An S-CUBED Perspective on Be/White Dwarf Binaries as Rare Soft X-ray Transients

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Be/X-ray Binaries: The Standard Theory

- Be star + Neutron Star Compact Object
- Moderately eccentric orbit
- Orbital Period: 10s - 100s of days

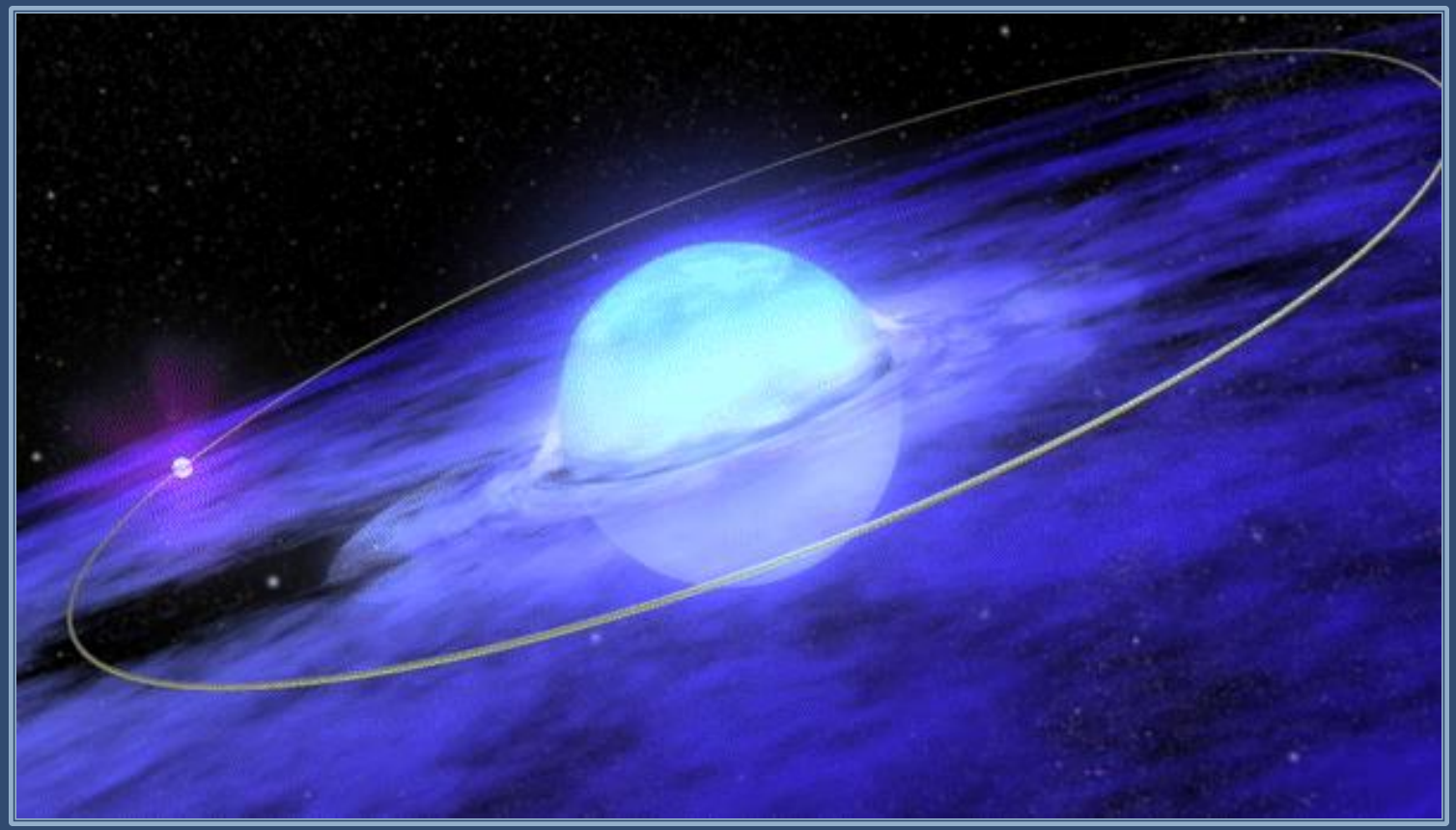


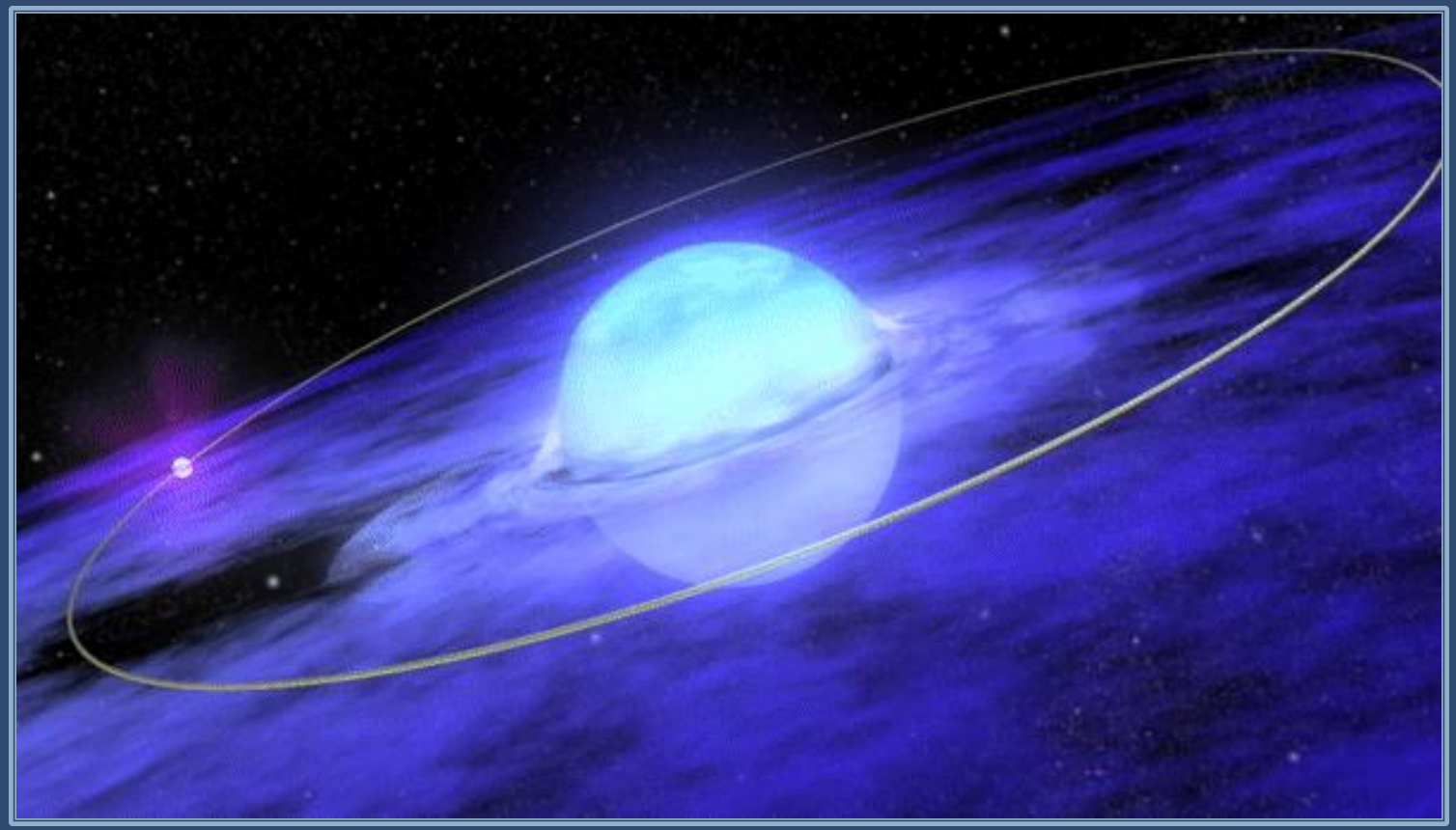
Image Credit: Walt Feimer, NASA/Goddard Space Flight Center

Be/X-ray Binaries: The Standard Theory

- Transient X-ray emitters
- 2 Types of X-ray Outburst:
  - Type I

    $L_X \sim 10^{36} - 10^{37}$ erg s^{-1}
  - Type II

    $L_X \geq 10^{37}$ erg s^{-1}



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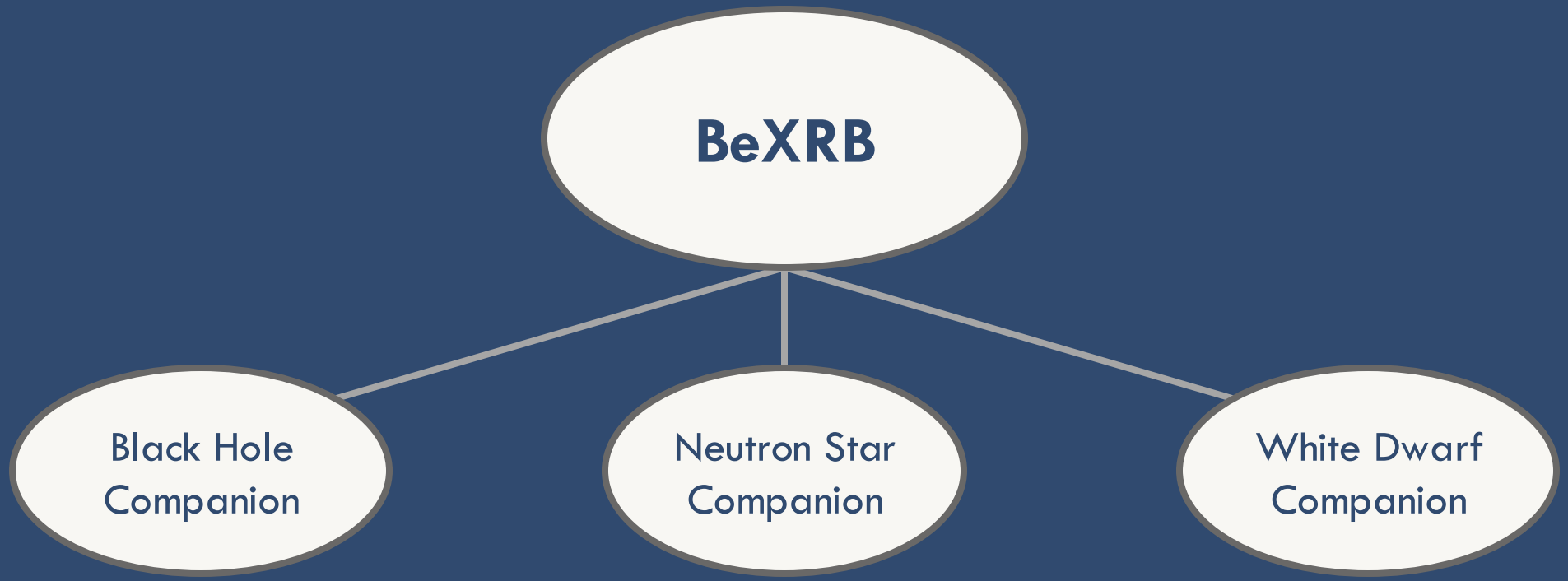
Be/X-ray Binaries: A More Complex View



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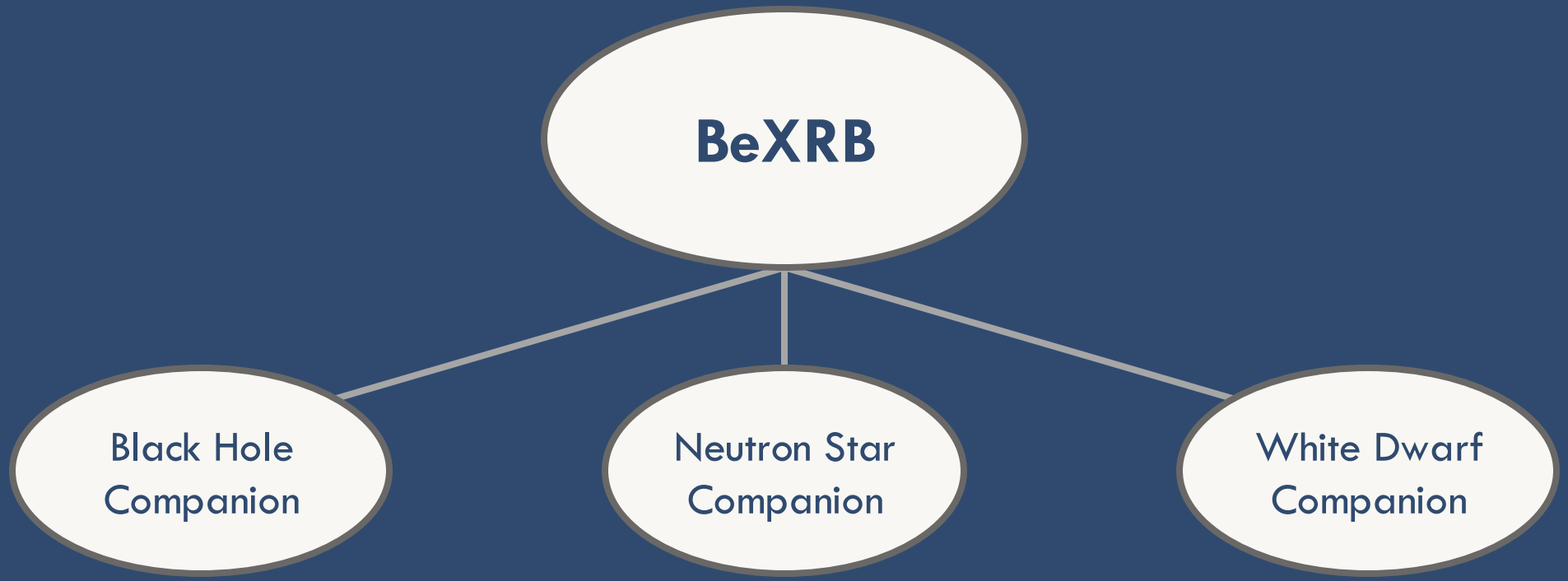
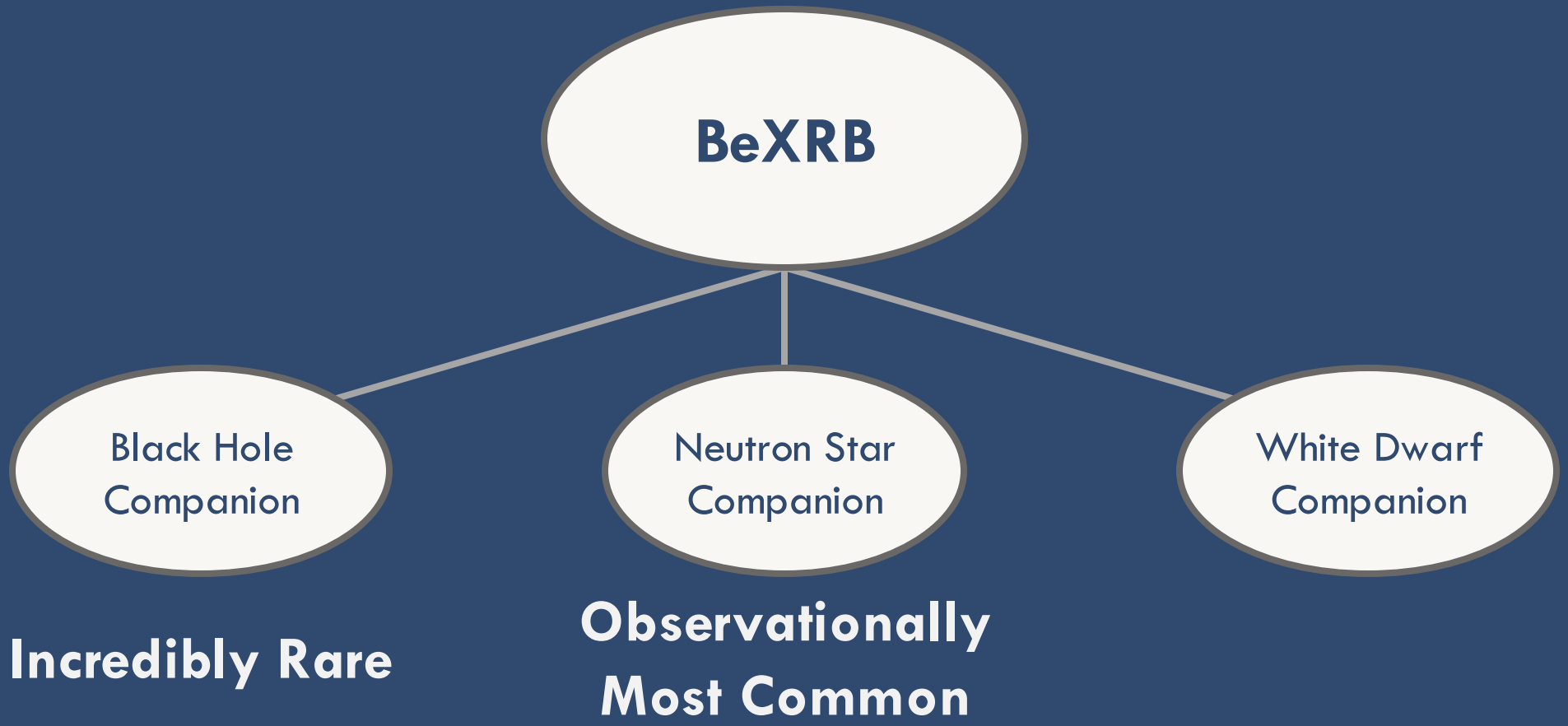


Incredibly Rare

Be/X-ray Binaries: A More Complex View



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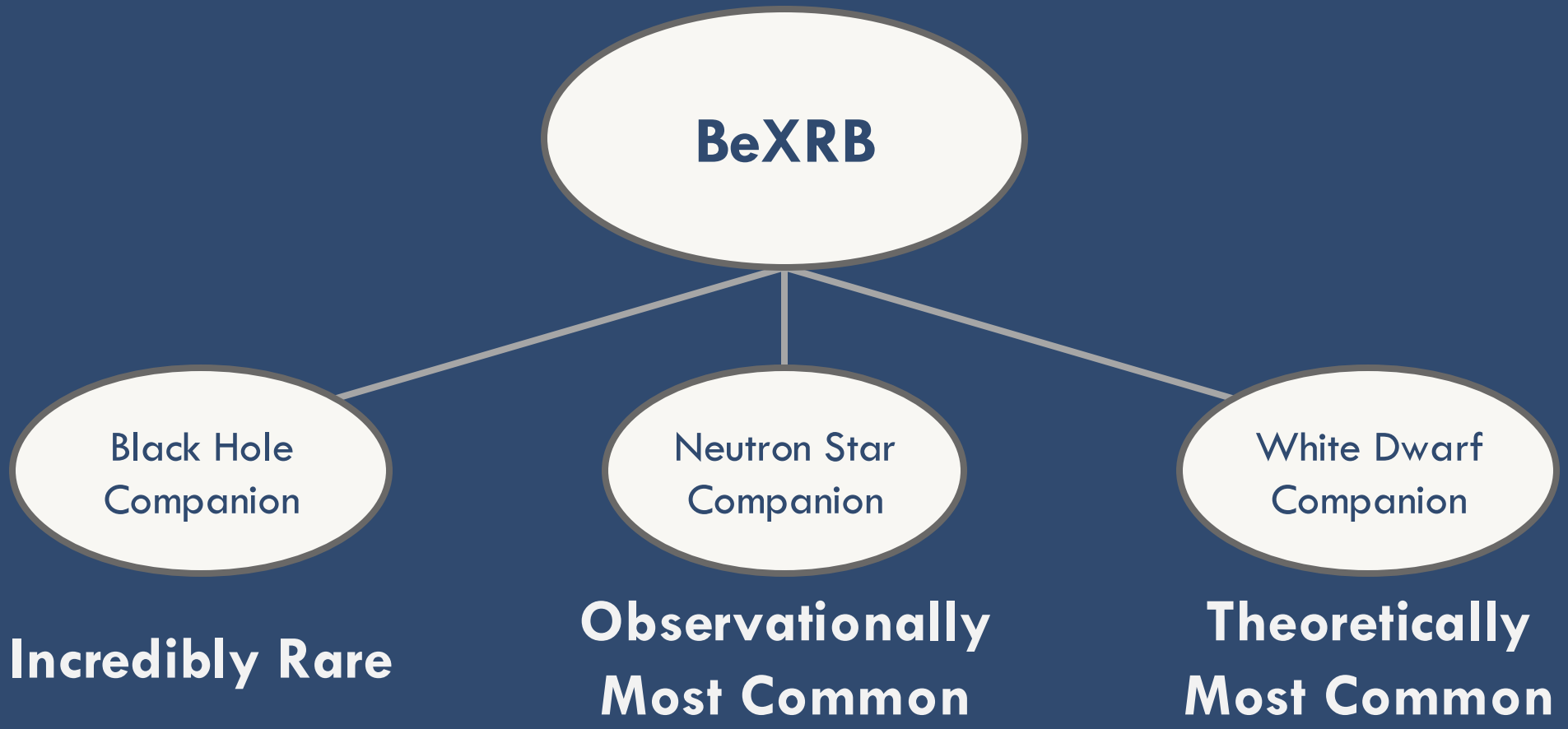
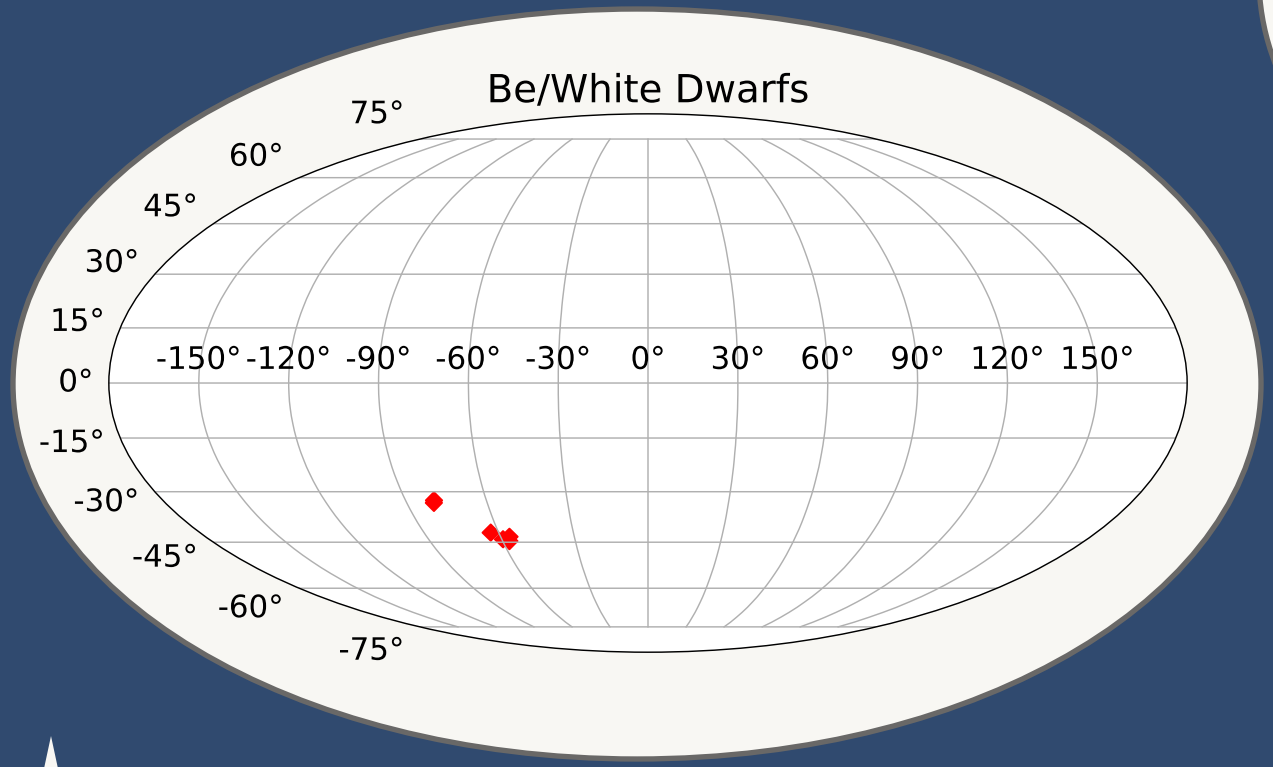
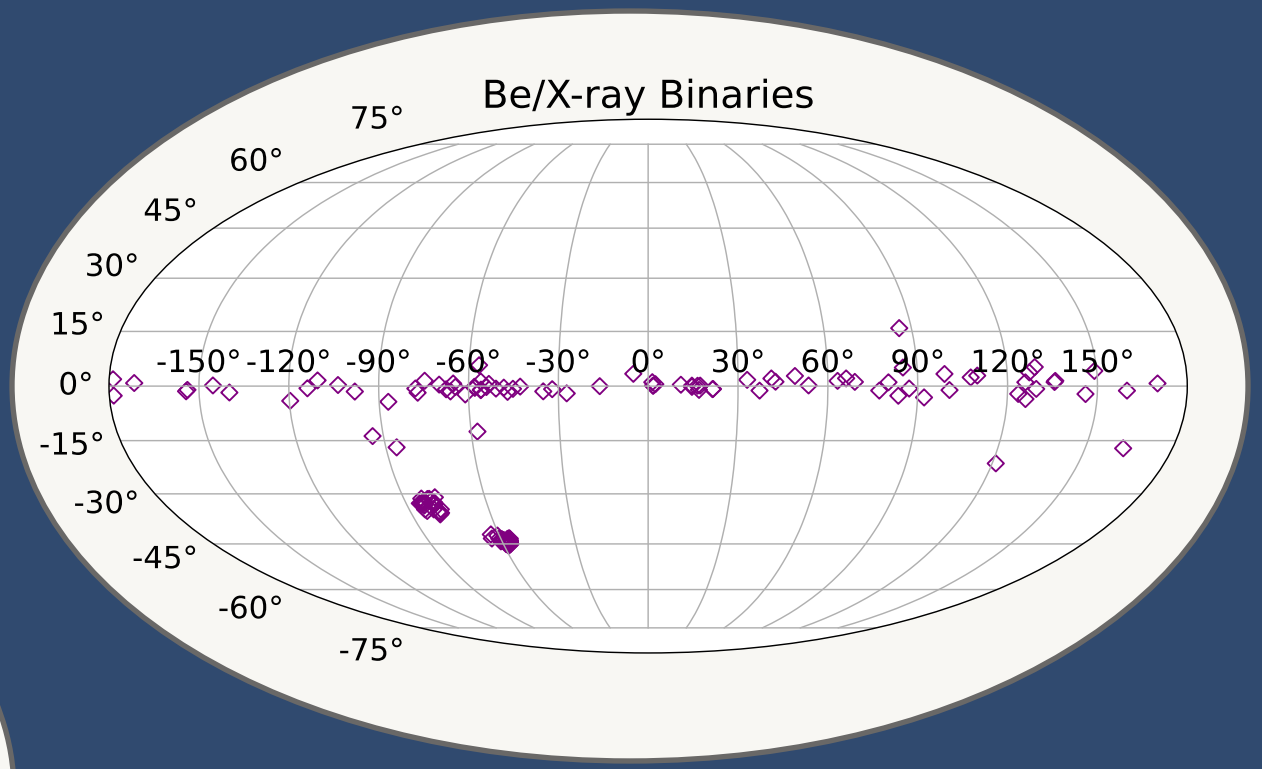



