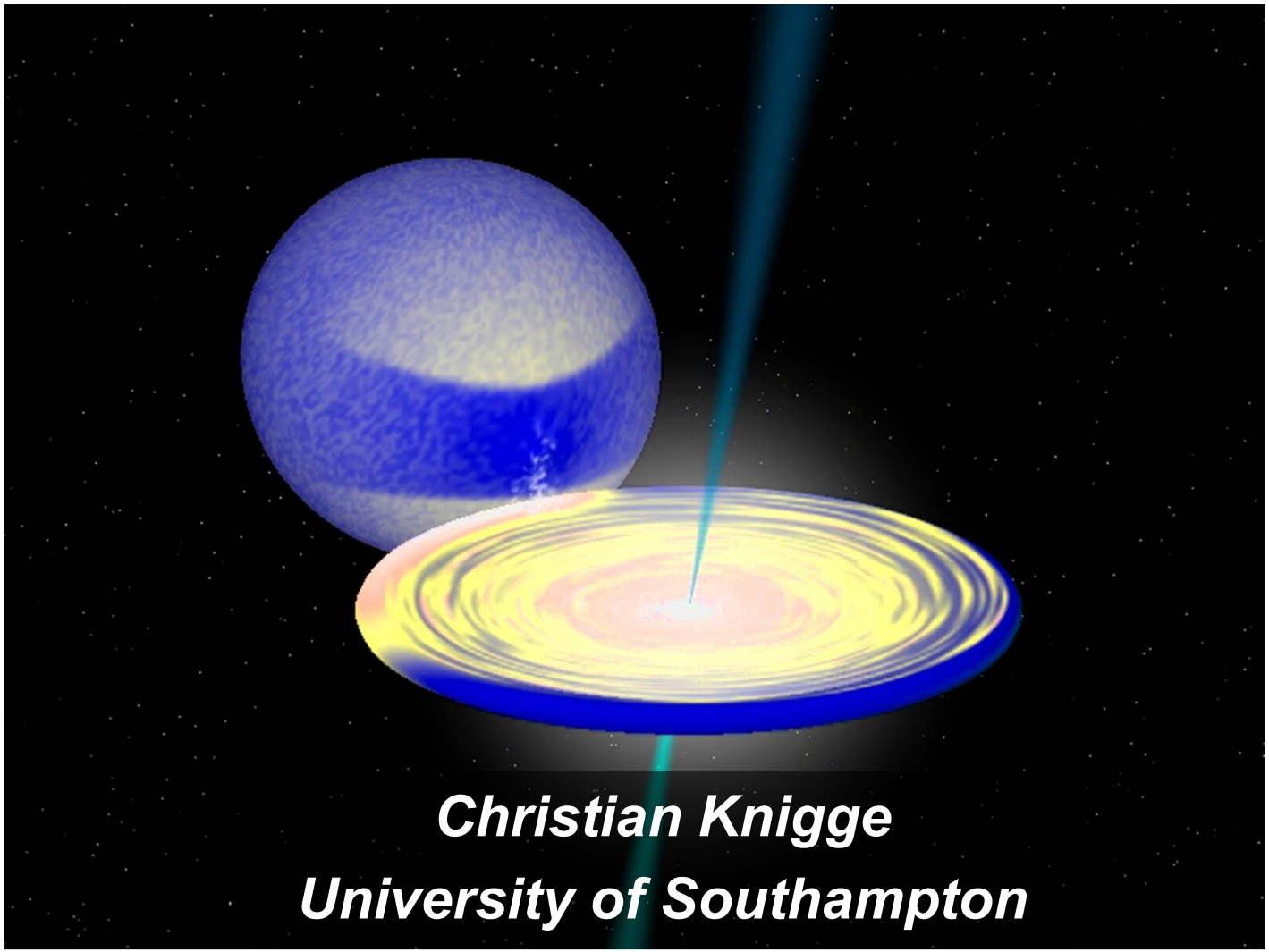
Cataclysmic Variables As Universal Accretion Laboratories



Outline

- Cataclysmic variables
  - A primer

- CVs as universal accretion disk laboratories
  - From phenomenology to physics
  - New results and open questions…

