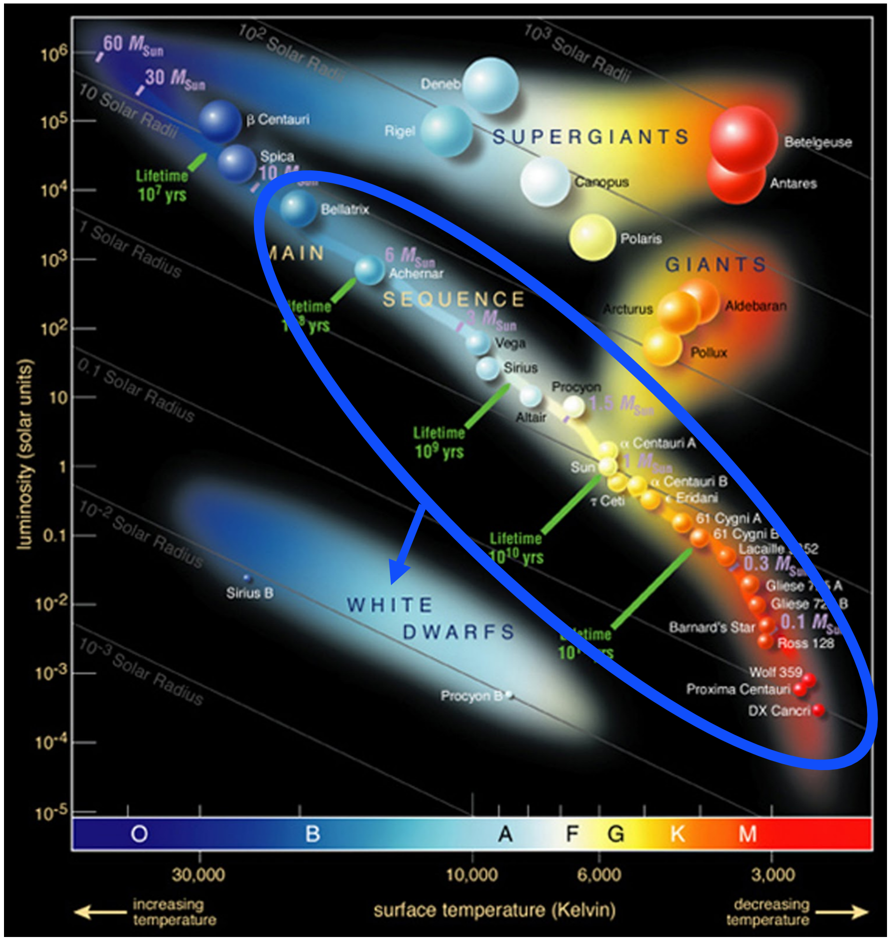


Image credit: NASA

HR Diagram



- Stellar evolution dependent on initial mass

Image credit: ESO

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Stellar Remnants

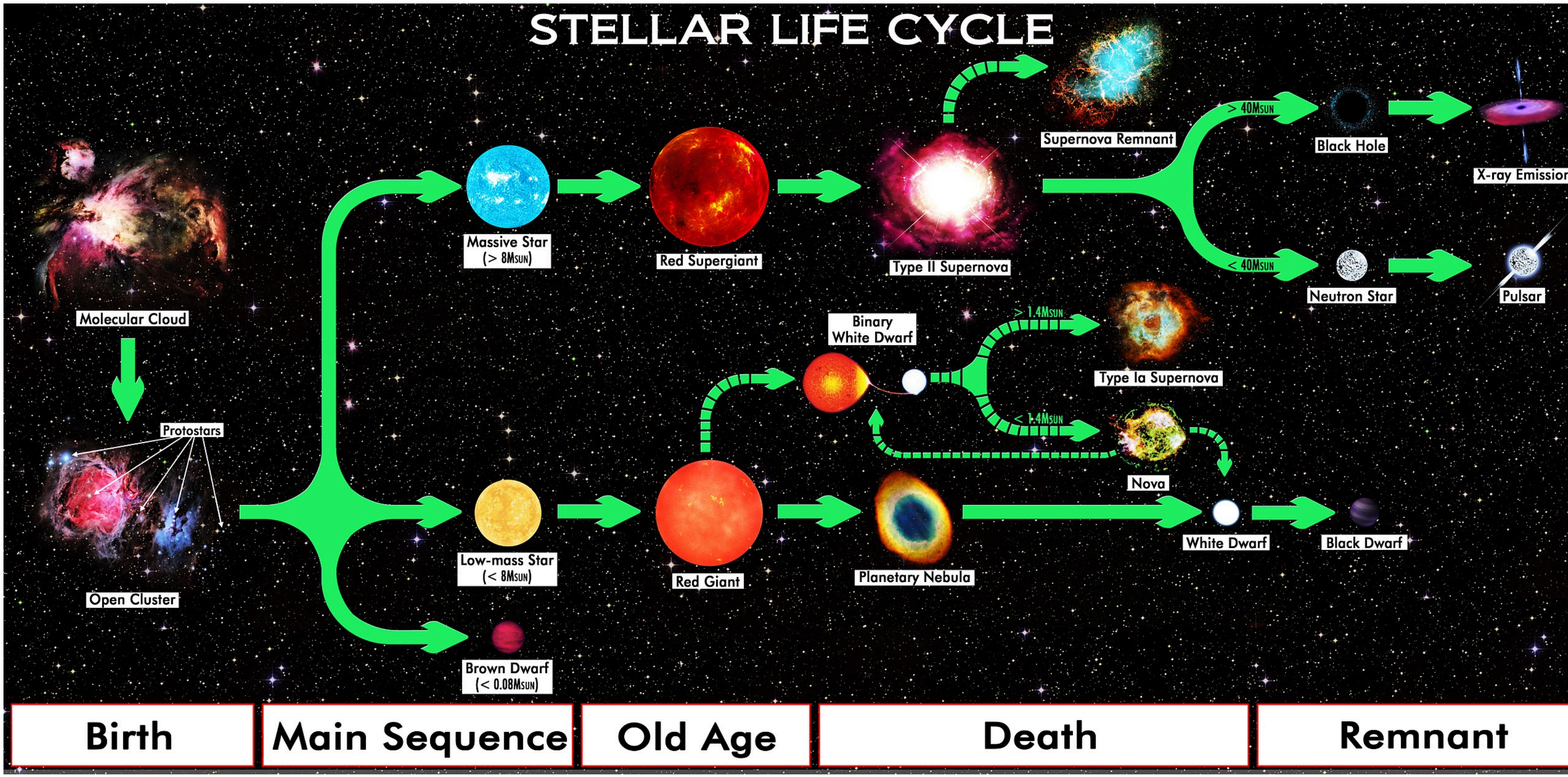

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Image credit:
R.N. Bailey