Be/White Dwarfs
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150° -120° -90° -60° -30° 0° 30° 60° 90° 120° 150°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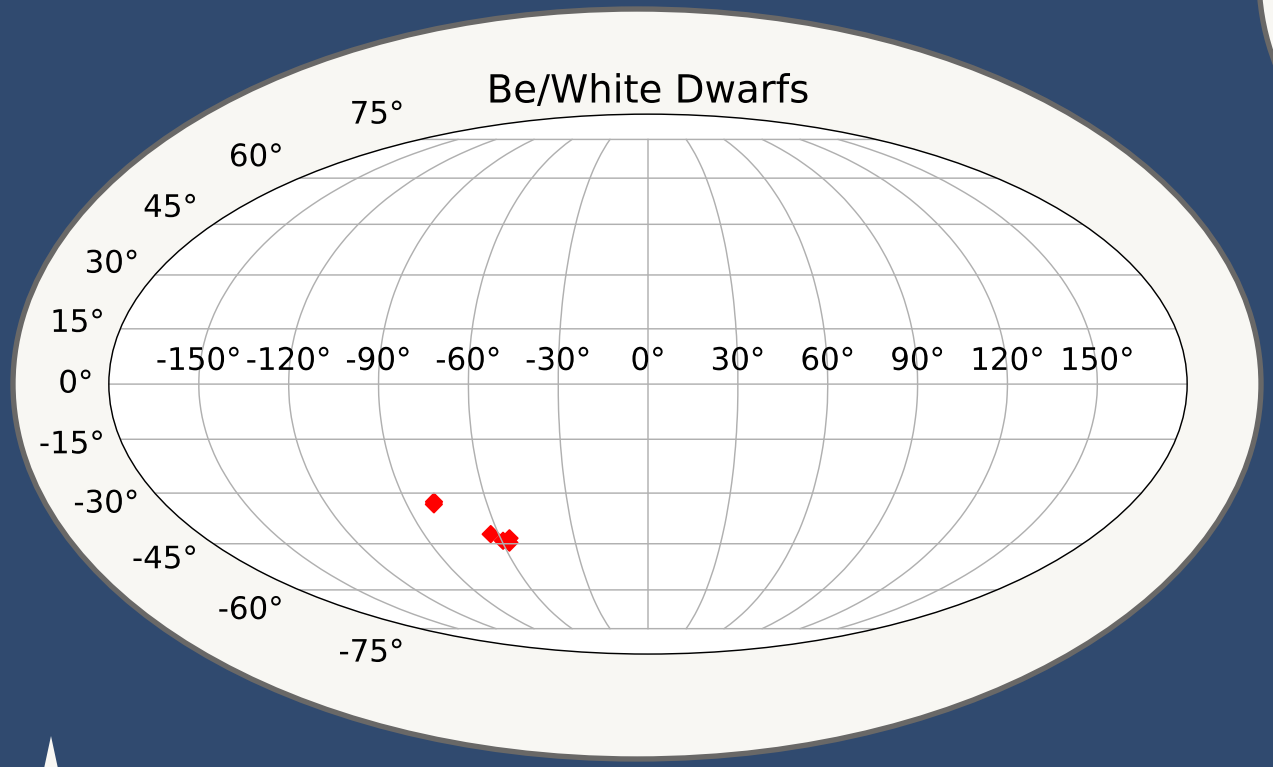
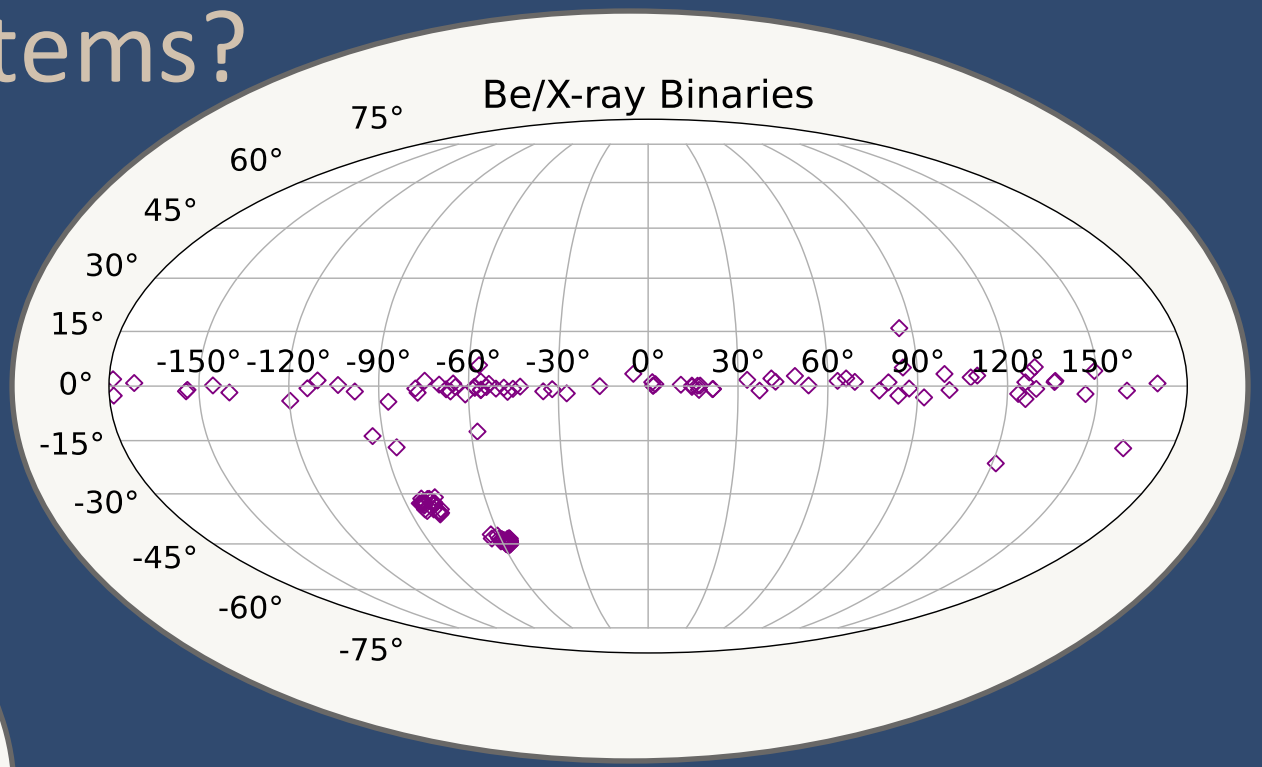
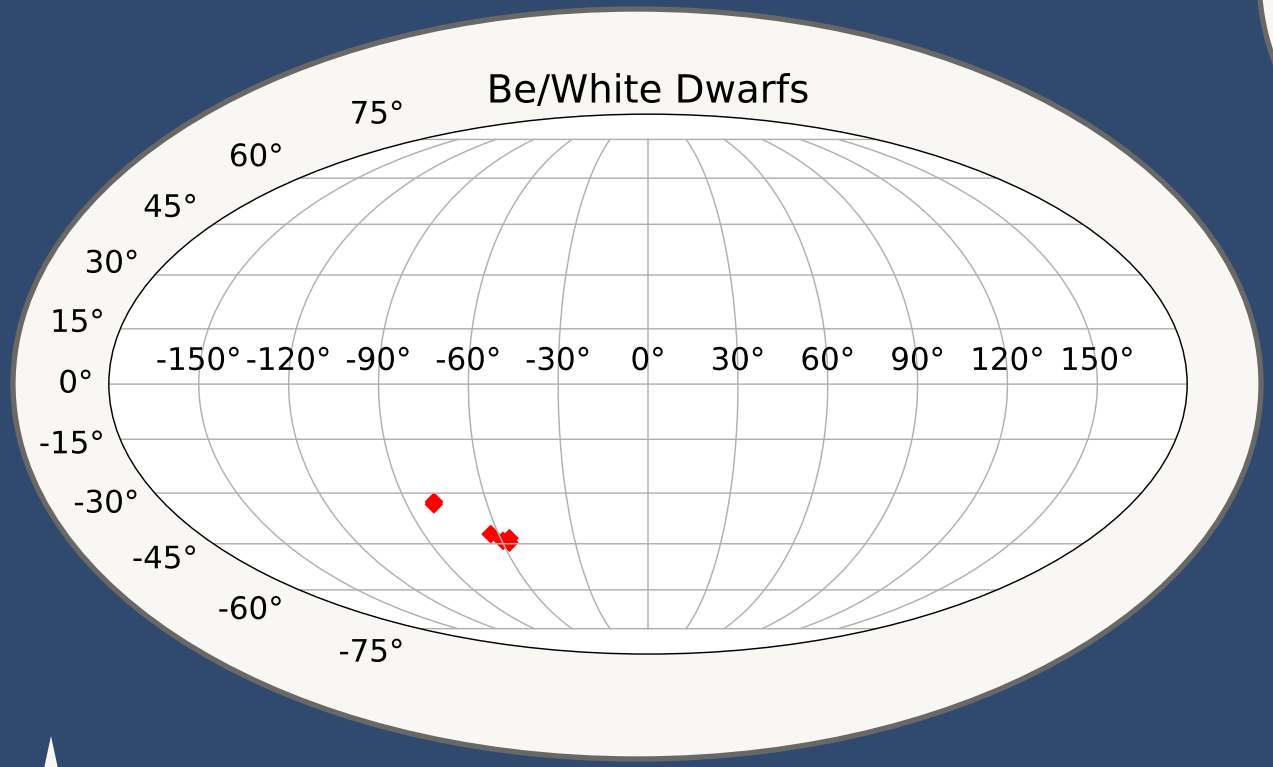
Where are the Be/WD Systems?

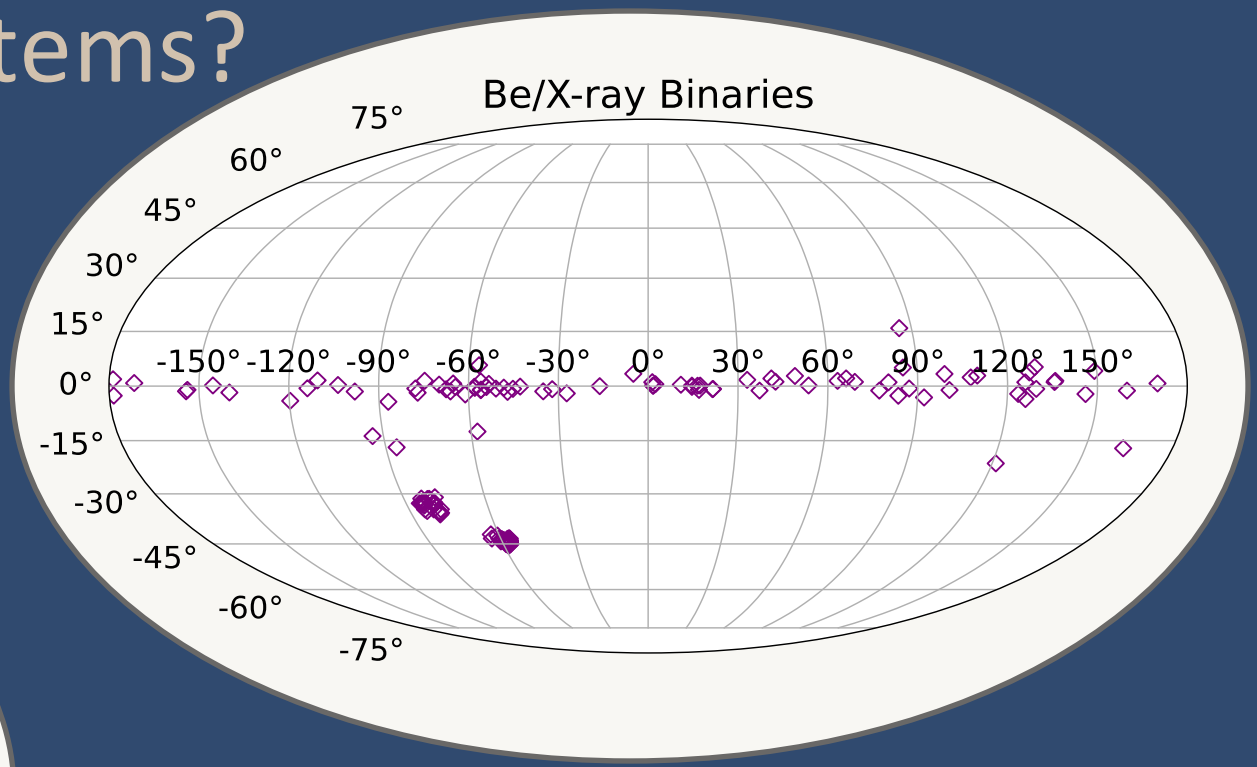




Where are the Be/WD Systems?

Theoretical Problem?





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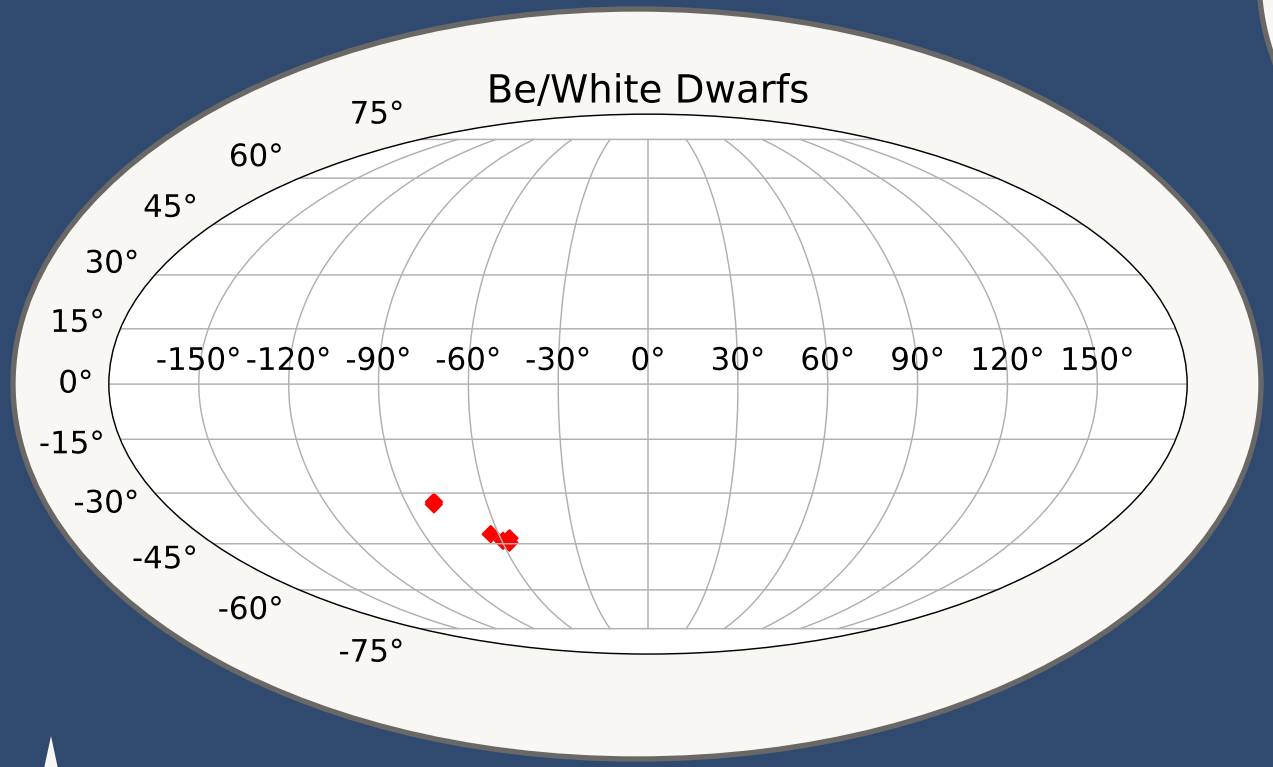
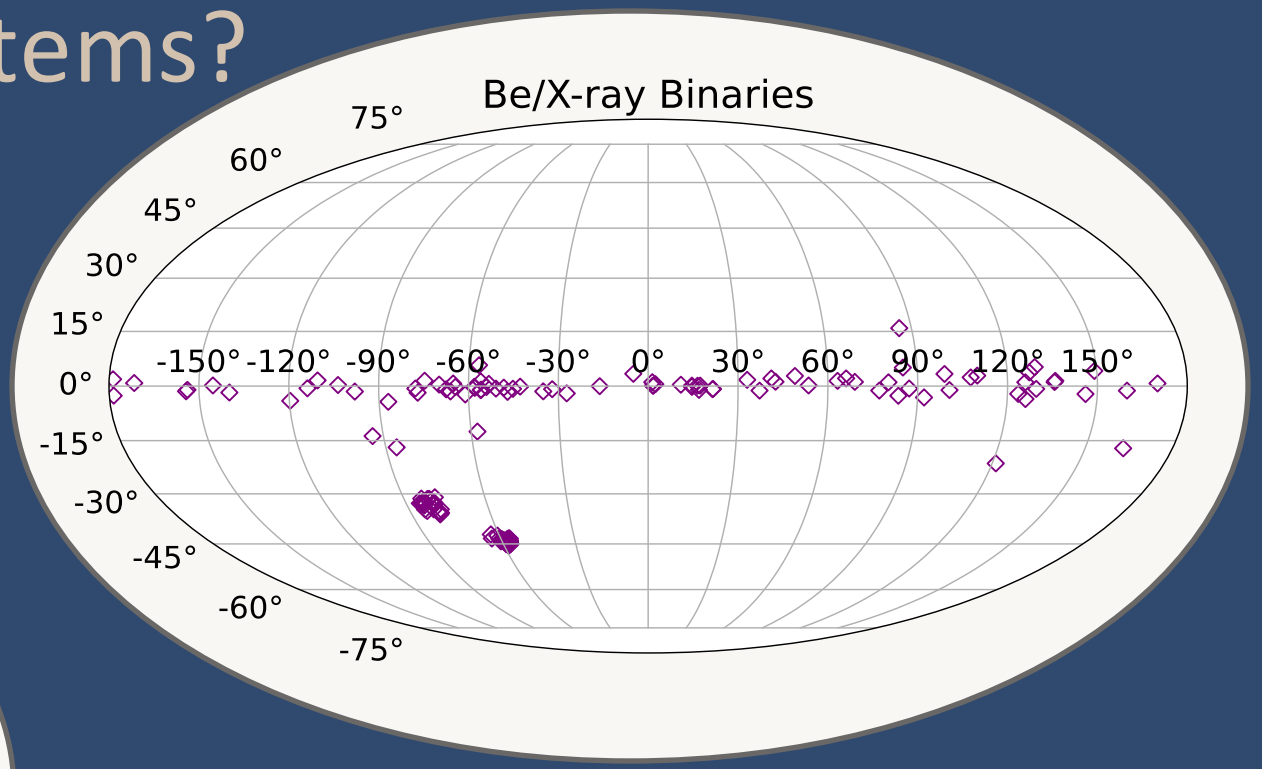
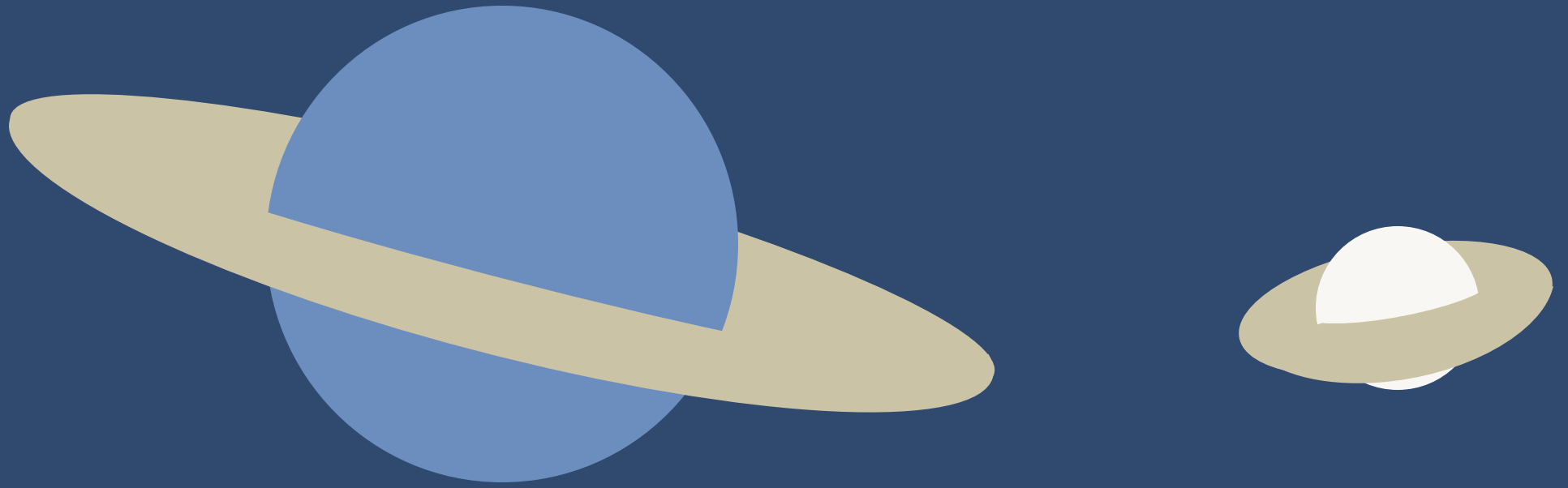




Observational Problem?