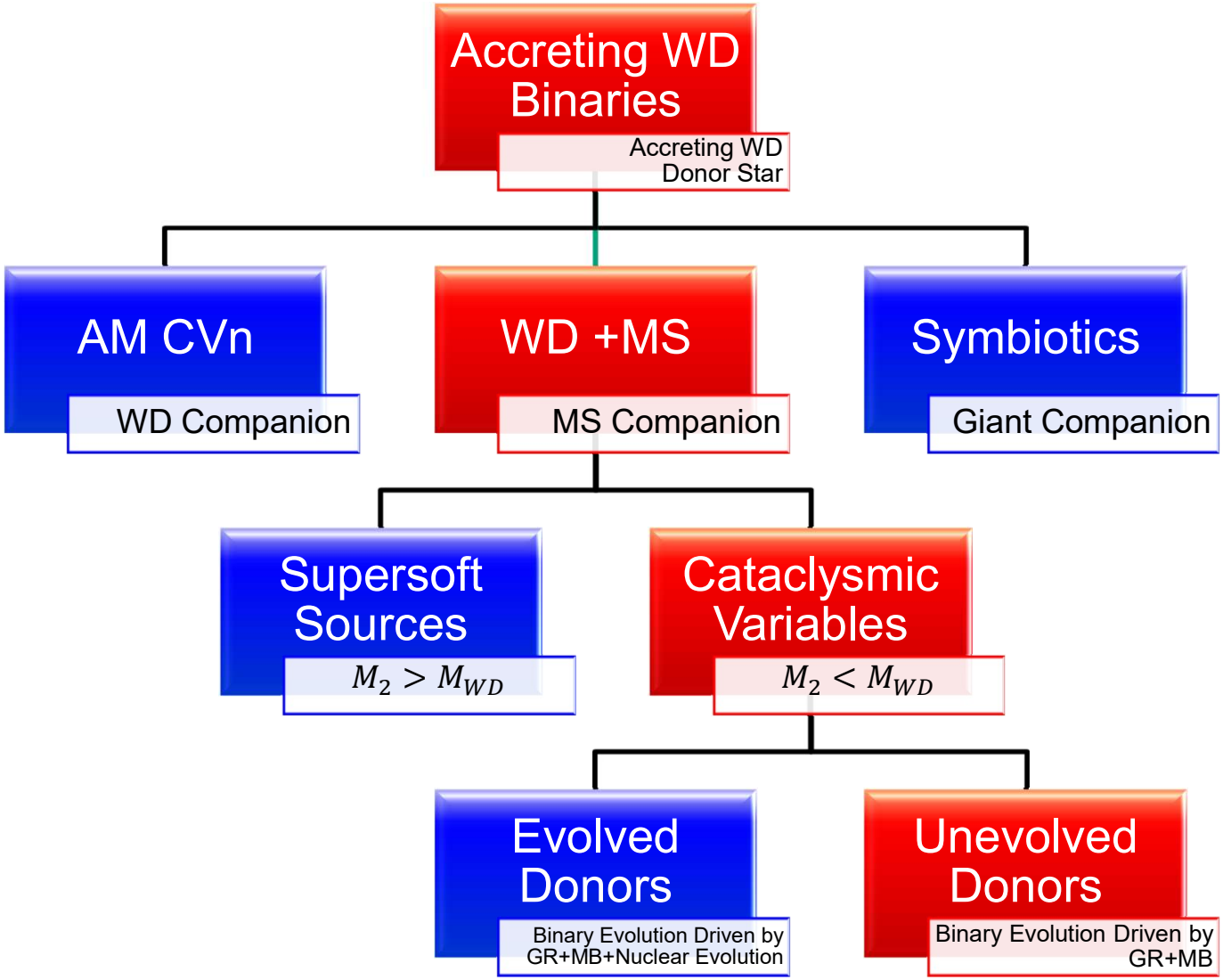
Cataclysmic Variables:

A Primer

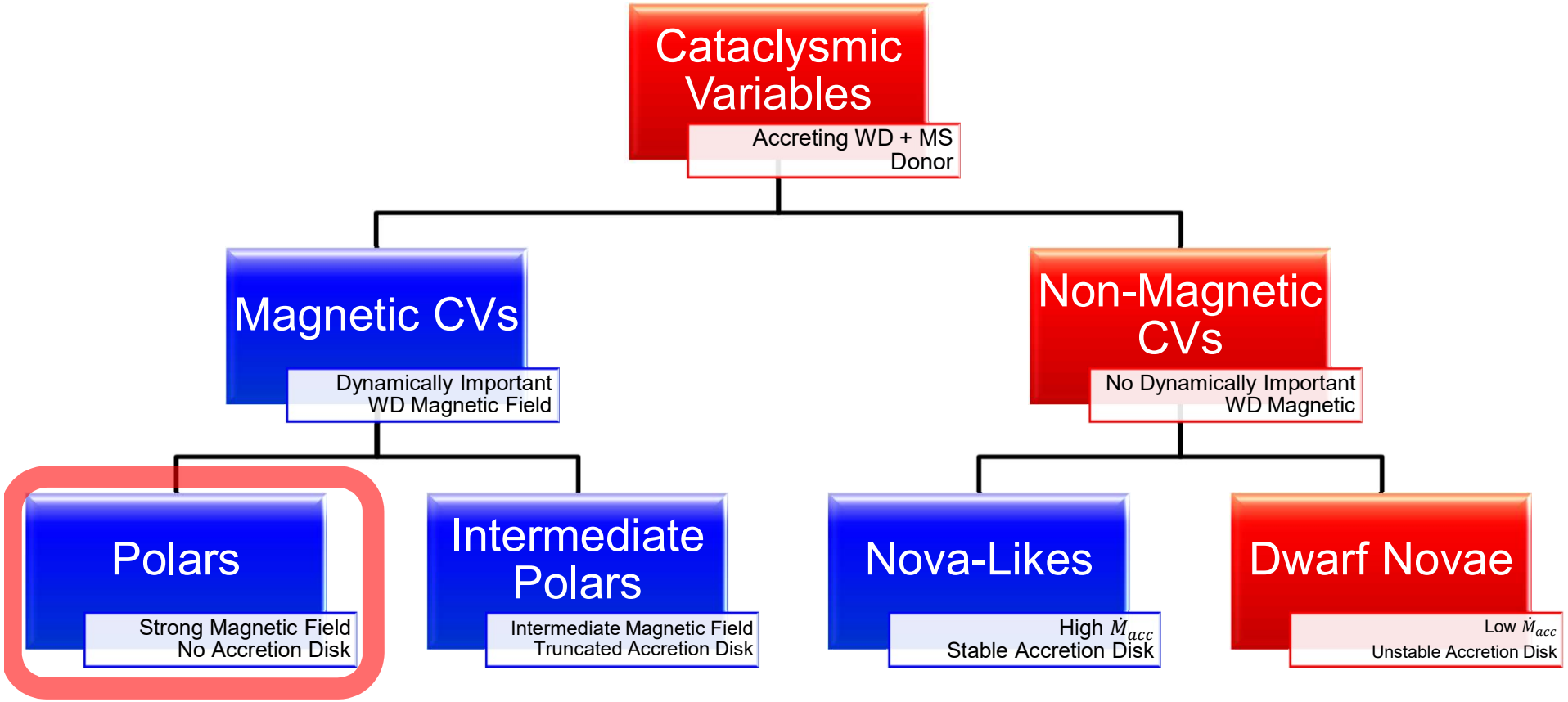
Christian

Department of Physics & Astronomy