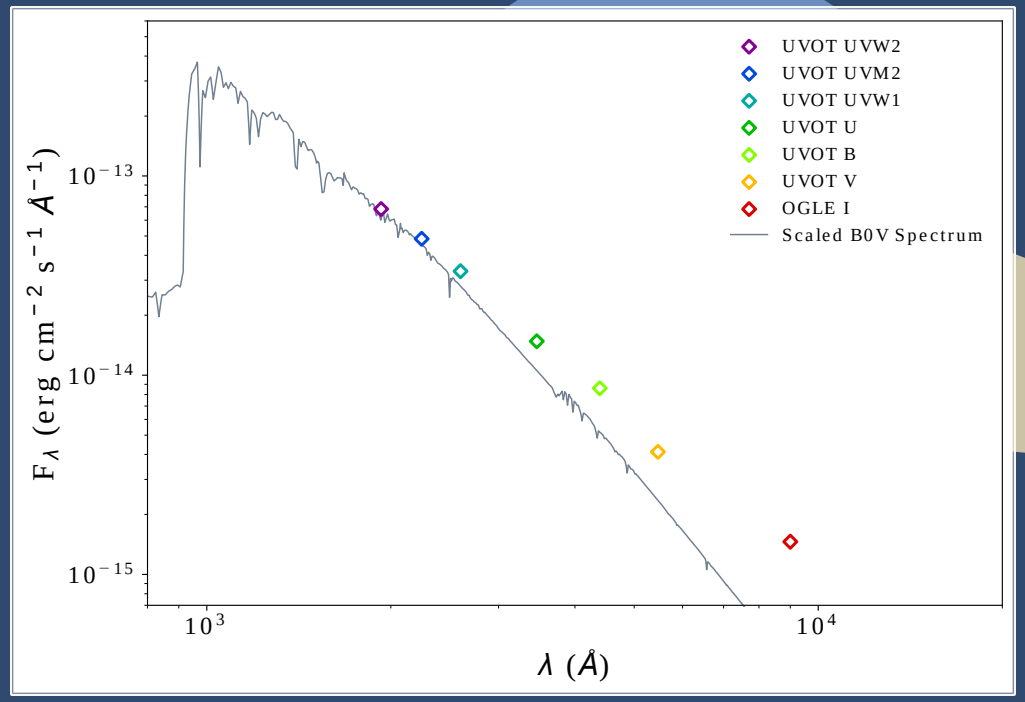
Be/White Dwarf Binaries: Observational Properties



IR Optical UV Soft X-Ray Hard X-Ray

Be/White Dwarf Binaries: Observational Properties

Be Star + Circumstellar Disk
dominates IR – UV emission



IR Optical UV Soft X-Ray Hard X-Ray

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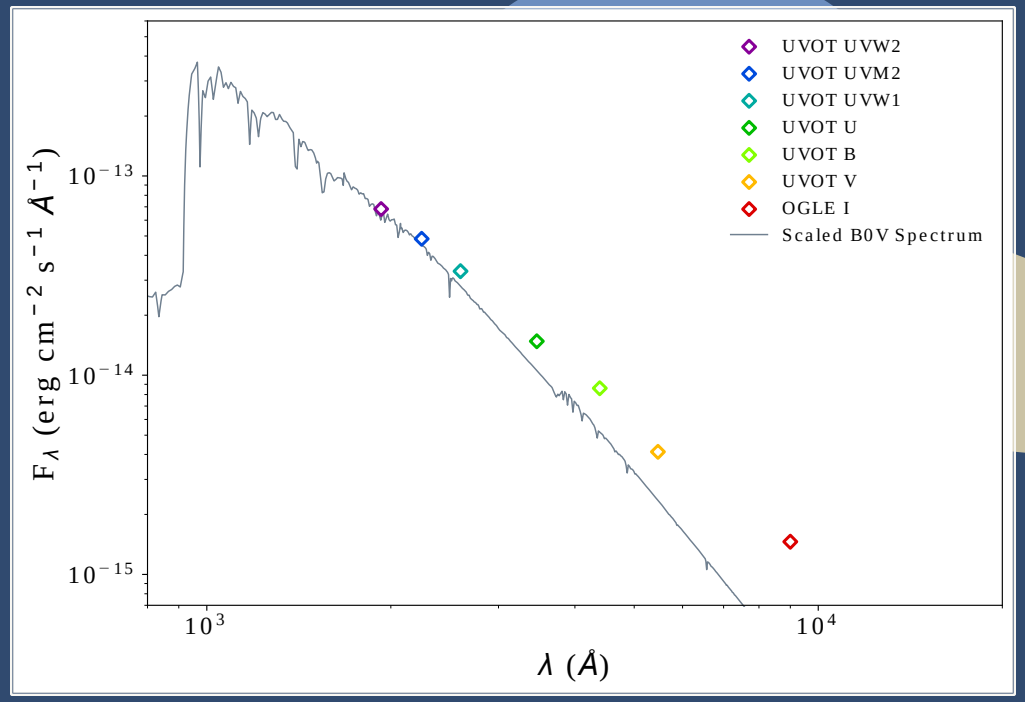


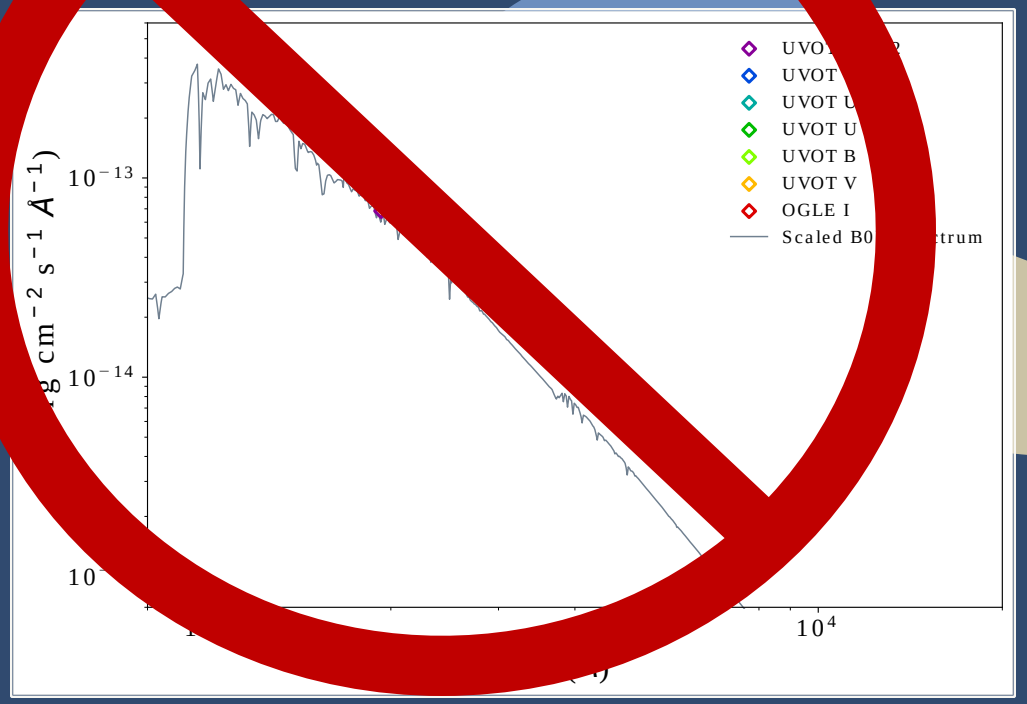
Accreting WD produces faint Hard X-ray Emission

$L_X \sim 10^{29} - 10^{33}$ erg s^{-1}

IR Optical UV Soft X-Ray **Hard X-Ray**

Be/White Dwarf Binaries: Observational Properties

Be Star [illegible] circumstellar [illegible]
dominates IR – UV emission

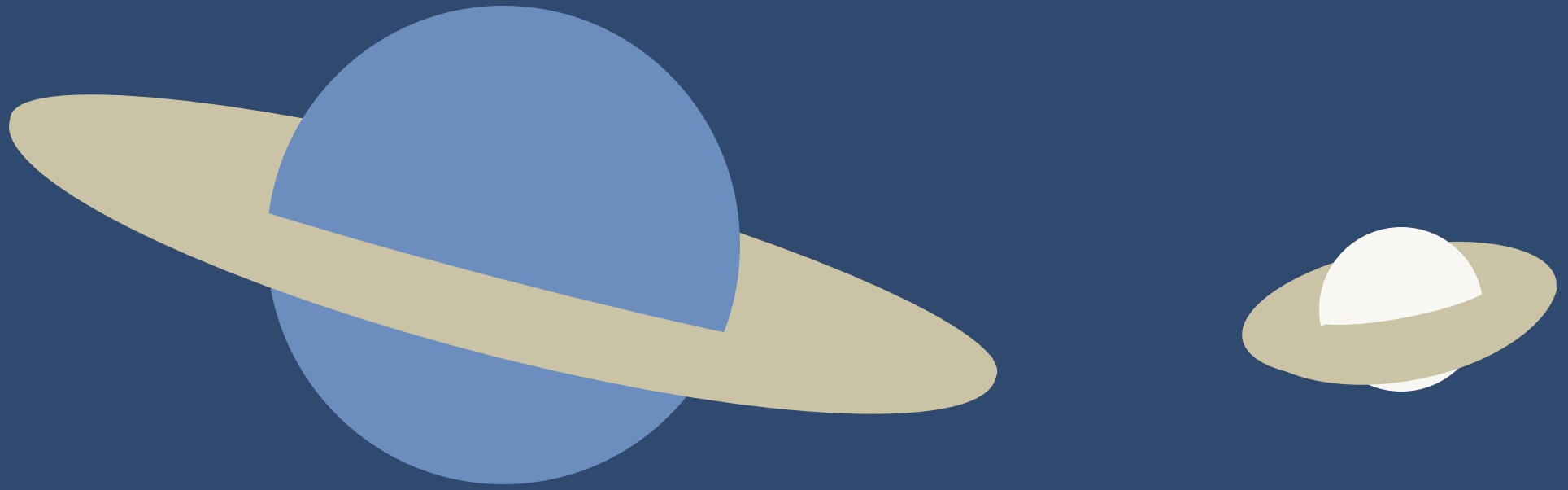


Accreti[illegible]WD produ[illegible] faint
Hard X-ray Emiss[illegible]

$L_X \sim 10^{2[illegible]} - 10^{33}$ erg s^{-1}

IR Optical UV Soft X-Ray Hard X-Ray

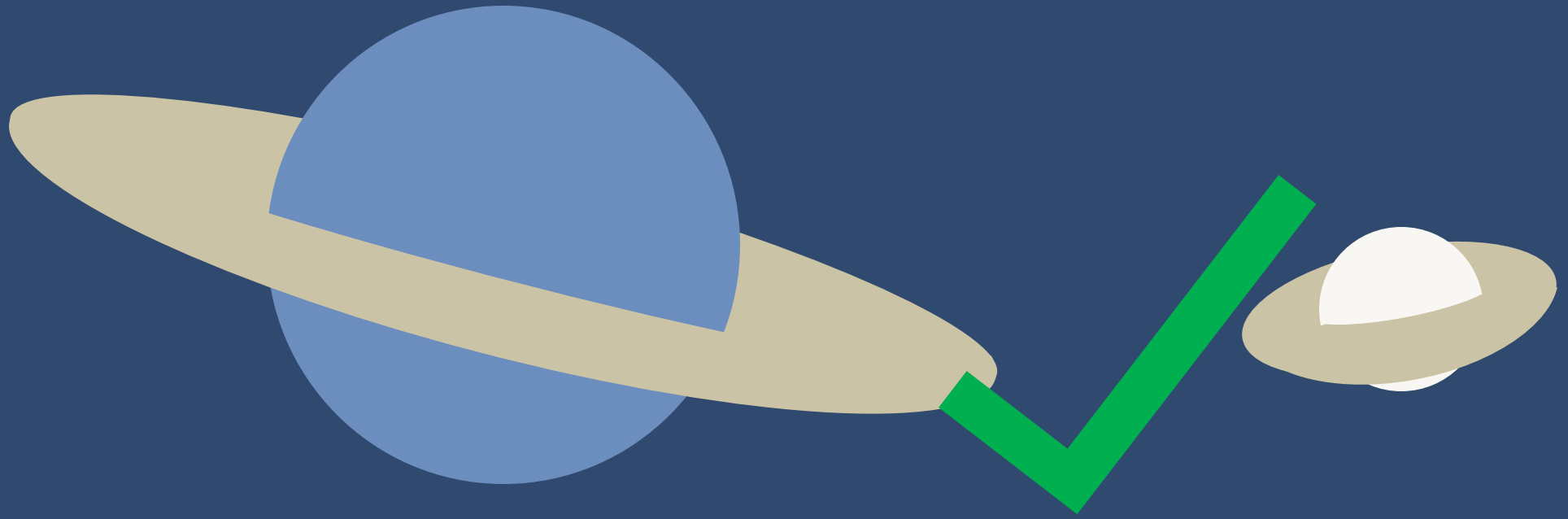
Be/White Dwarf Binaries: Observational Properties



WD produces bright, transient
Soft X-ray outbursts

IR Optical UV **Soft X-Ray** Hard X-Ray

Be/White Dwarf Binaries: Observational Properties



WD produces bright, transient
Soft X-ray outbursts

IR Optical UV **Soft X-Ray** Hard X-Ray

Finding Be/White Dwarf Binaries

- Best Found through Soft X-ray Surveys:
  - Scan a large area of the sky
  - Take frequent observations
  - Need low Column Density of material along the line of sight

Finding Be/White Dwarf Binaries

- Best Found through Soft X-ray Surveys:
  - Scan a large area of the sky
  - Take frequent observations
  - Need low Column Density of material along the line of sight
- Best Place to Search:
  - The Small Magellanic Cloud (SMC)

Image Credit: NASA/Swift/S. Immler (GSFC) and M. Siegel (Penn State)

S-CUBED: The Swift SMC Survey

- Ongoing since 2016
- Designed to detect outbursts from new and existing Be/X-ray Binaries
- Science Highlights:
  - Detection of several important outbursts (e.g. SMC X-3)
  - Detection of several new BeXRB systems (e.g. SXP 182)

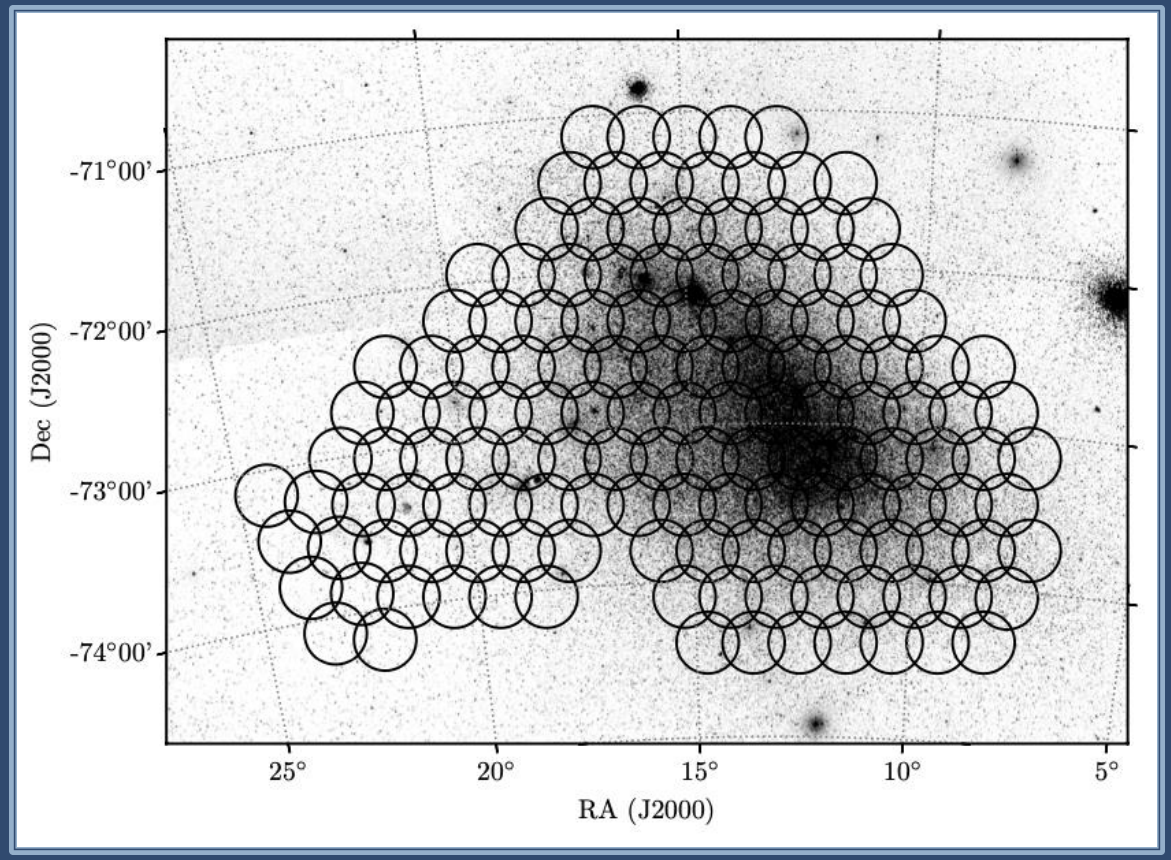


Image Credit: Kennea et al. 2018

S-CUBED: The Swift SMC Survey

- Weekly Swift monitoring of the SMC
- 60s observations of 149 tiles
- Simultaneous UV and X-ray observations
  - **UVOT**: UVW1-band
  - **XRT**: 0.3-10 keV band

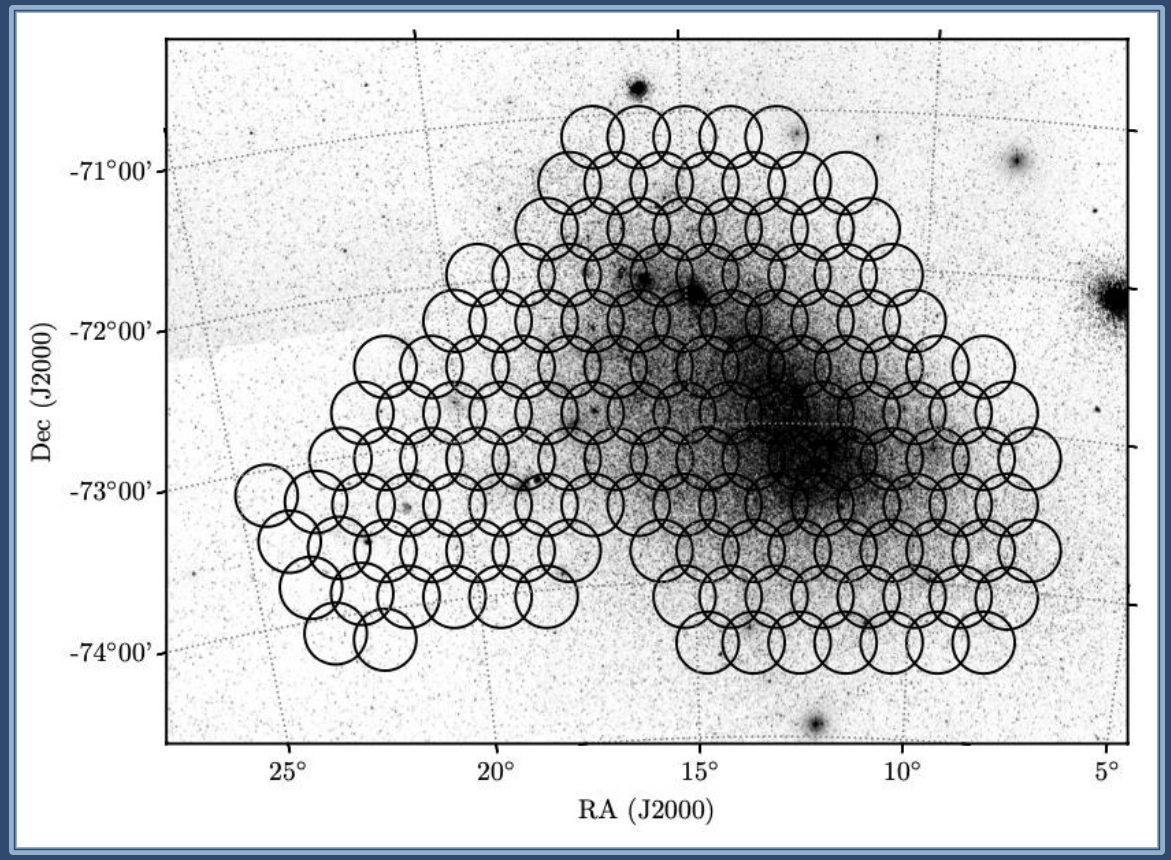
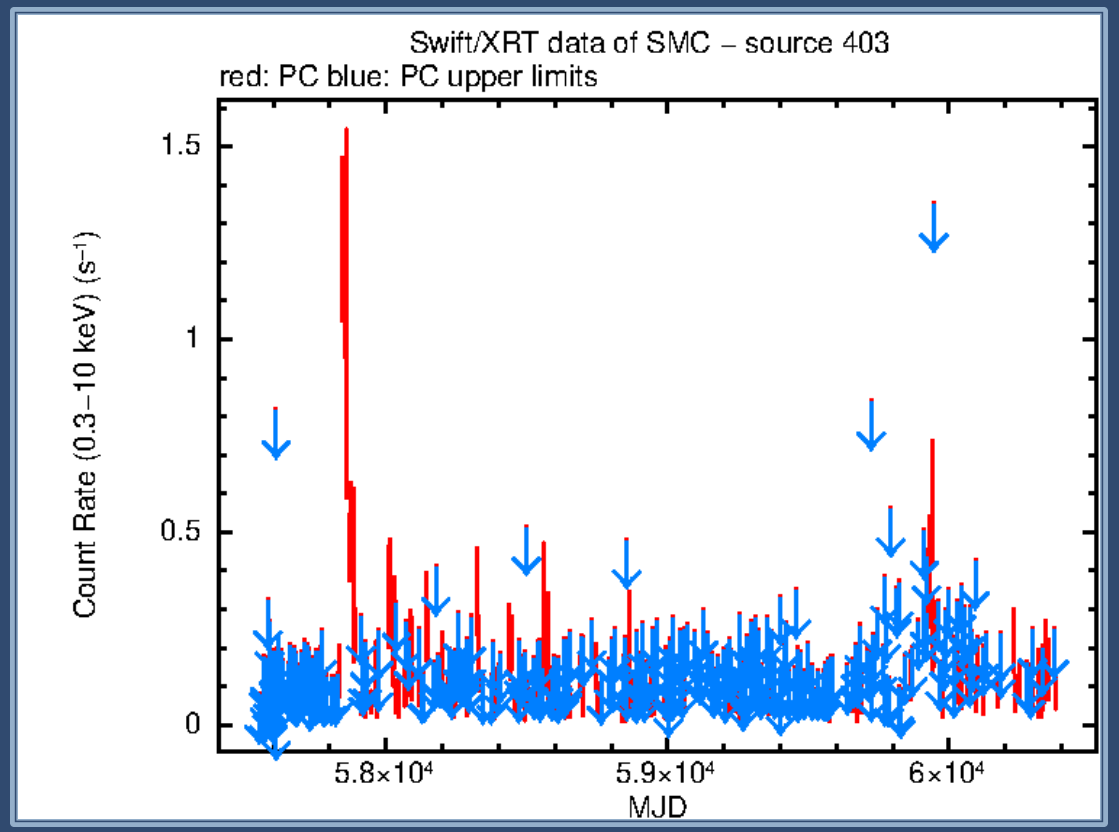
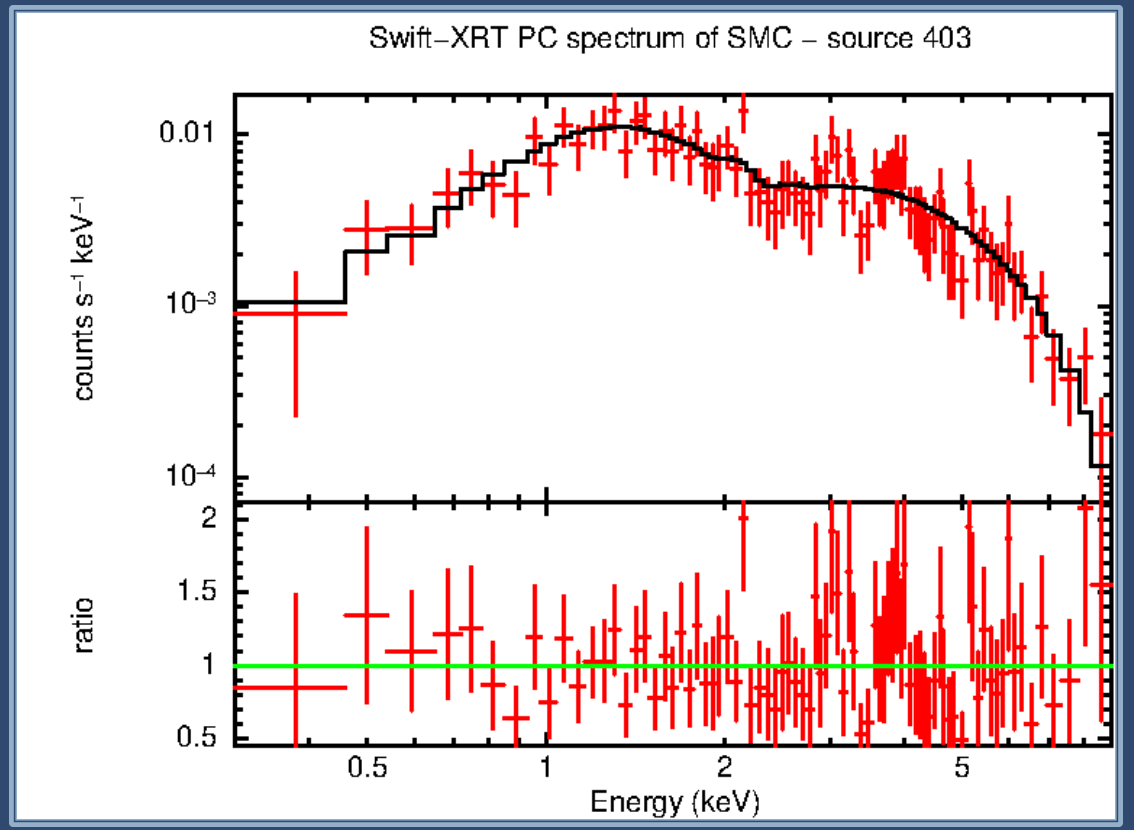


Image Credit: Kennea et al. 2018

S-CUBED: The Swift SMC Survey

Data Products





S-CUBED: The Swift SMC Survey

Source Name	First Detection	Reference
Swift J004427.3−734801	January 2020	Coe et al. 2020
Swift J011511.0-725611	December 2020	Kennea et al. 2021
CXOU J005245.0−722844	May 2024	Gaudin et al. 2024

Swift J004427.3−734801: 2020 Outburst

X-ray Spectroscopy of Swift J004427.3−734801

- **Model for Fitting:**
  Absorbed Thermal Blackbody
  - $\mathrm{k}T_{BB} = 90 \pm 6$ eV
  - $N_H = 5.9 \times 10^{20}$ cm^{-2} (SMC standard)
- **Improved Fit:**
  - $\mathrm{k}T_{BB} = 58 \pm 6$ eV
  - $N_H = (3.4 \pm 2.0) \times 10^{21}$ cm^{-2}

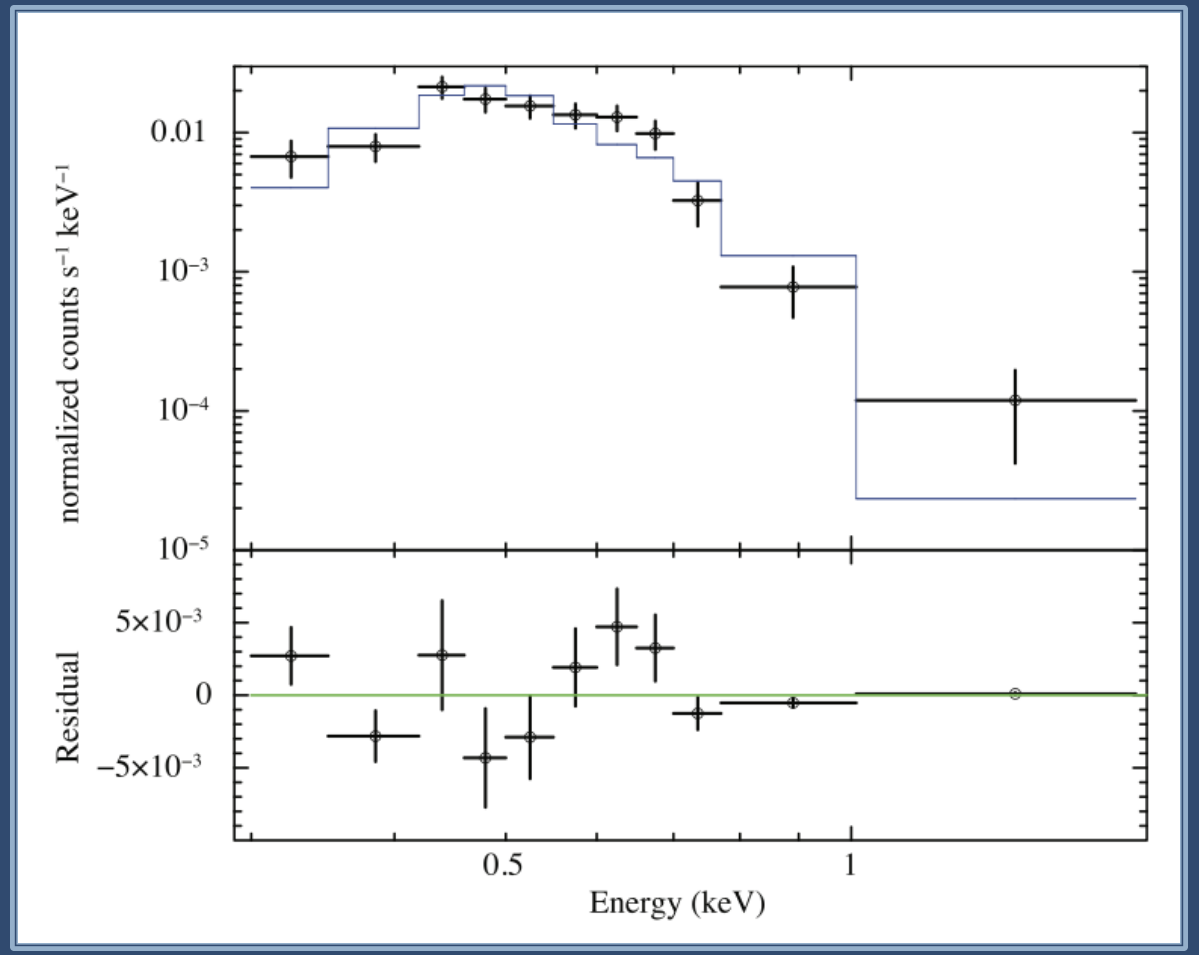


Image Credit: Coe et al. 2020

X-ray Photometry of Swift J004427.3−734801

- **First Detection:**
  - 00:48 UTC on 22 Jan 2020
- **Duration of Outburst:**
  - ~120 days
- **Max Luminosity:**
  - $L_X = 4.1^{+1.6}_{-2.2} \times 10^{36}$ erg s^{-1}

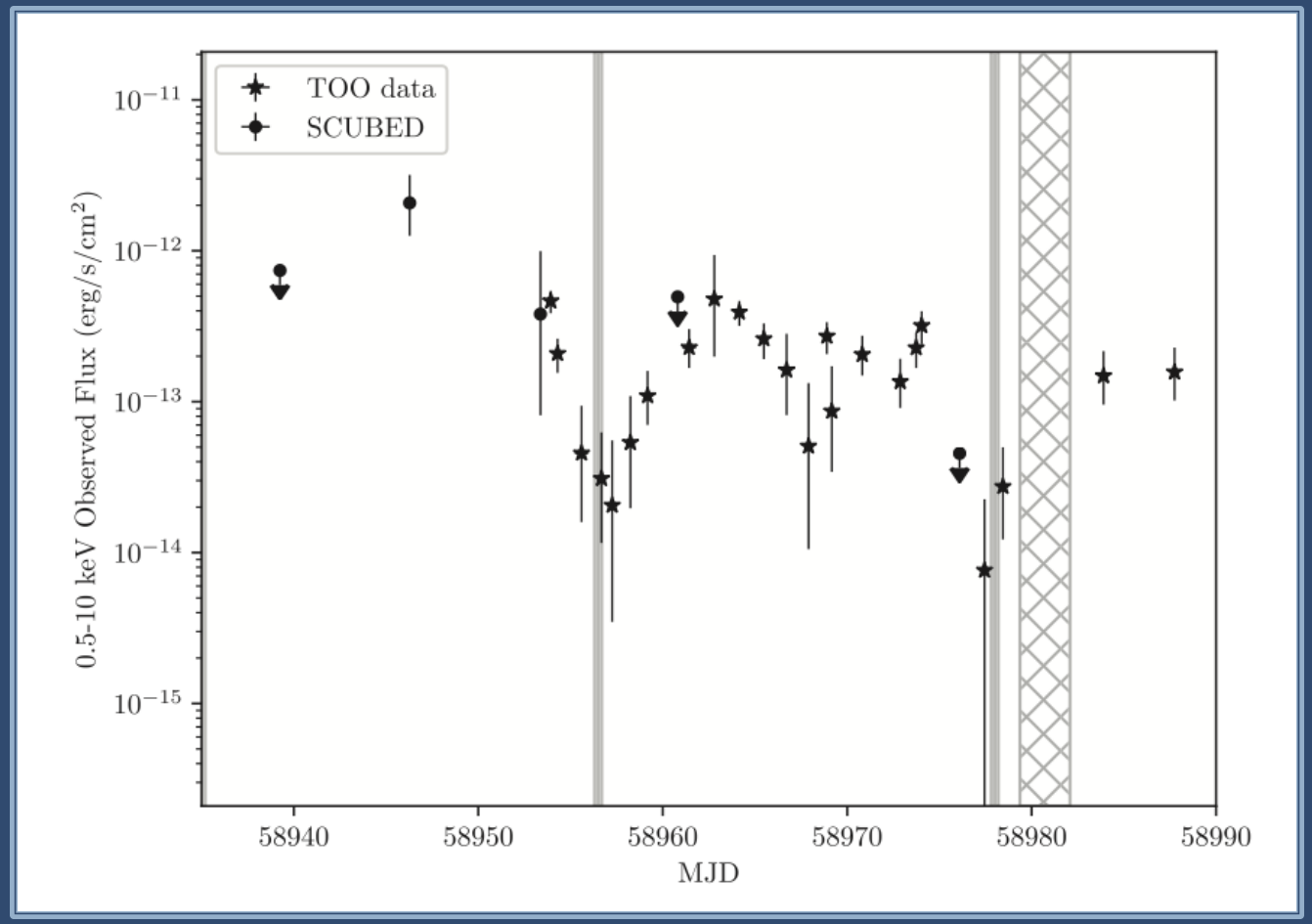
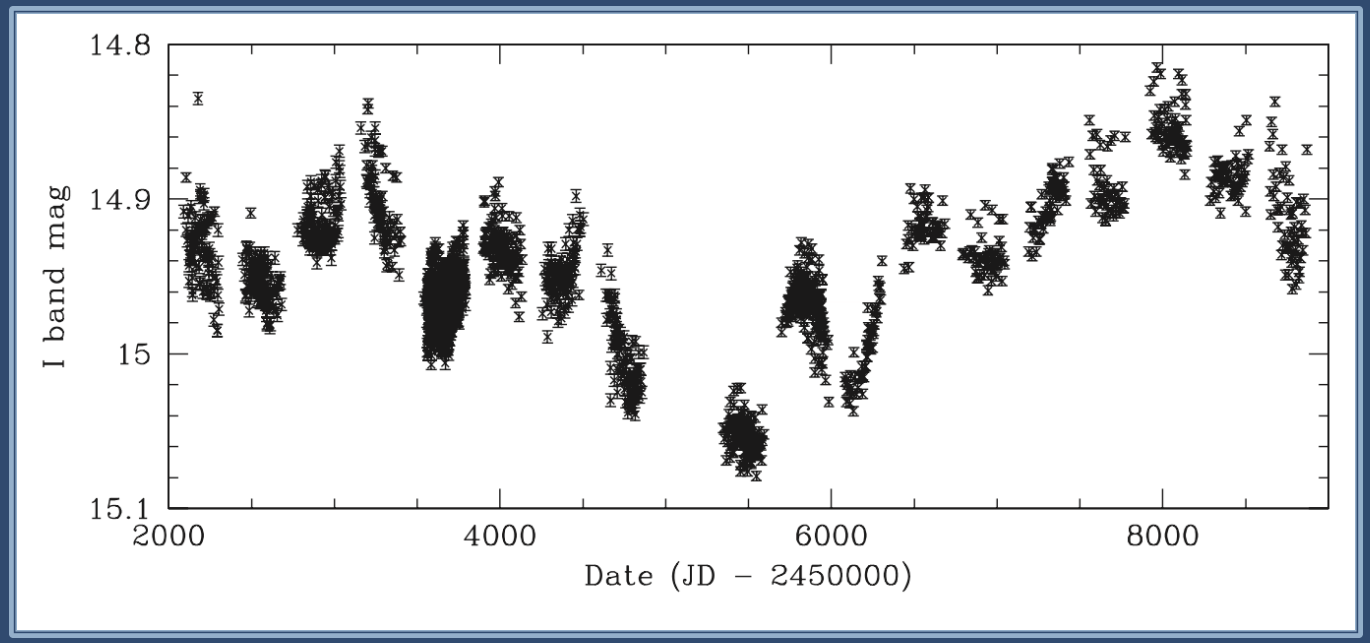


Image Credit: Coe et al. 2020

Multiwavelength Variability of Swift J004427.3−734801



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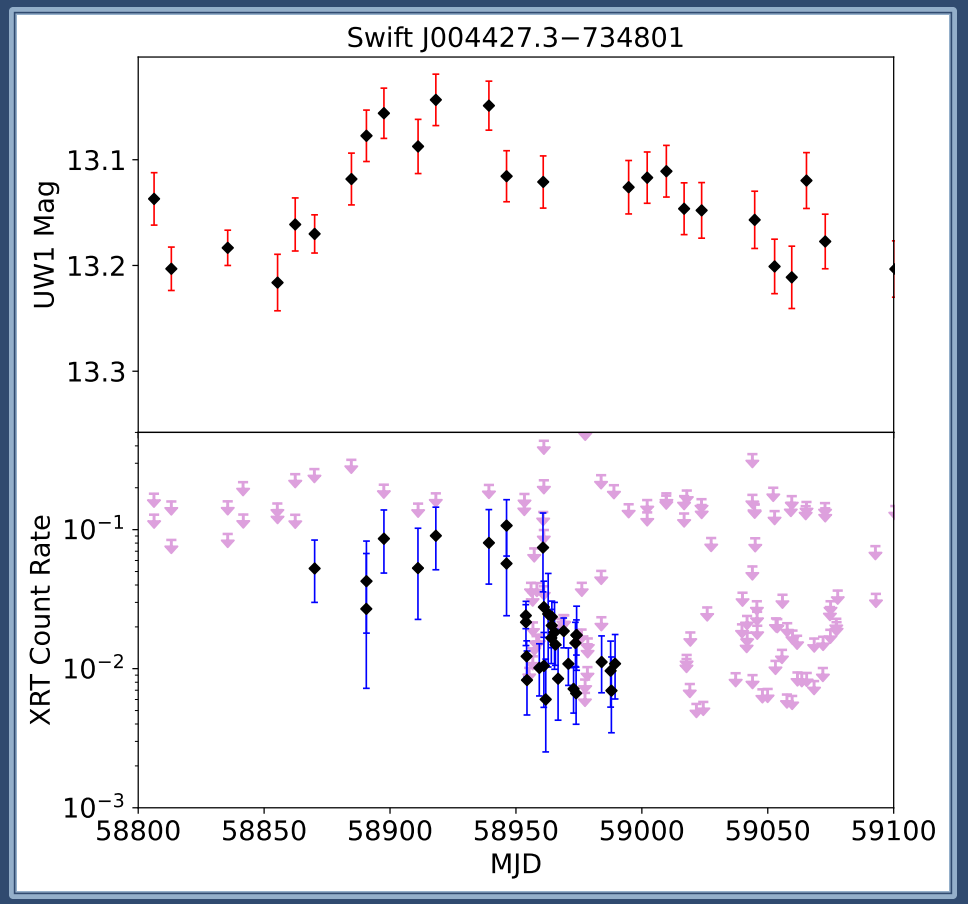
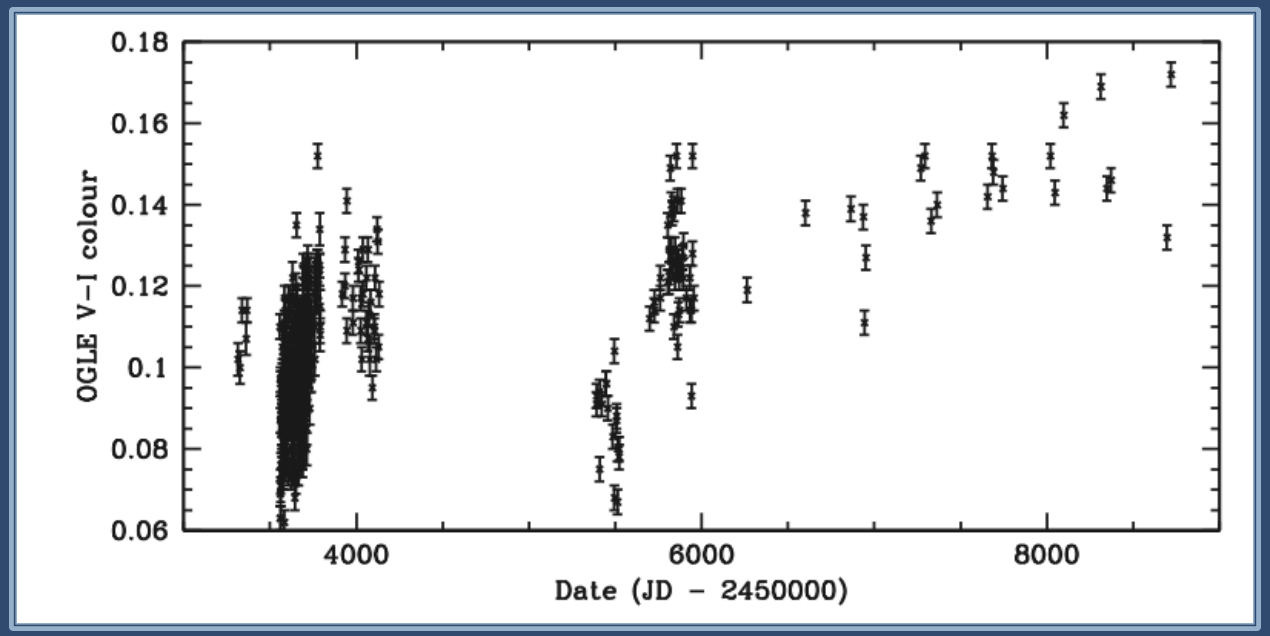