The Zoo of Accreting White Dwarfs

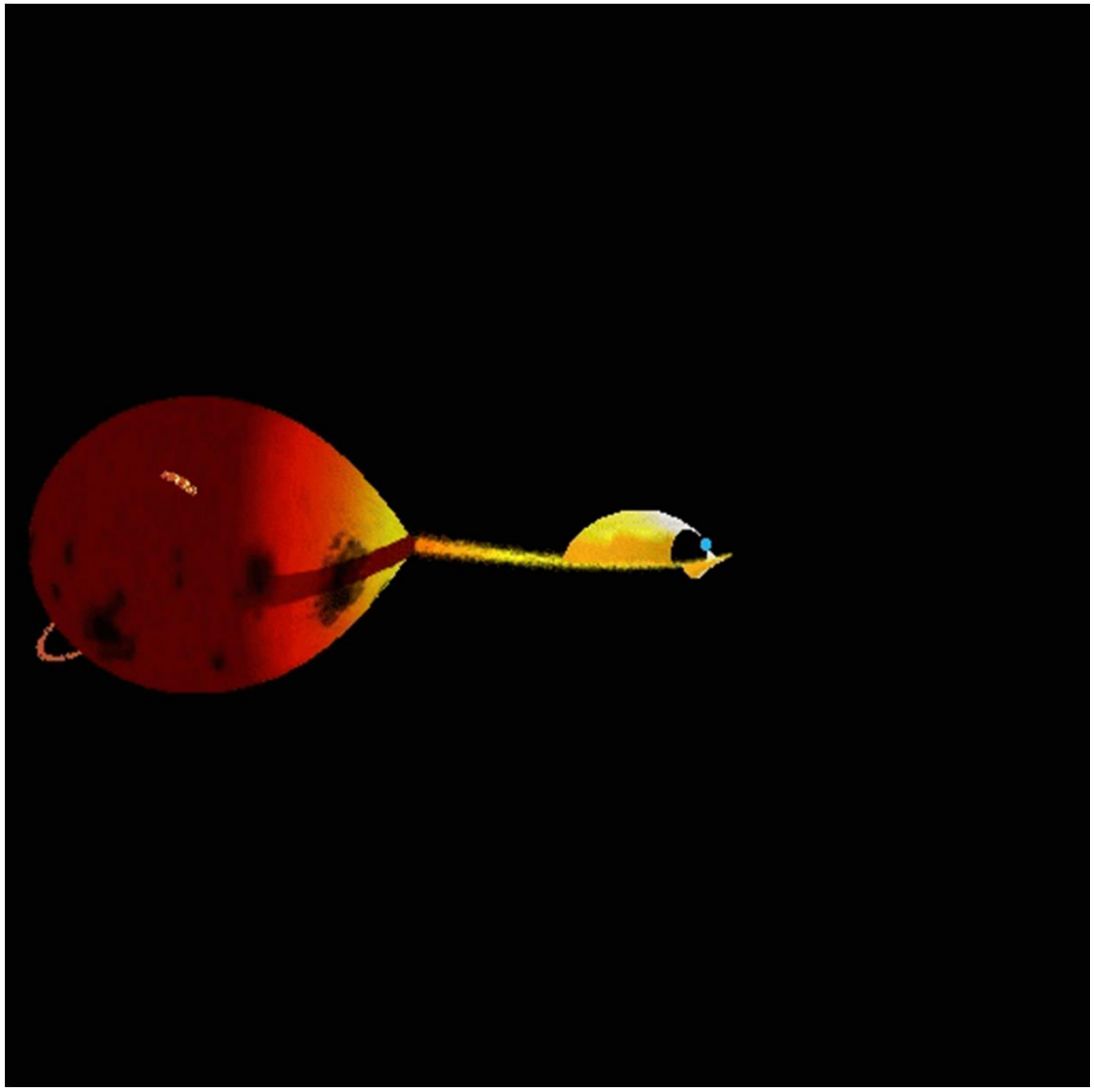


The Menagerie of CVs