Multiwavelength Variability of Swift J004427.3−734801



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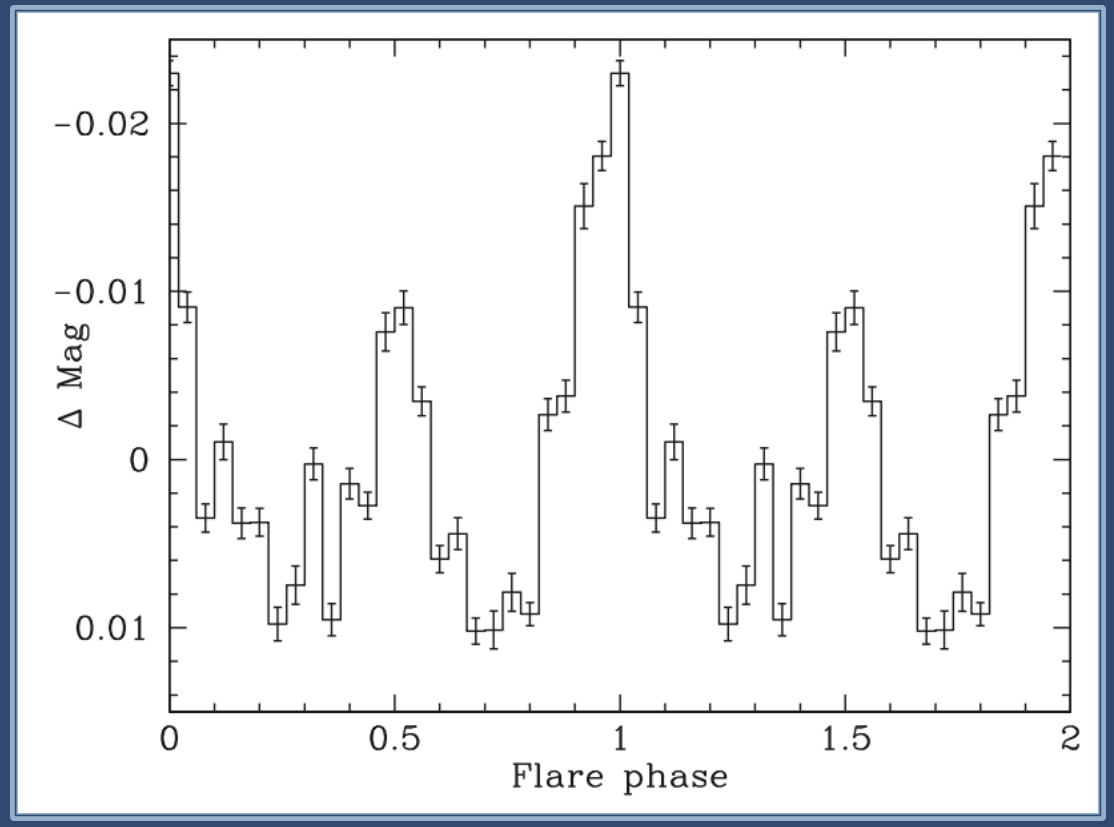

Image Credit: Coe et al. 2020

P_{orb} = 21.5 days

Multiwavelength Properties of Swift J004427.3−734801

- **Increased I-Band and UVW1-Band Brightness**
- **Redder When Brighter**
- **Orbital Period:**
  - 21.5 days
- **Conclusion:**
  - CSD has grown
  - ”Type II” outburst
  - Stable Nuclear Burning

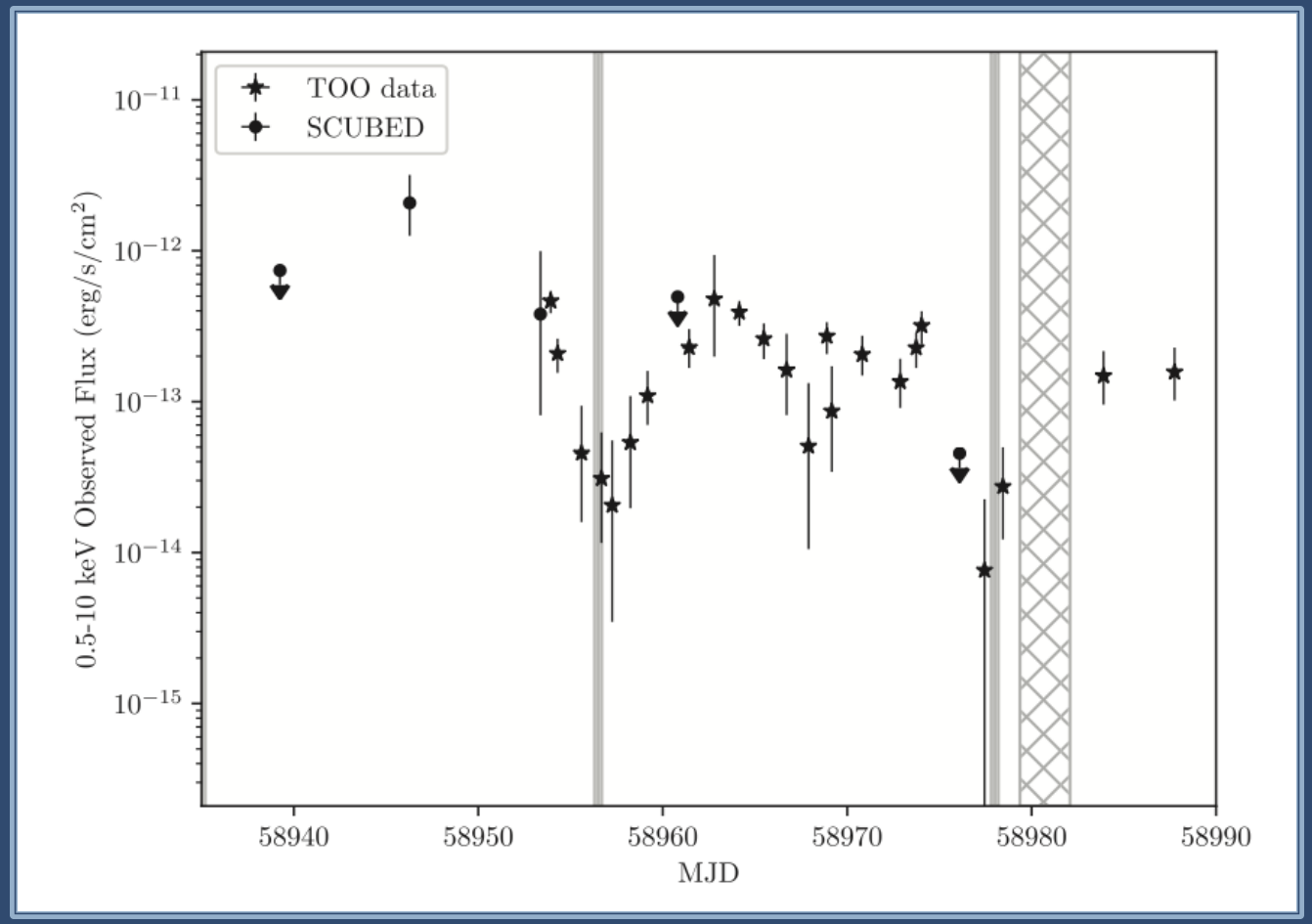

Image Credit: Coe et al. 2020

Swift J011511.0-725611: 2021 Outburst

X-ray Spectroscopy of Swift J011511.0-725611

- **Best-Fitting Model:**
  Absorbed Thermal Blackbody with 1 Absorption Edge
  - $kT_{BB} = 96.7 \pm 4.2$ eV
  - $E_{edge} = 0.864 \pm 0.011$ keV
    O VIII edge (0.871 keV)
  - $R_{emit} = 1{,}642 \pm 83$ km

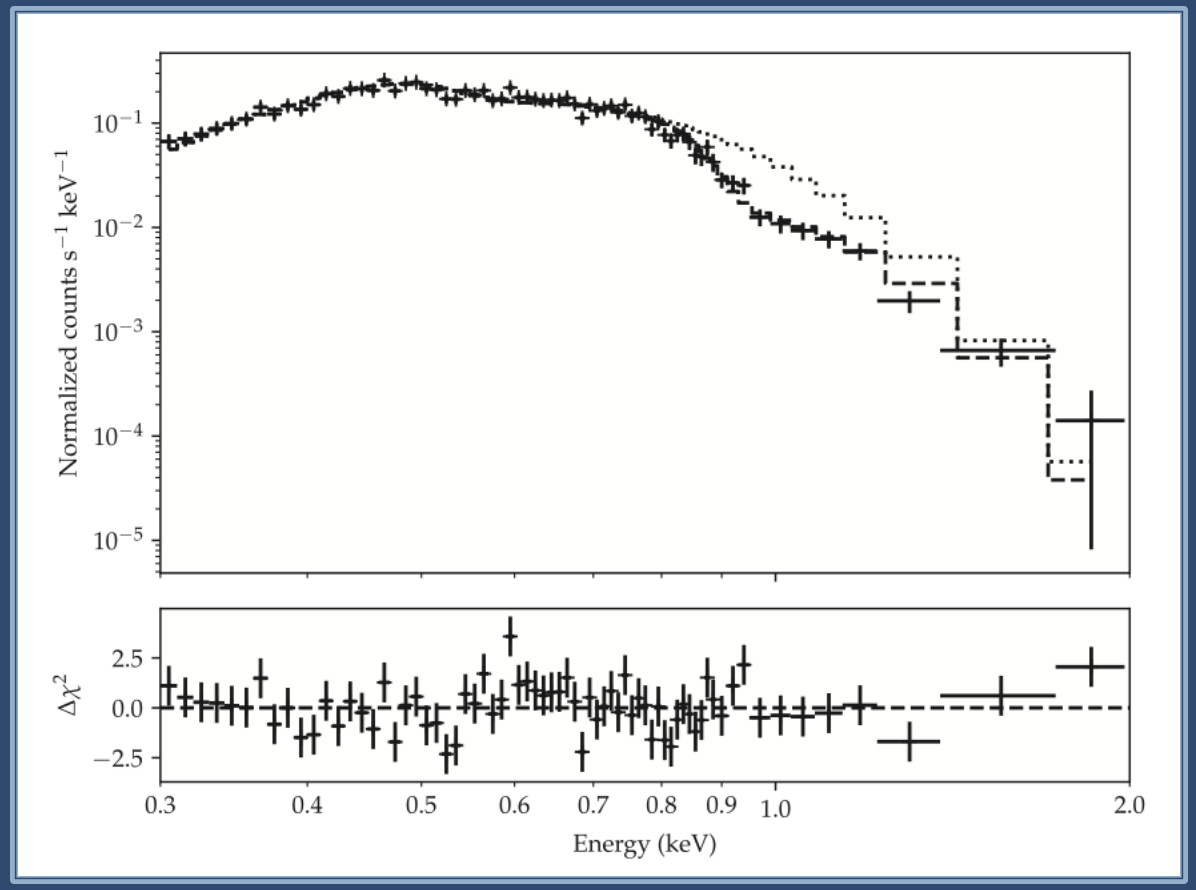

Image Credit: Kennea et al. 2021

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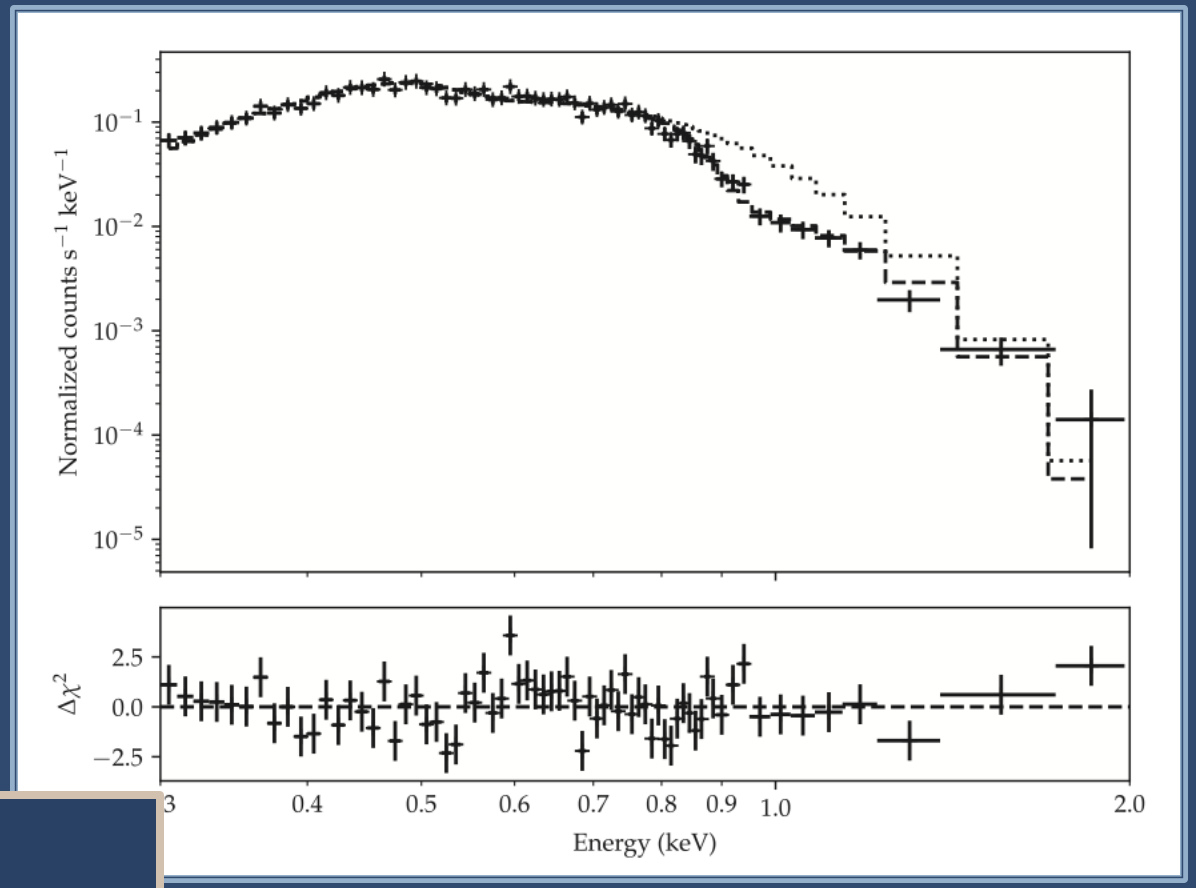


Credit: Kennea et al. 2021

Consistent with a
1.2 $M_\odot$ Carbon/Oxygen White Dwarf

X-ray Photometry of Swift J011511.0-725611

- **First Detection:**
  - 08:37 UTC on 29 Dec 2020
- **Duration of Outburst:**
  - ~120 days
- **Max Luminosity:**
  - $L_X = 3.3^{+0.2}_{-0.2} \times 10^{36}$ erg s^{-1}

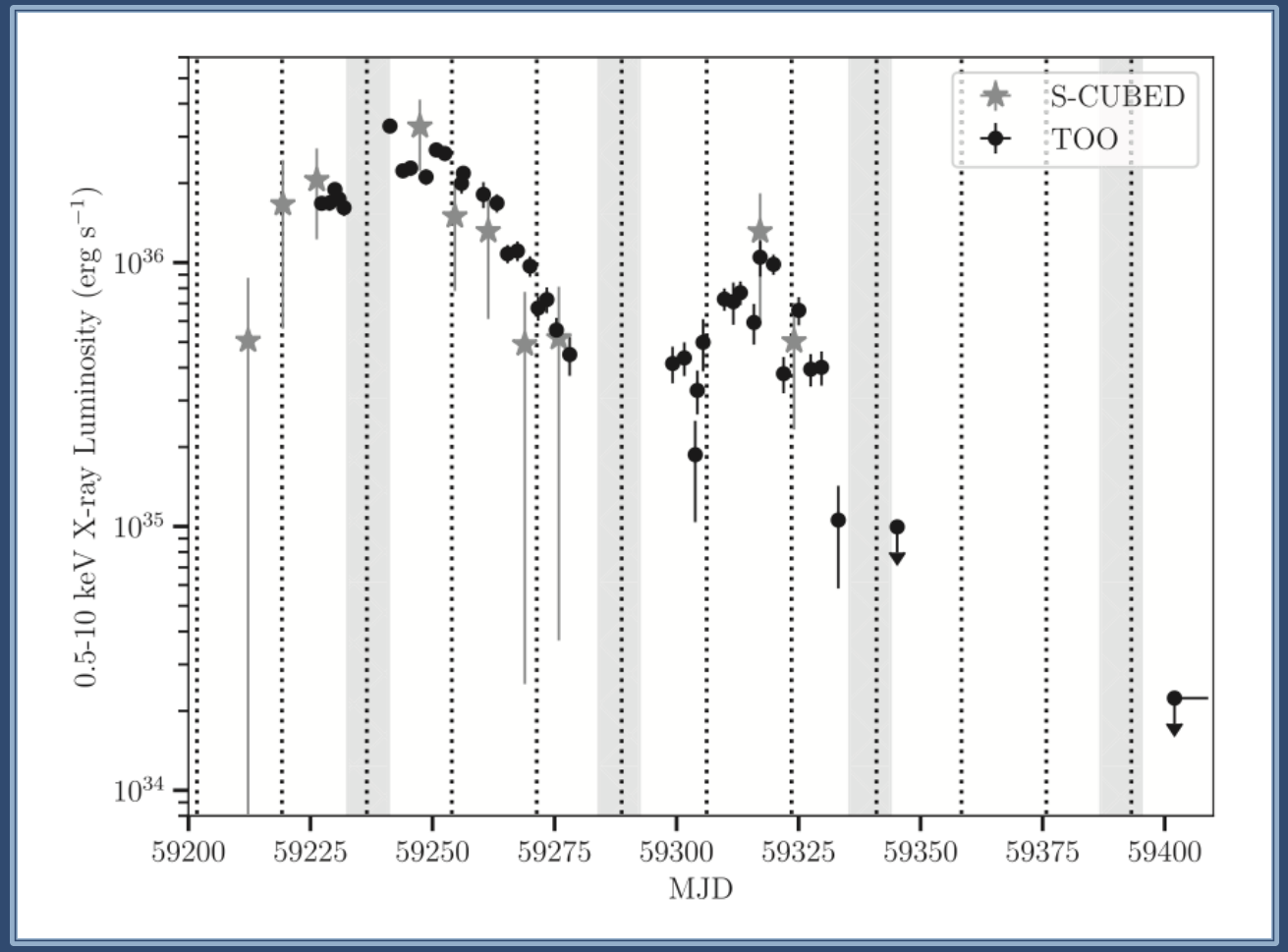
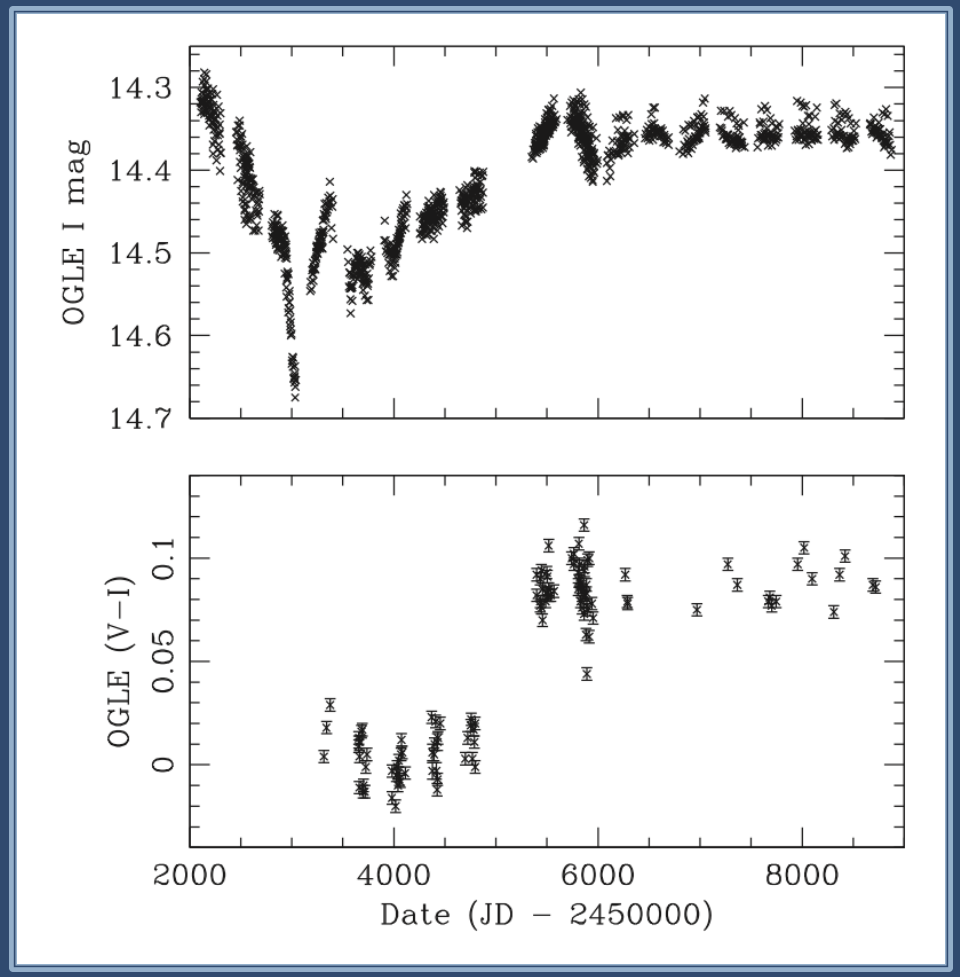


Image Credit: Kennea et al. 2021

Multiwavelength Variability of Swift J011511.0-725611



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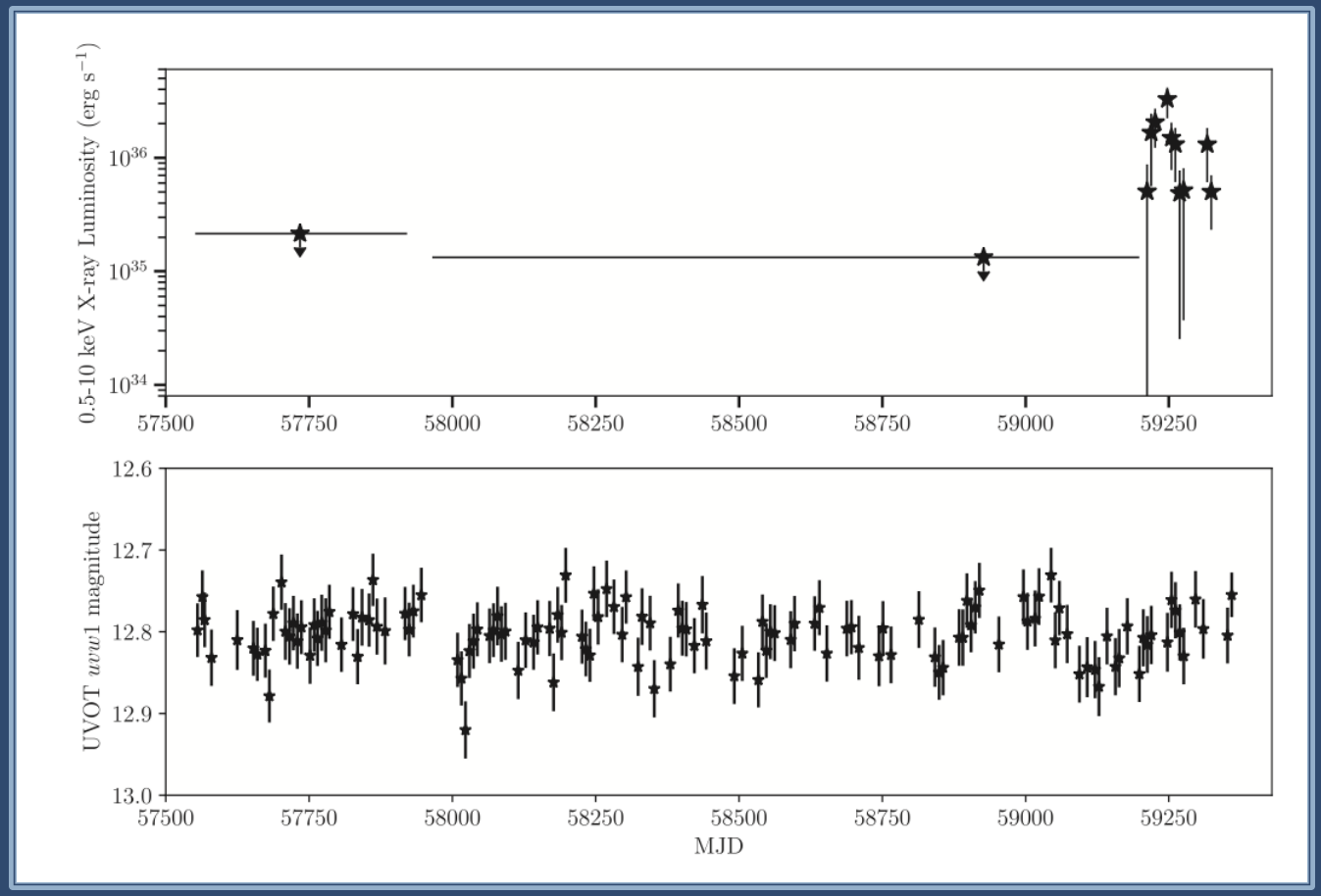

Image Credit: Kennea et al. 2021

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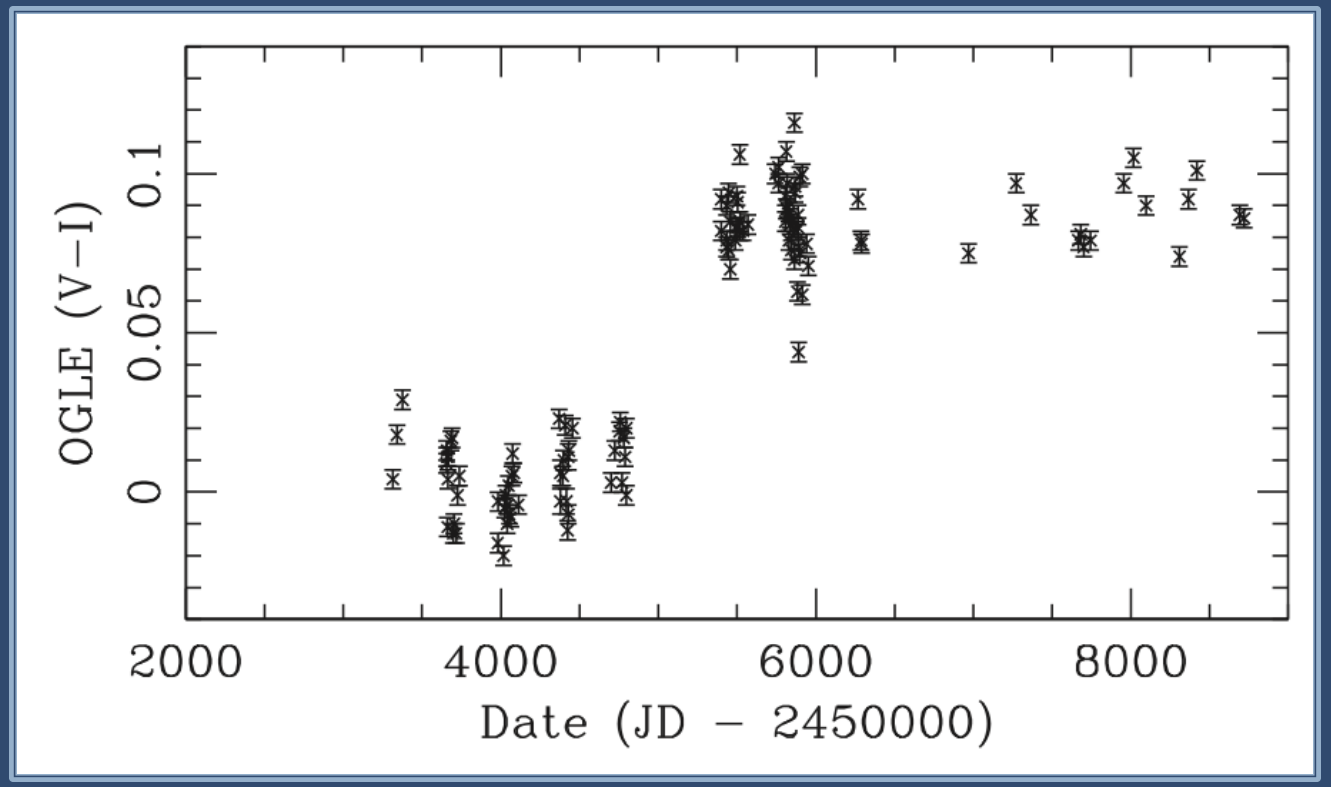

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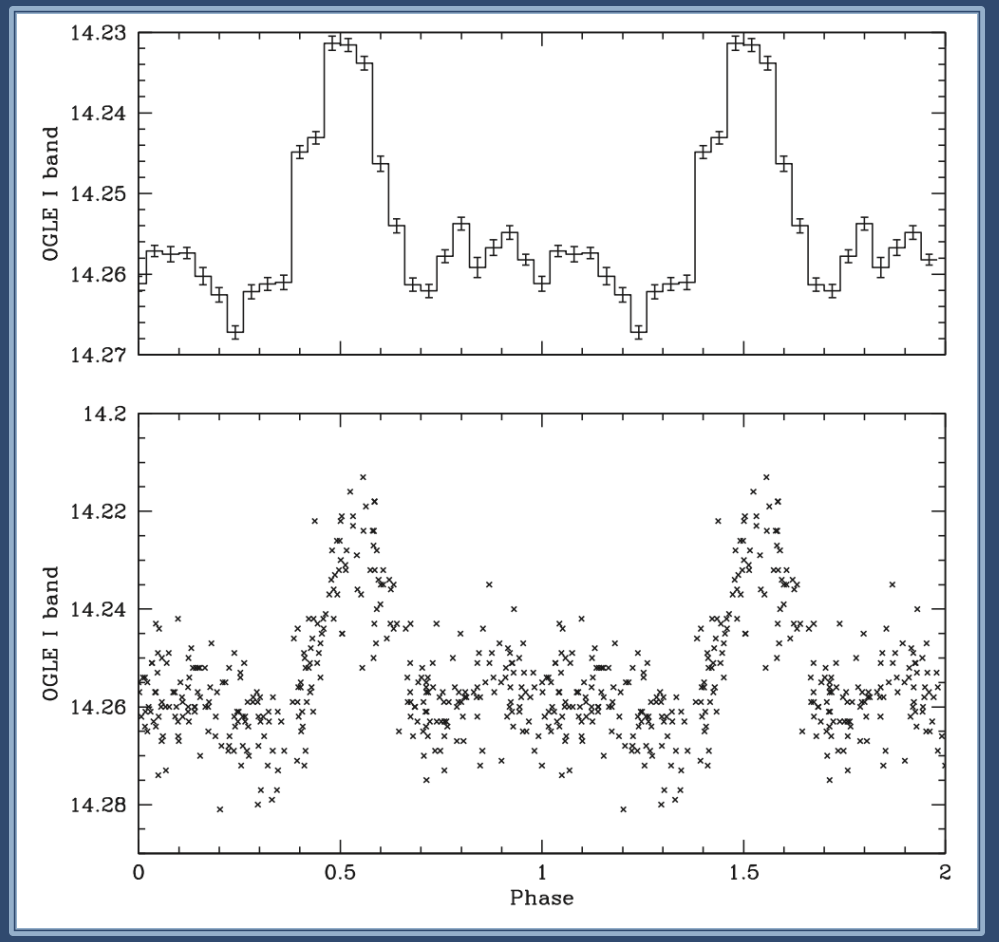

Image Credit: Kennea et al. 2021

P_{orb} = 17.4 days

Multiwavelength Properties of Swift J011511.0-725611

- **Increased I-Band Brightness**
- **Redder When Brighter**
- **Orbital Period:**
  - 17.4 days
- **Conclusion:**
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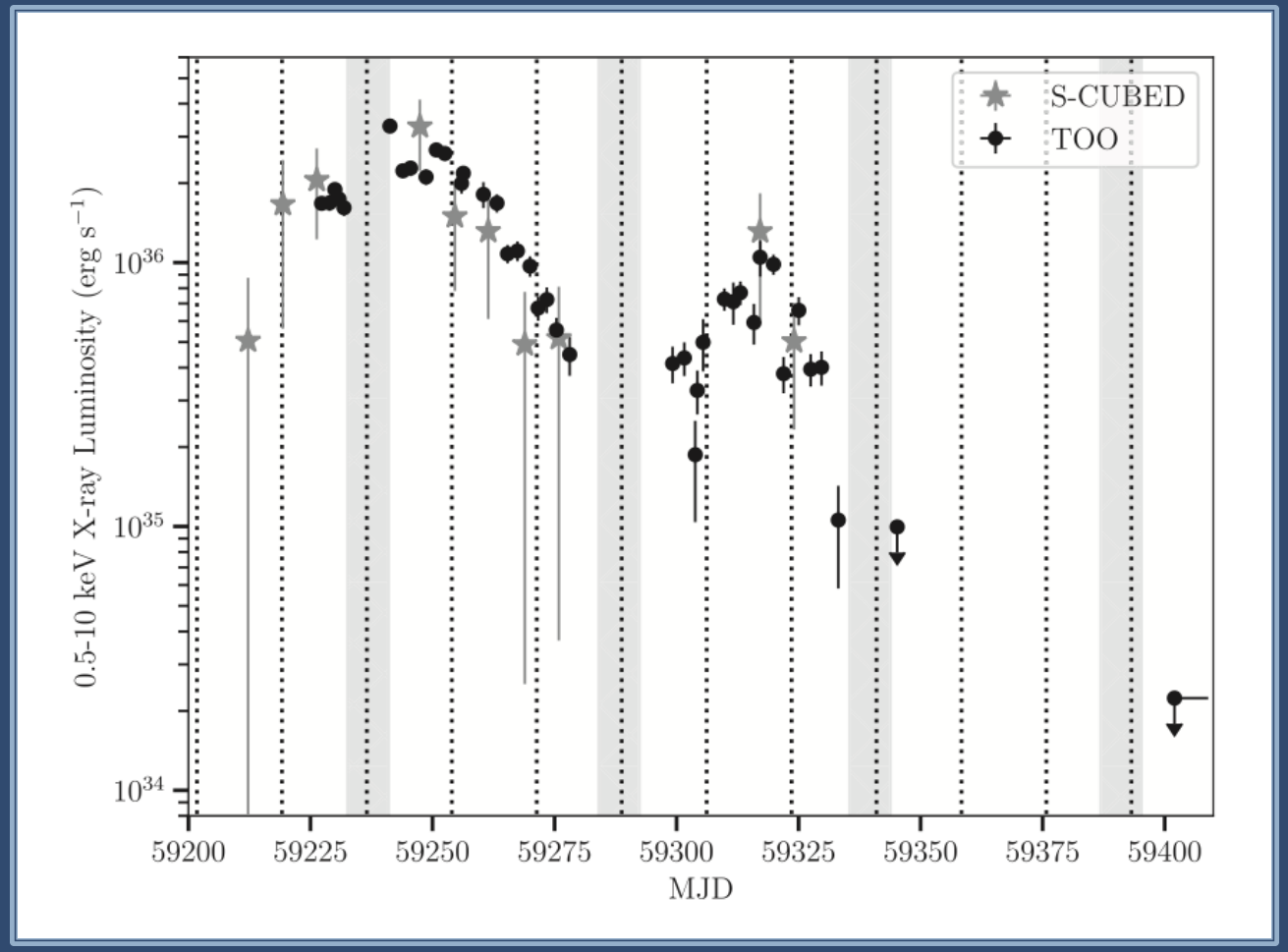
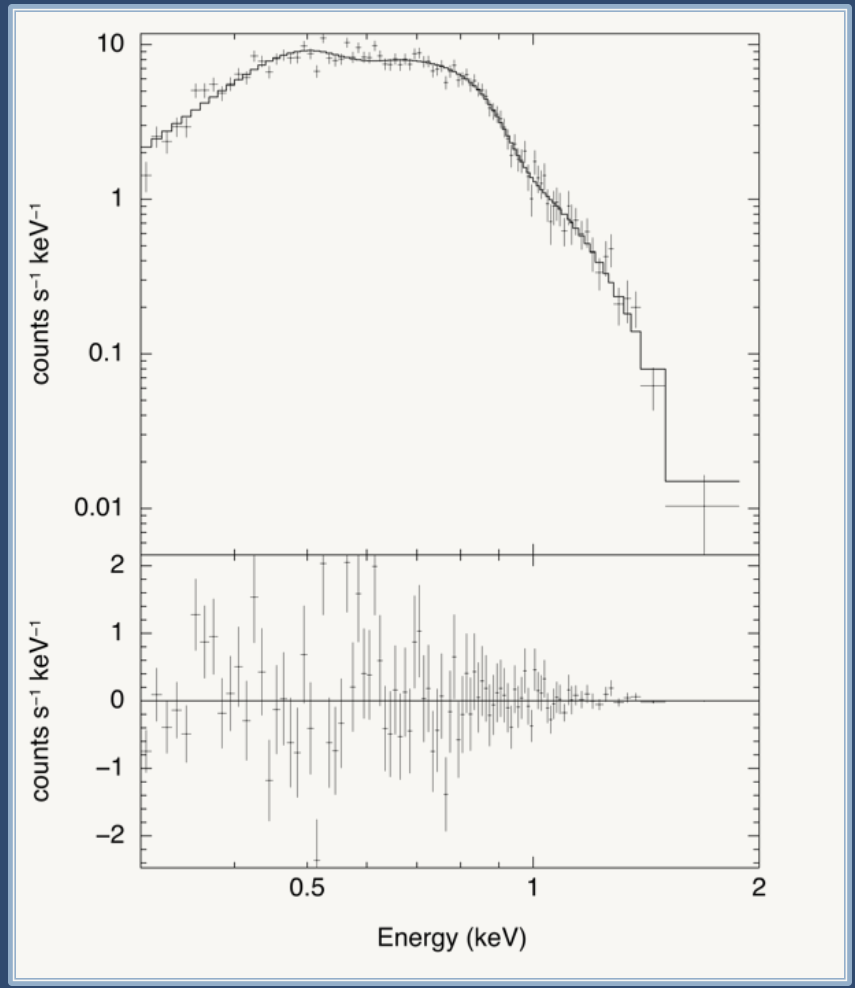


Image Credit: Kennea et al. 2021

CXOU J005245.0−722844: 2024 Outburst

X-ray Spectroscopy of CXOU J005245.0−722844

- **Best-Fitting Model:**
  Absorbed Thermal Blackbody with 2 Absorption Edges
  - $\mathrm{k}T_{BB} = 91.3 \pm 3.7$ eV
  - $E_{edge,1} = 0.385 \pm 0.020$ keV
    C VI edge (0.49 keV)
  - $E_{edge,2} = 0.896 \pm 0.011$ keV
    O VIII edge (0.871 keV)
  - $R_{emit} = 11{,}648 \pm 64$ km



X-ray Spectroscopy of CXOU J005245.0−722844

- **Best-Fitting Model:**
  Absorbed Thermal Blackbody with 2 Absorption Edges
  - $\mathrm{k}T_{BB} = 91.3 \pm 3.7$ eV
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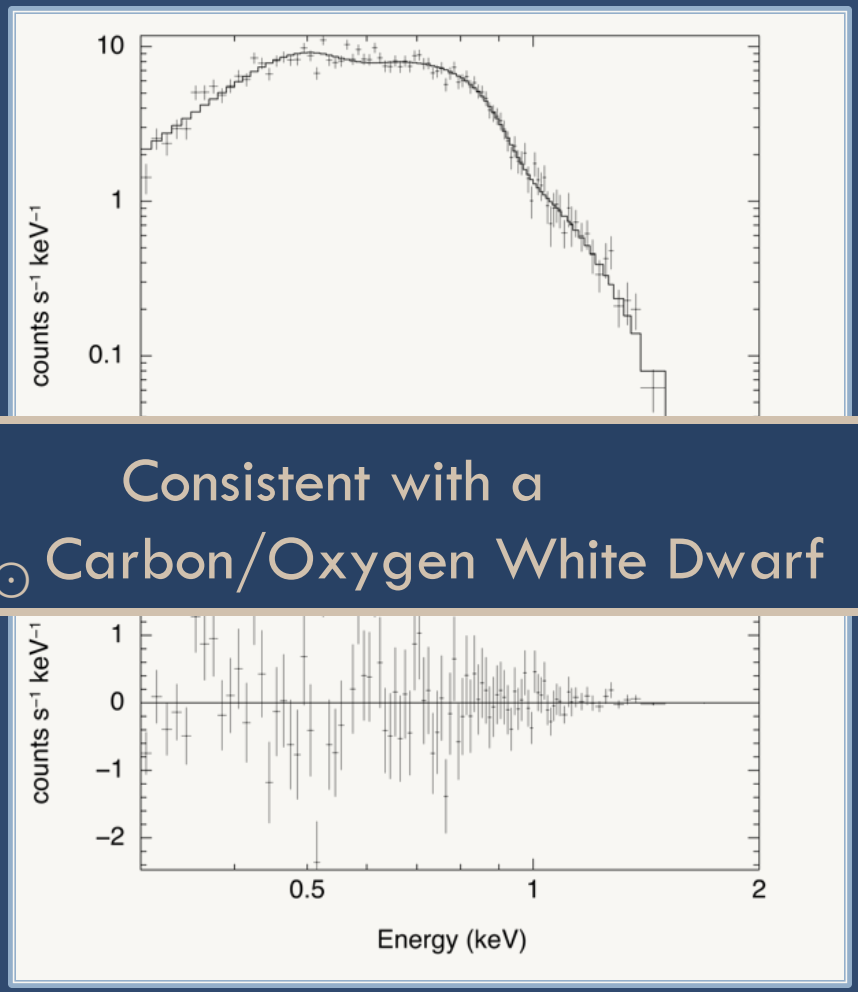
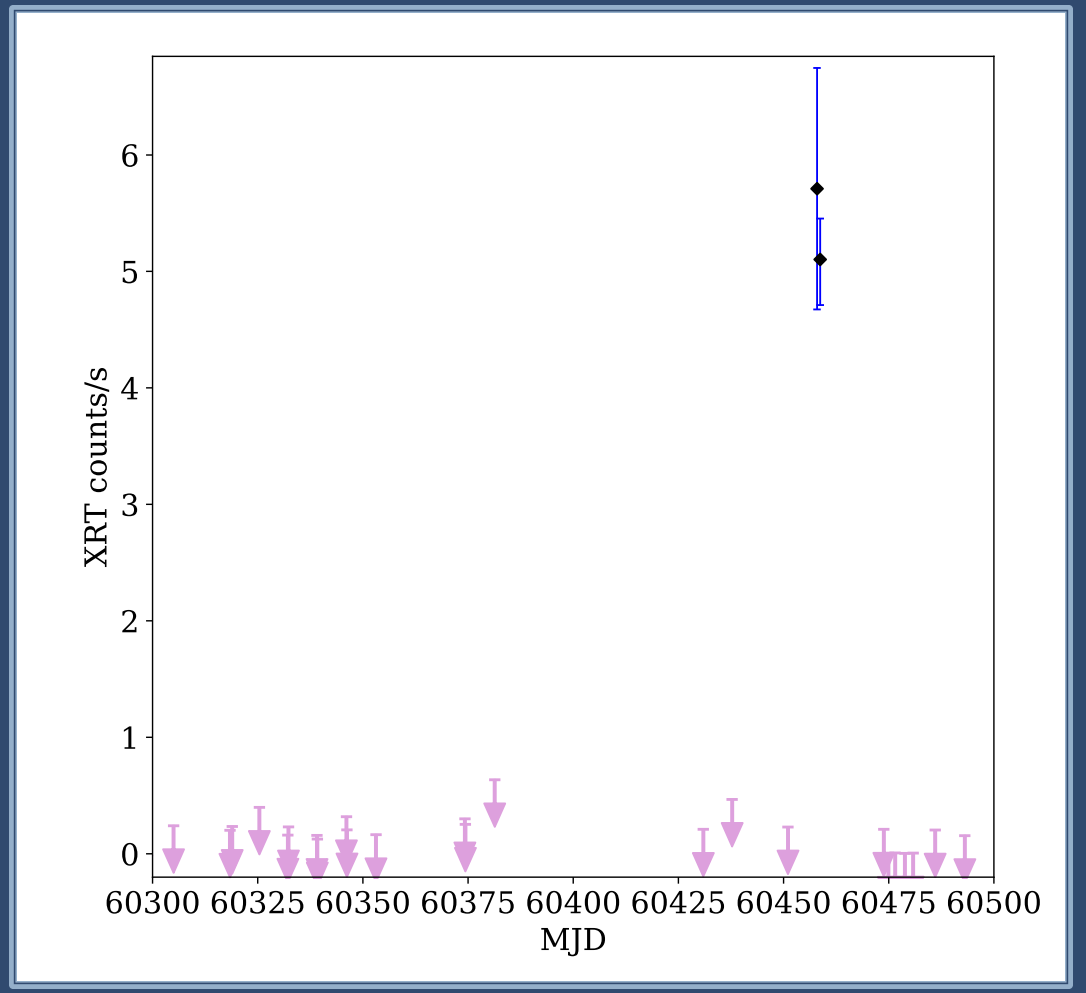


Consistent with a
1.2 $M_\odot$ Carbon/Oxygen White Dwarf

X-ray Photometry of CXOU J005245.0−722844

- Previously known to be a BeXRB
- **First Detection (Einstein Probe):**
  - 08:41 UTC on 27 May 2024
- **First Detection (S-CUBED):**
  - 22:29 UTC on 27 May 2024
- **Duration of Outburst:**
  - < 16 days
- **Max Luminosity:**
  - $L_X = 6.51^{+2.5}_{-1.2} \times 10^{38}$ erg s^{-1}