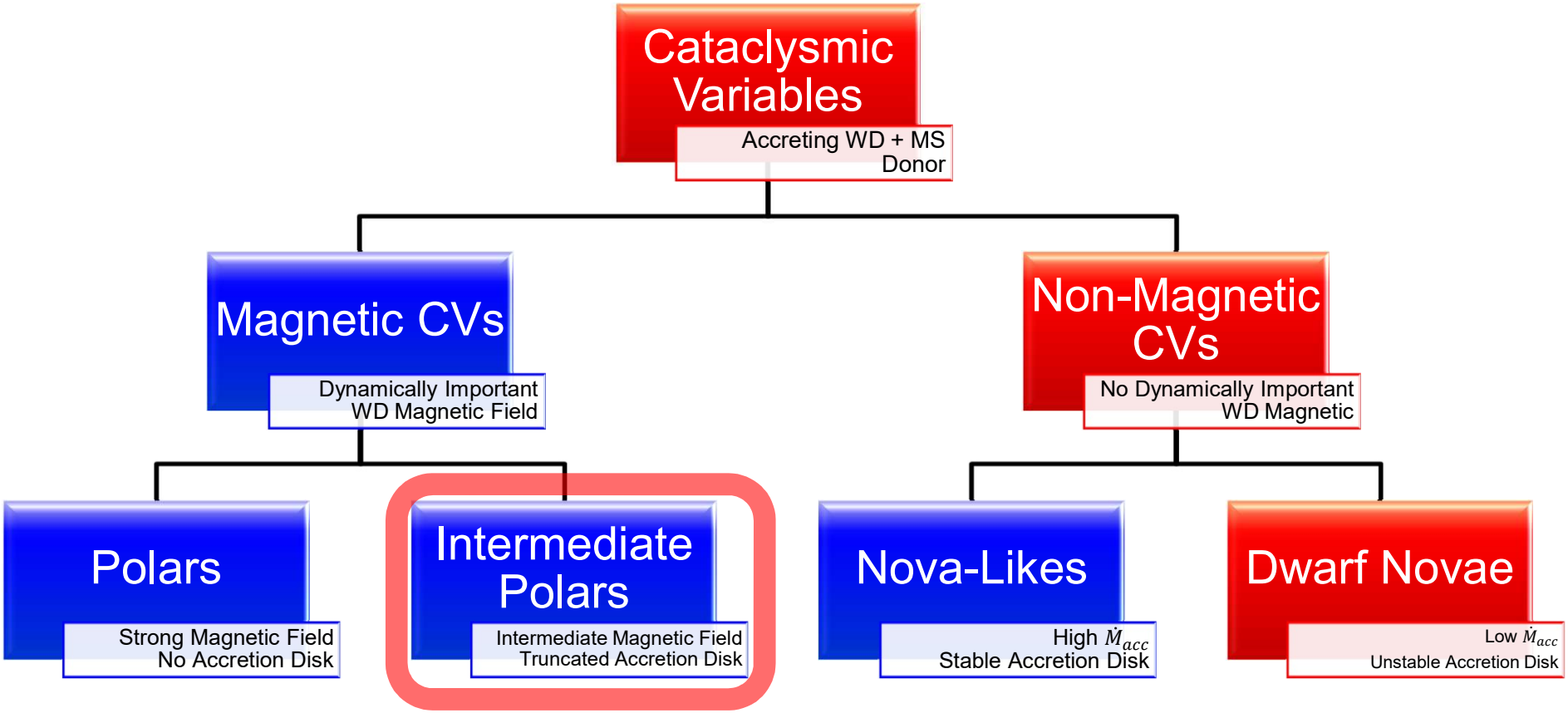


The Menagerie of CVs

Polars

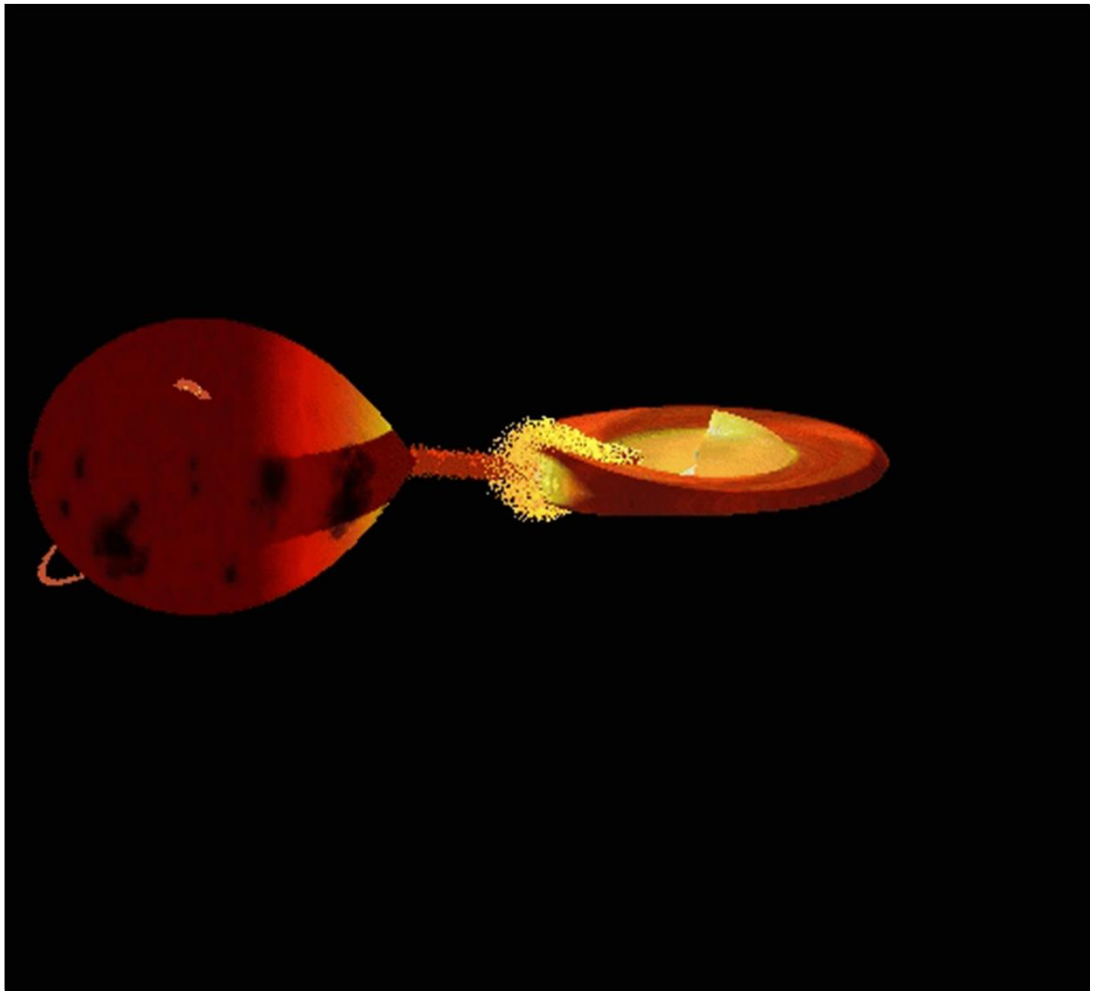


The Menagerie of CVs