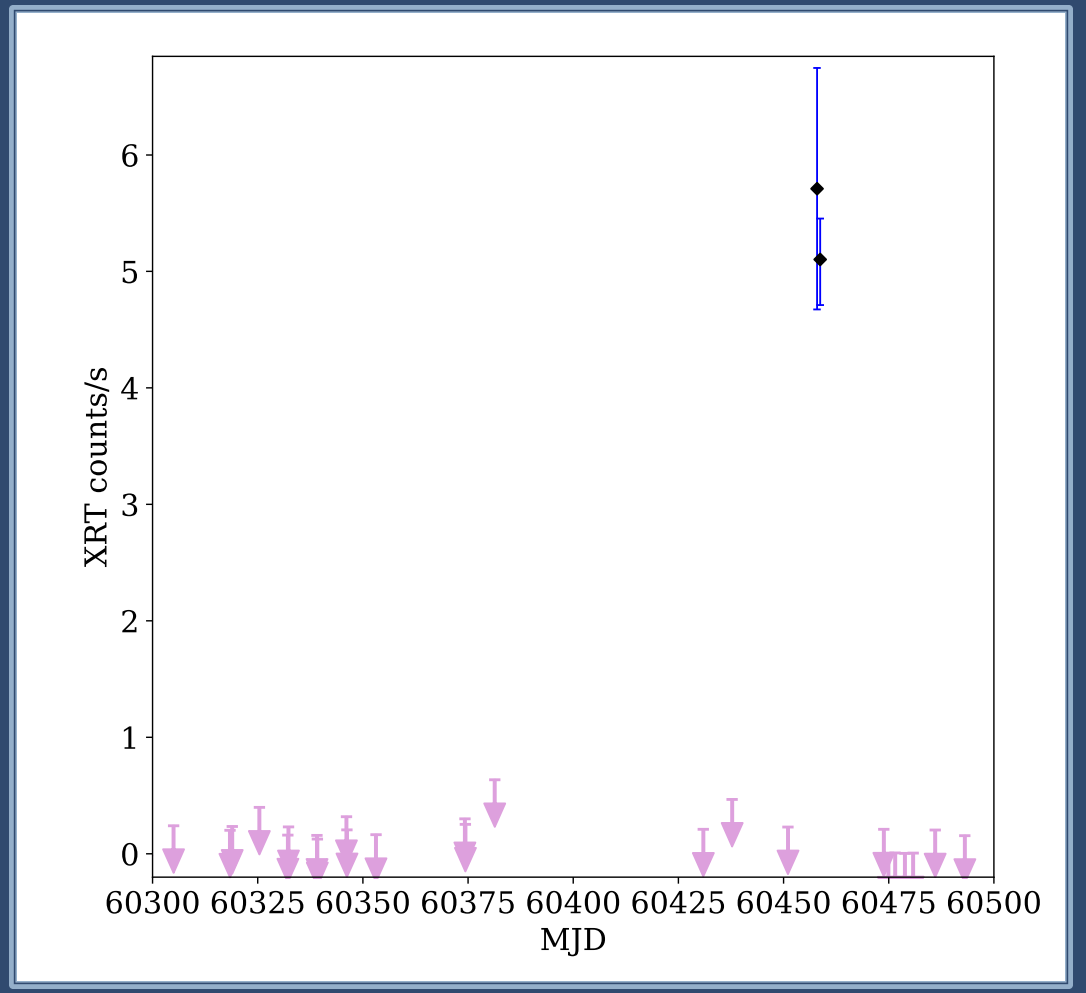


X-ray Photometry of CXOU J005245.0−722844

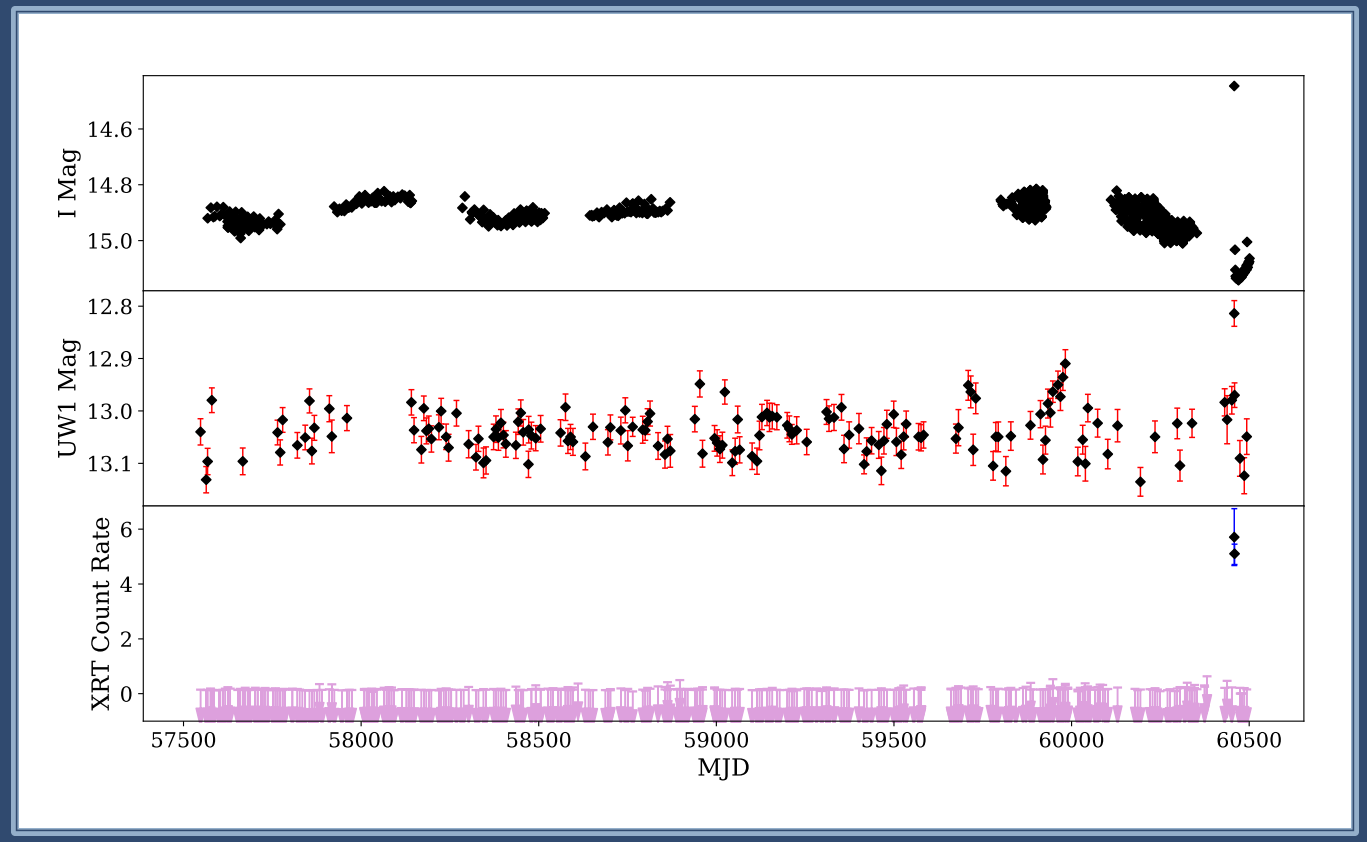
- Previously known to be a BeXRB
- **First Detection (Einstein Probe):**
  - 08:41 UTC on 27 May 2024
- **First Detection (S-CUBED):**
  - 22:29 UTC on 27 May 2024

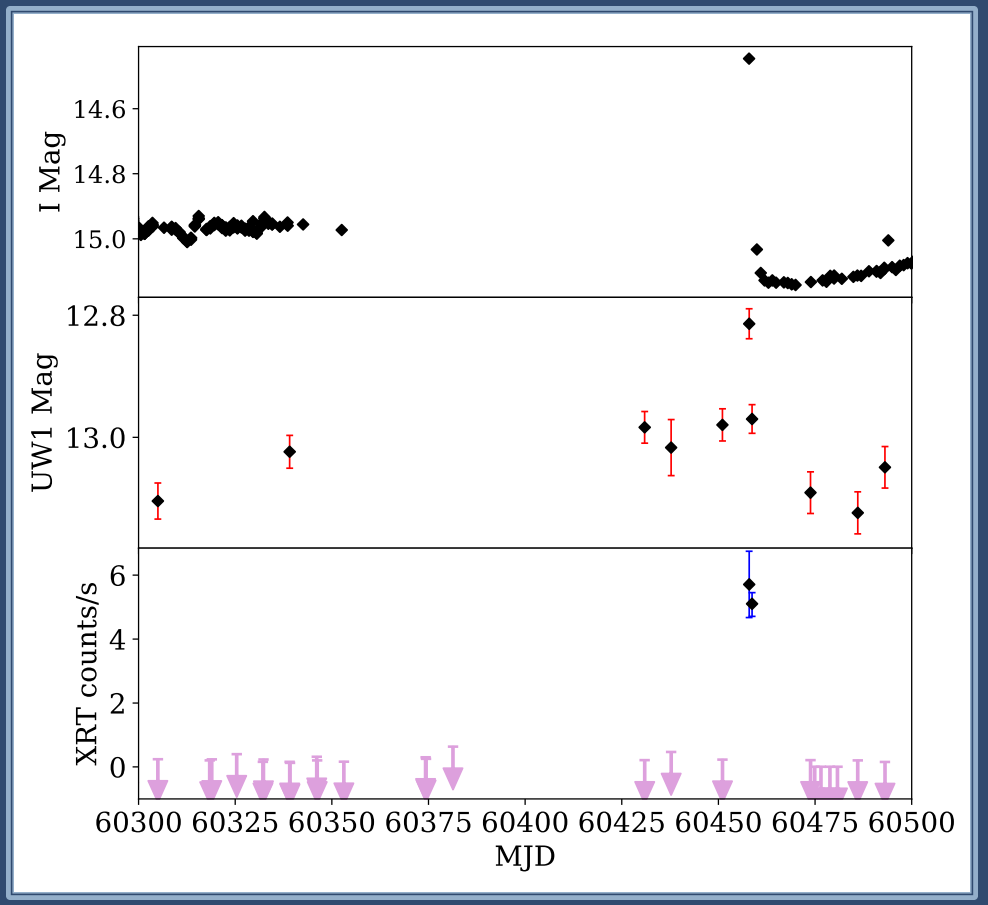
Greater than the Eddington Luminosity for a 1 $M_\odot$ object

- **Max Luminosity:**
  - $L_X = 6.51^{+2.5}_{-1.2} \times 10^{38}$ erg s^{-1}

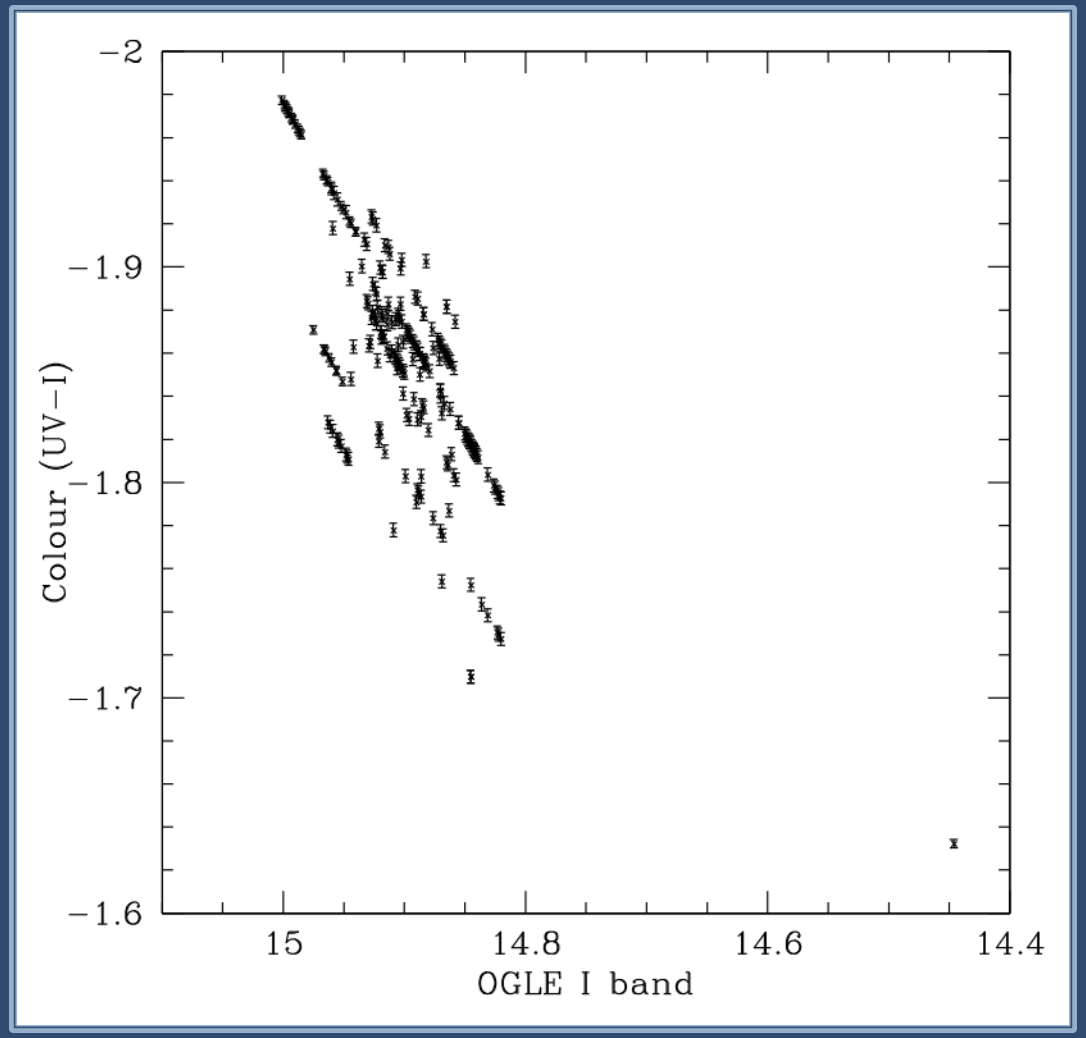


Multiwavelength Variability of CXOU J005245.0−722844



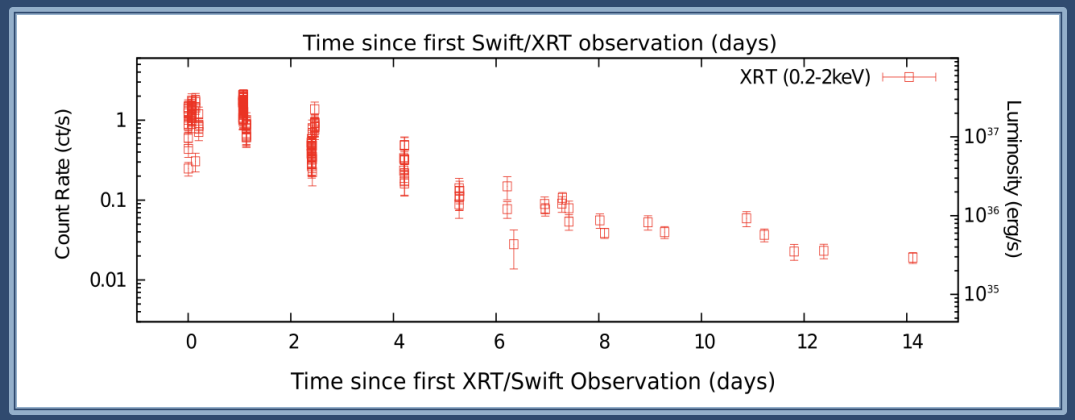


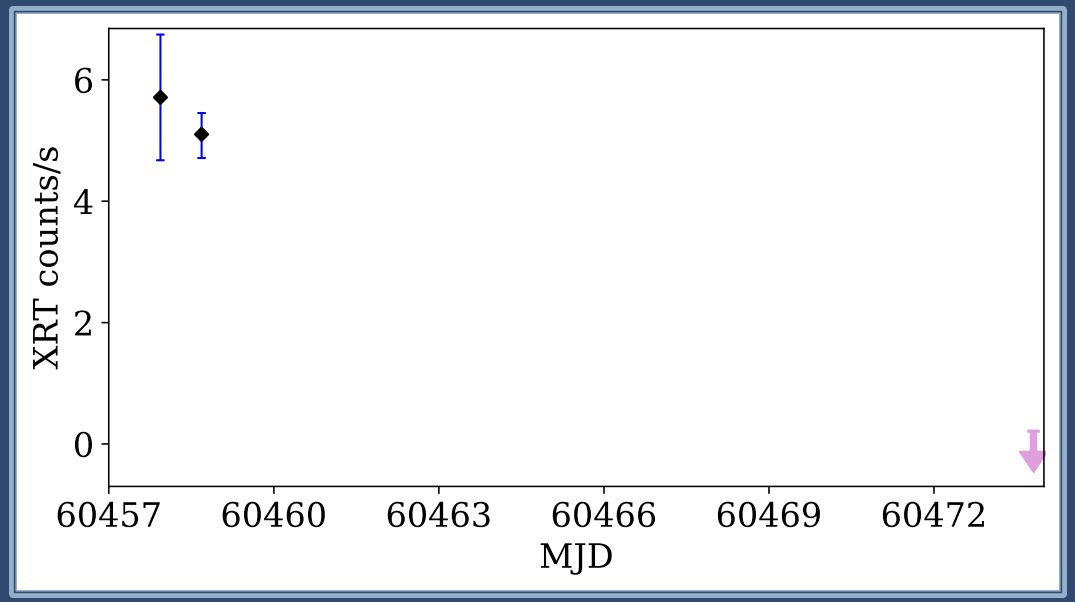
Multiwavelength Variability of CXOU J005245.0−722844



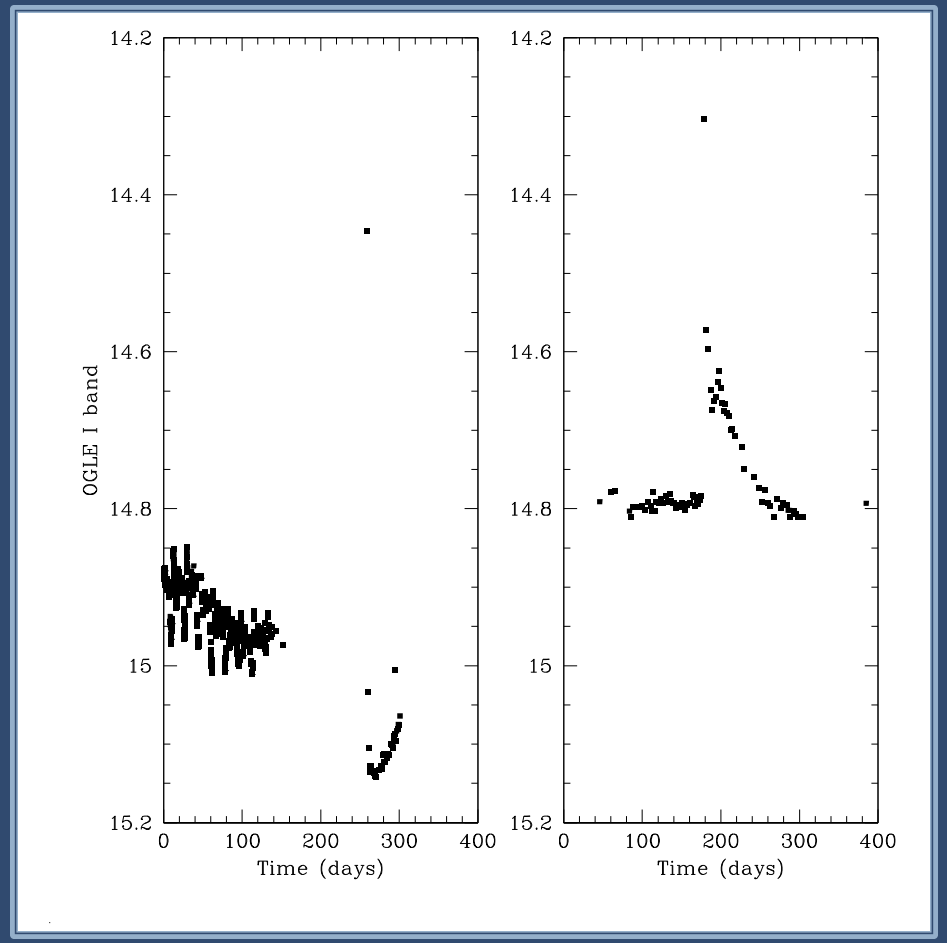
A Super-Luminous, Very Fast Nova? (Morii et al. 2013)

2011
MAXI J0158-477
(Li et al. 2012)





2024
CXOU J005245.0-722844



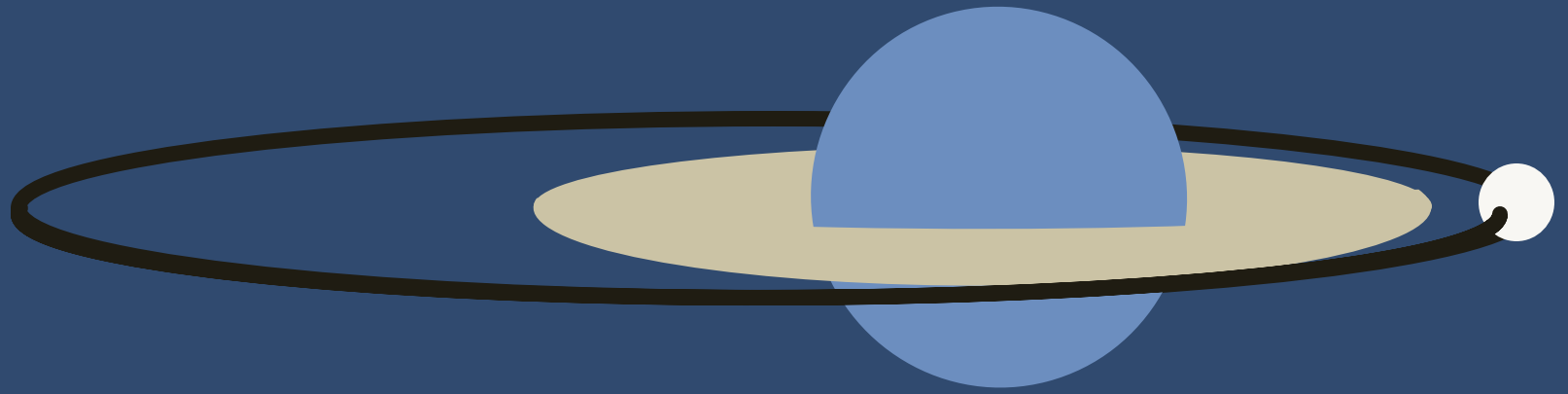
2024
CXOU J005245.0-722844

2011
MAXI J0158-477

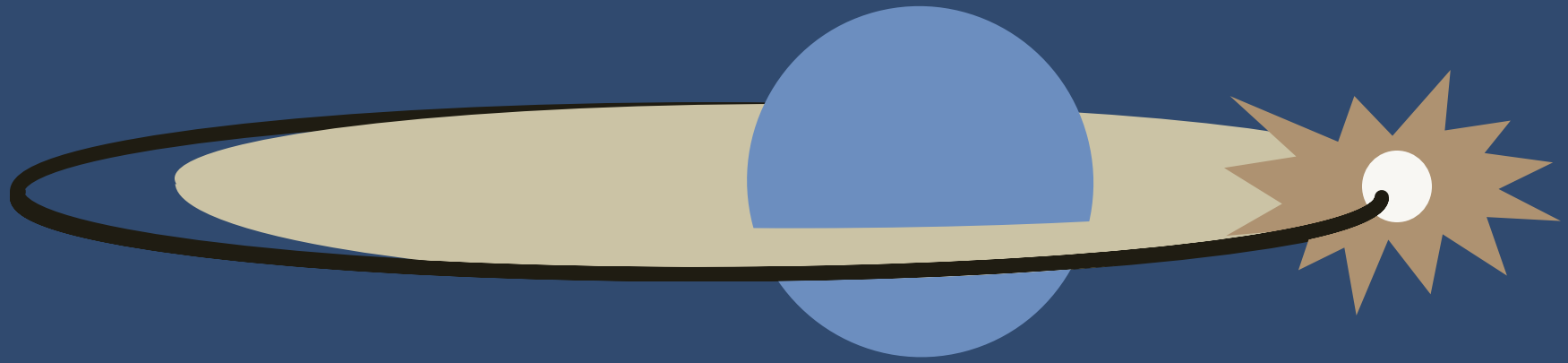
BeWDs in Outburst

Source Name	Duration (days)	Max L_X (erg s^{-1})	kT_{BB} (eV)	M_{WD} ($M_\odot$)	Likely Cause?
Swift J004427.3–734801	~120	4.1×10^{36}	58	?	Stable Nuclear Burning (Type II Outburst)
Swift J011511.0-725611	~120	3.3×10^{36}	96.7	1.2	Stable Nuclear Burning (Type II Outburst)
CXOU J005245.0–722844	< 16	6.5×10^{38}	91.3	1.2	Thermonuclear Runaway (Nova w/ Limited Ejecta)

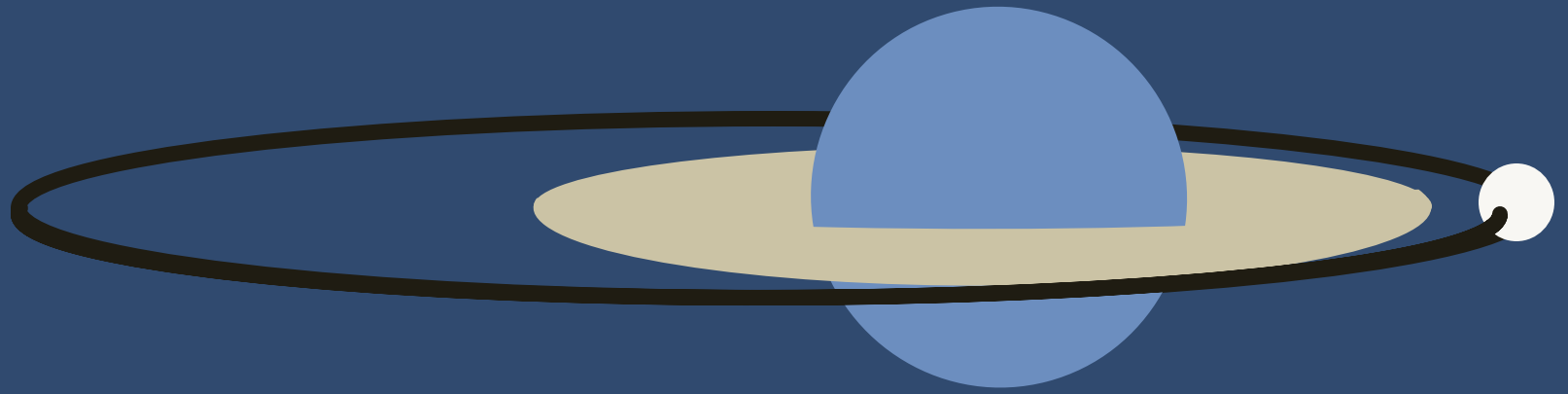
Stable Nuclear Burning (Type II Outburst)



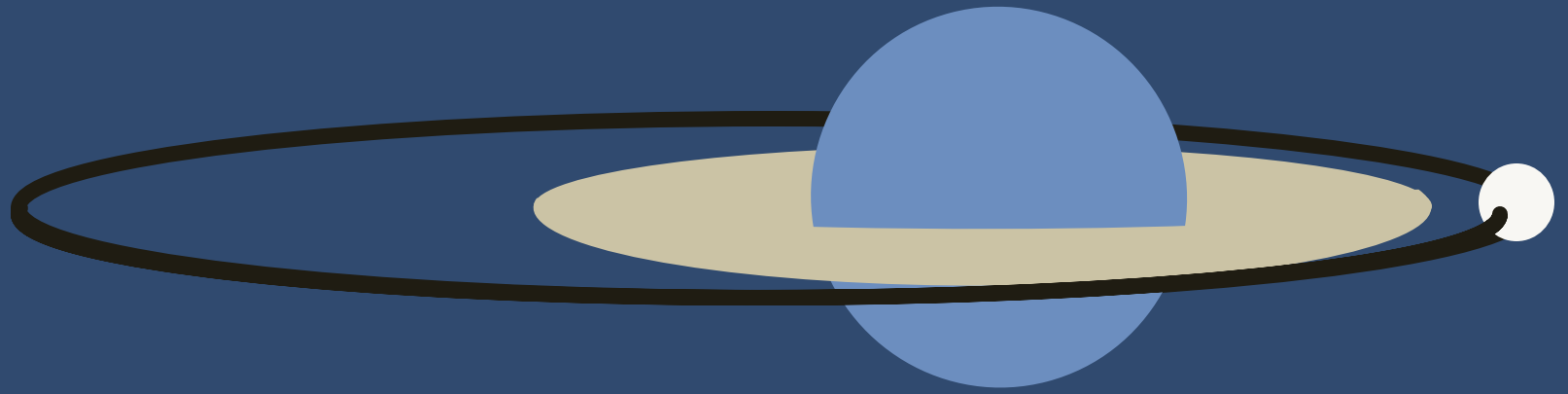
Stable Nuclear Burning (Type II Outburst)



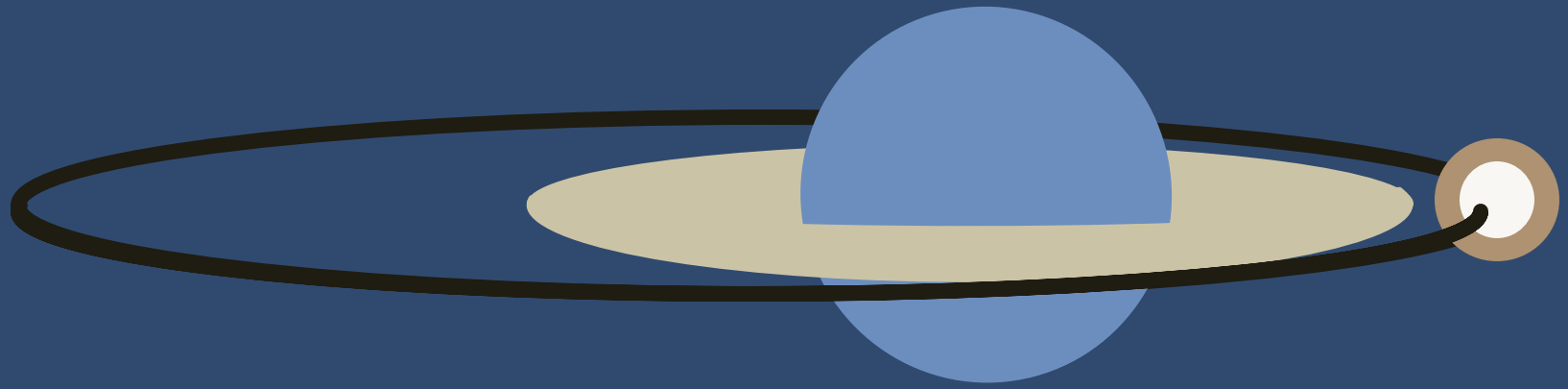
Stable Nuclear Burning (Type II Outburst)



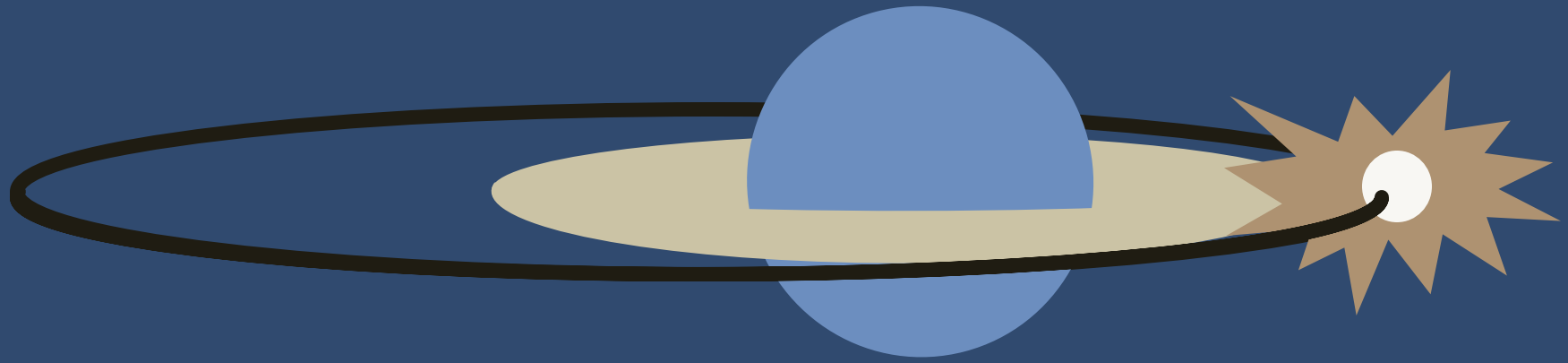
BeWD Nova



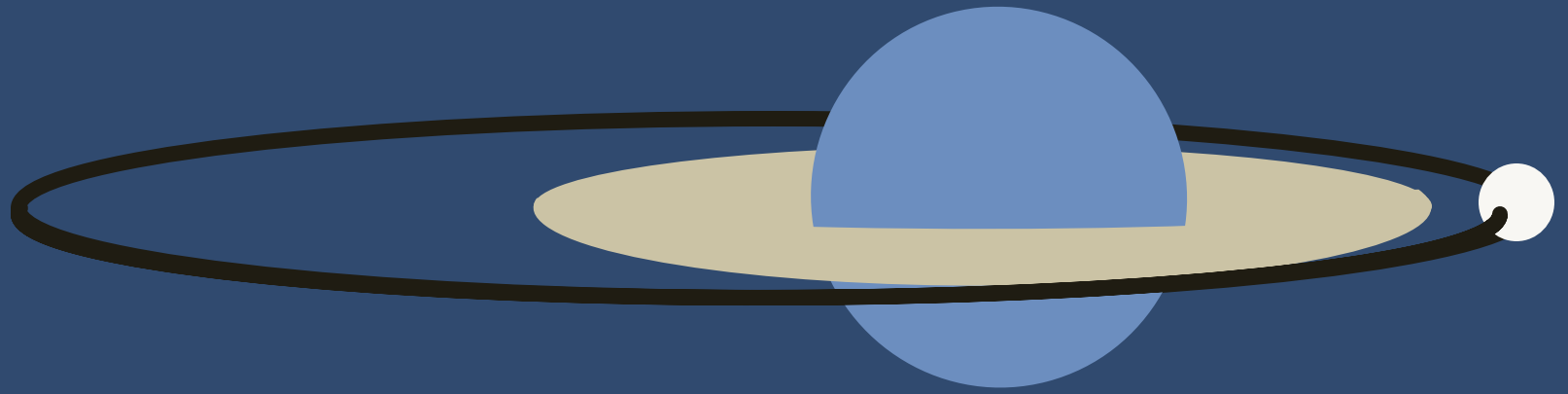
BeWD Nova



BeWD Nova

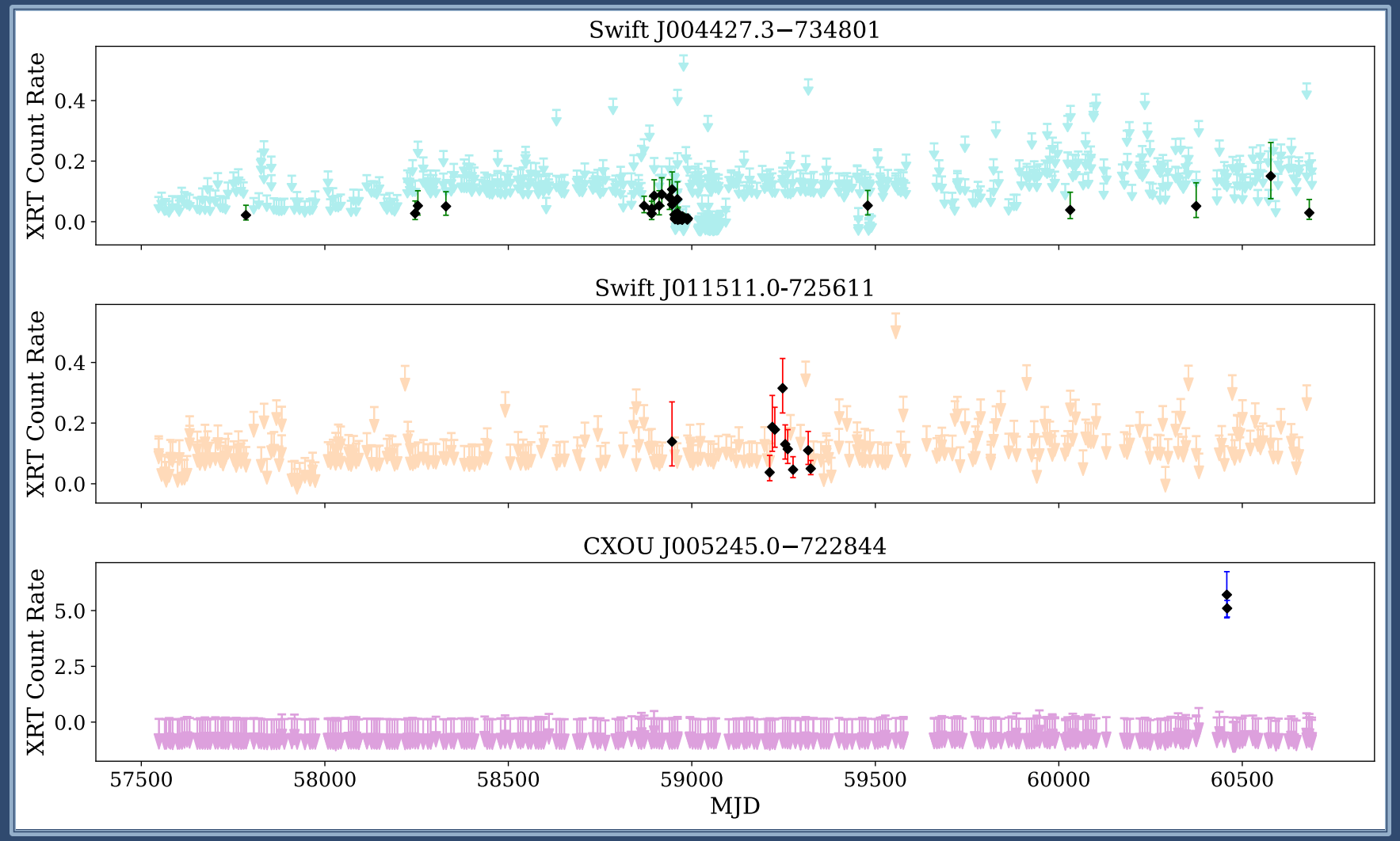


BeWD Nova



BeWDs in Quiescence

Full S-CUBED XRT Light Curves



Open Questions

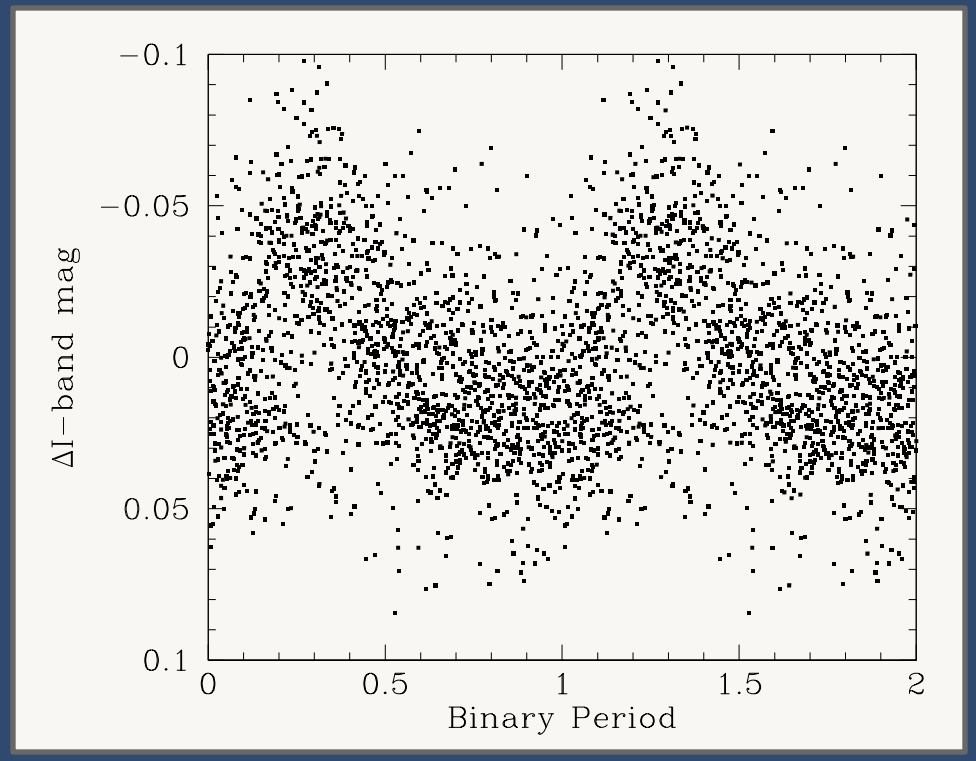
- Do BeWDs produce Type I outbursts?
- What are the recurrence rates of luminous soft X-ray outbursts?
- Are there any recurrent novae BeWD systems?
- How are super-Eddington novae produced?
- How are BeWDs connected to the Ultraluminous Supersoft Source (ULS) population?
- Does the WD gain mass despite producing these outbursts?

Conclusions

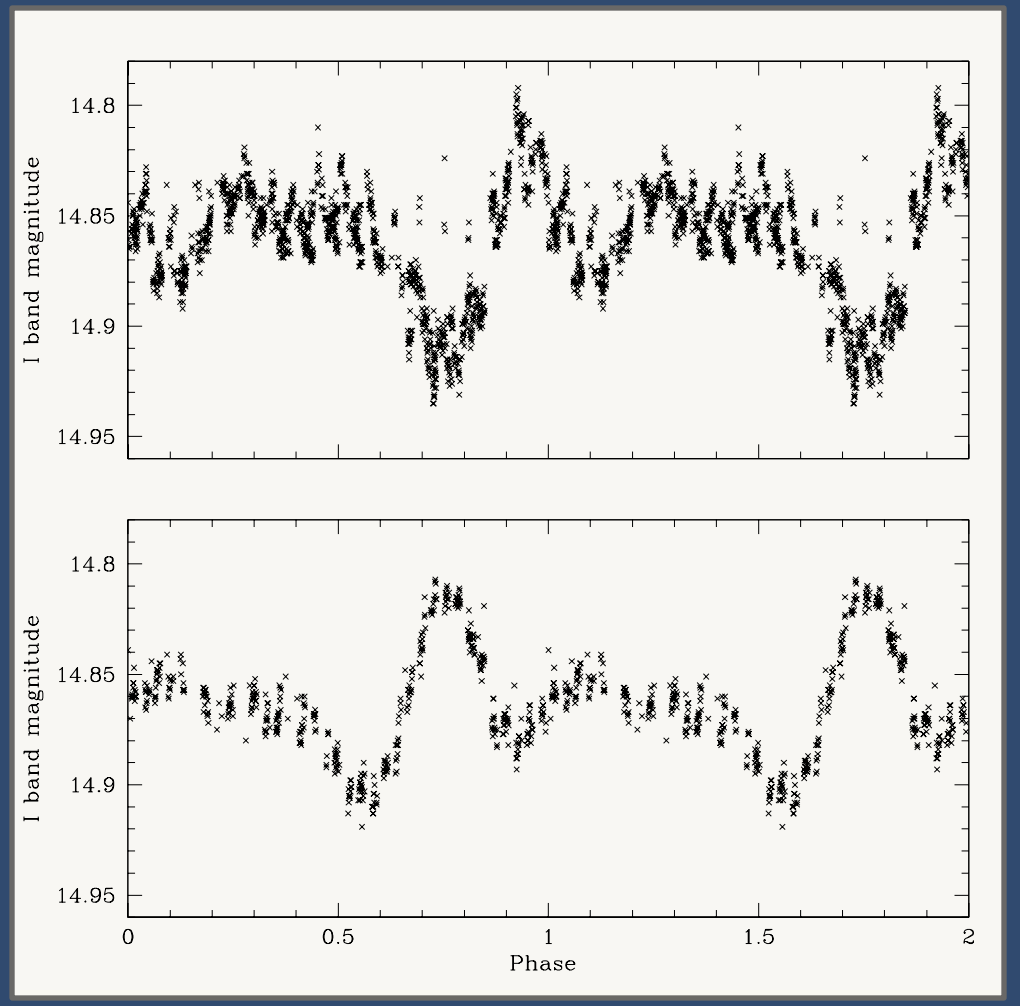
- BeWD binaries are a rarely-observed class of High Mass X-ray binary that are only detected by their transient soft X-ray outbursts.
- The S-CUBED survey has been responsible for detecting 3 of the 7 known BeWD systems.
  - Demonstrates the necessity of Soft X-ray survey data for the study of these systems
- S-CUBED data shows that both short- and long-duration Soft X-ray outbursts are possible.
- More observations are needed to improve our understanding of BeWDs and particularly the properties of their outbursts.

Questions?

Periodicity Problems



1992 – 2020
P = 17.55 Days

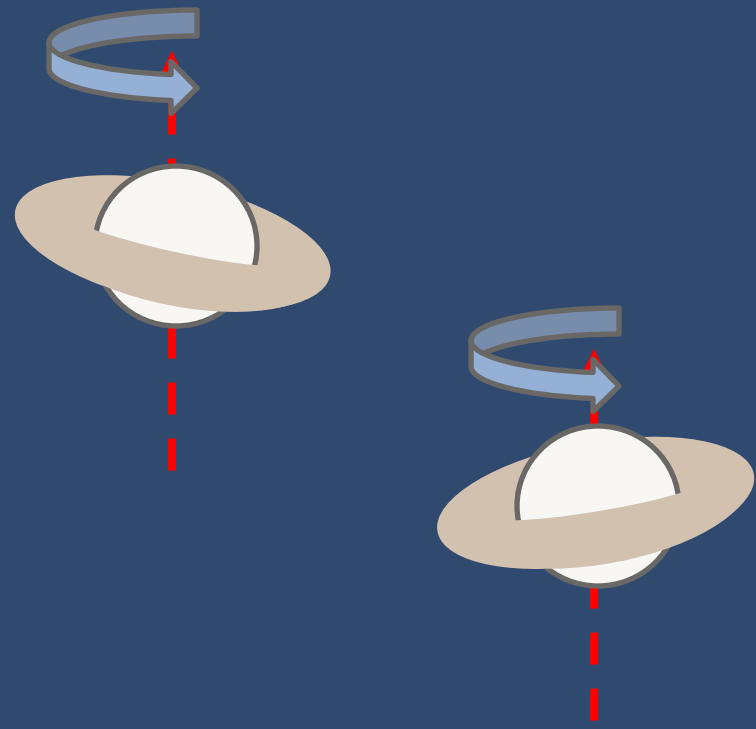


2022 – 2023
P = 17.41 Days

2023 – 2024
P = 17.17 Days

Periodicity Problems – Negative Superhumps?

- Can rule out the orbit having changed so rapidly
- Assume that the WD Accretion Disk is responsible
- Similar phenomena observed in cataclysmic variable stars



Be/White Dwarf Binaries: Observational Properties

- IR - UV:
  - Be star + disk dominates emission
- Hard X-Ray emission:
  - Very faint at quiescence

  $L_X \sim 10^{29} - 10^{33}$ erg s^{-1}
- Soft X-Ray emission:
  - Transient bright outbursts