The Menagerie of CVs

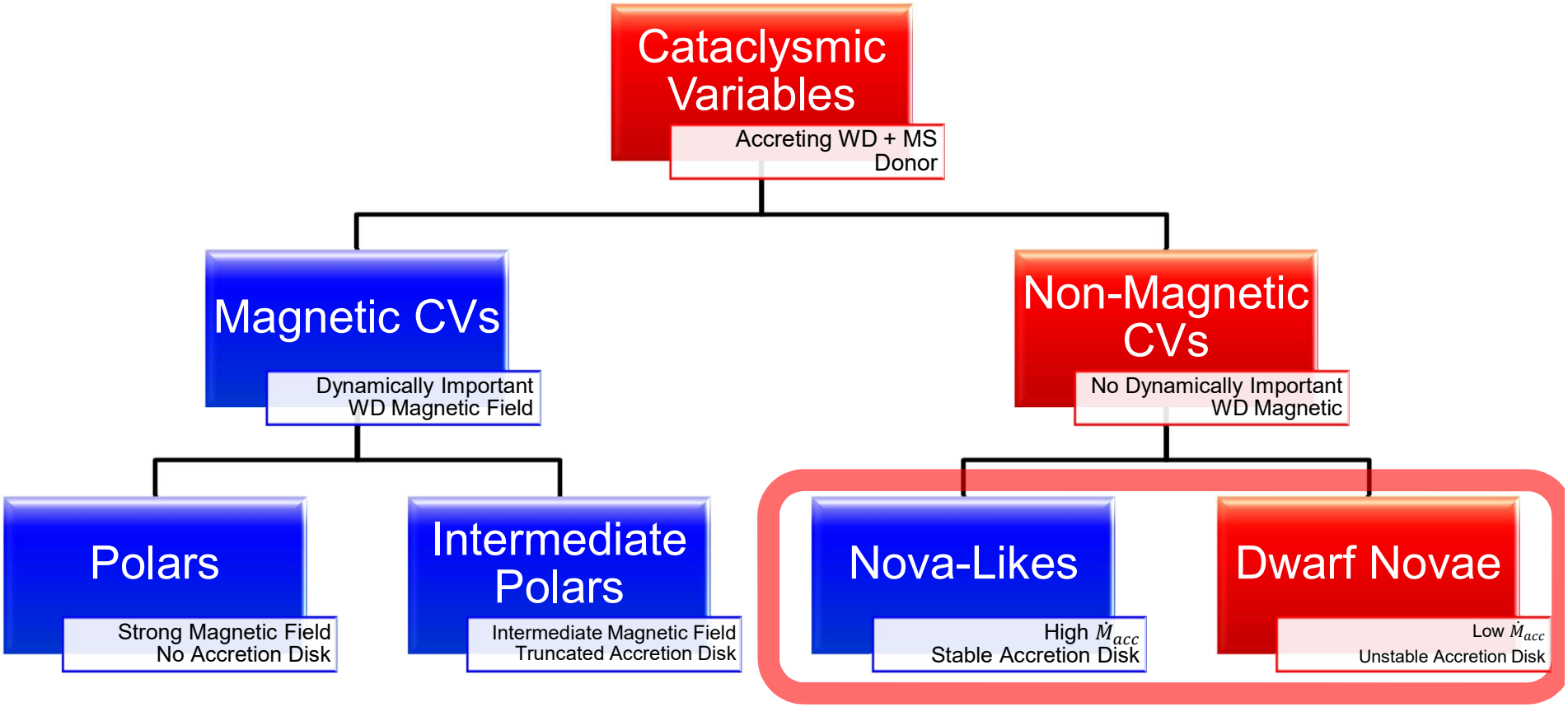
Intermediate Polars



Christian

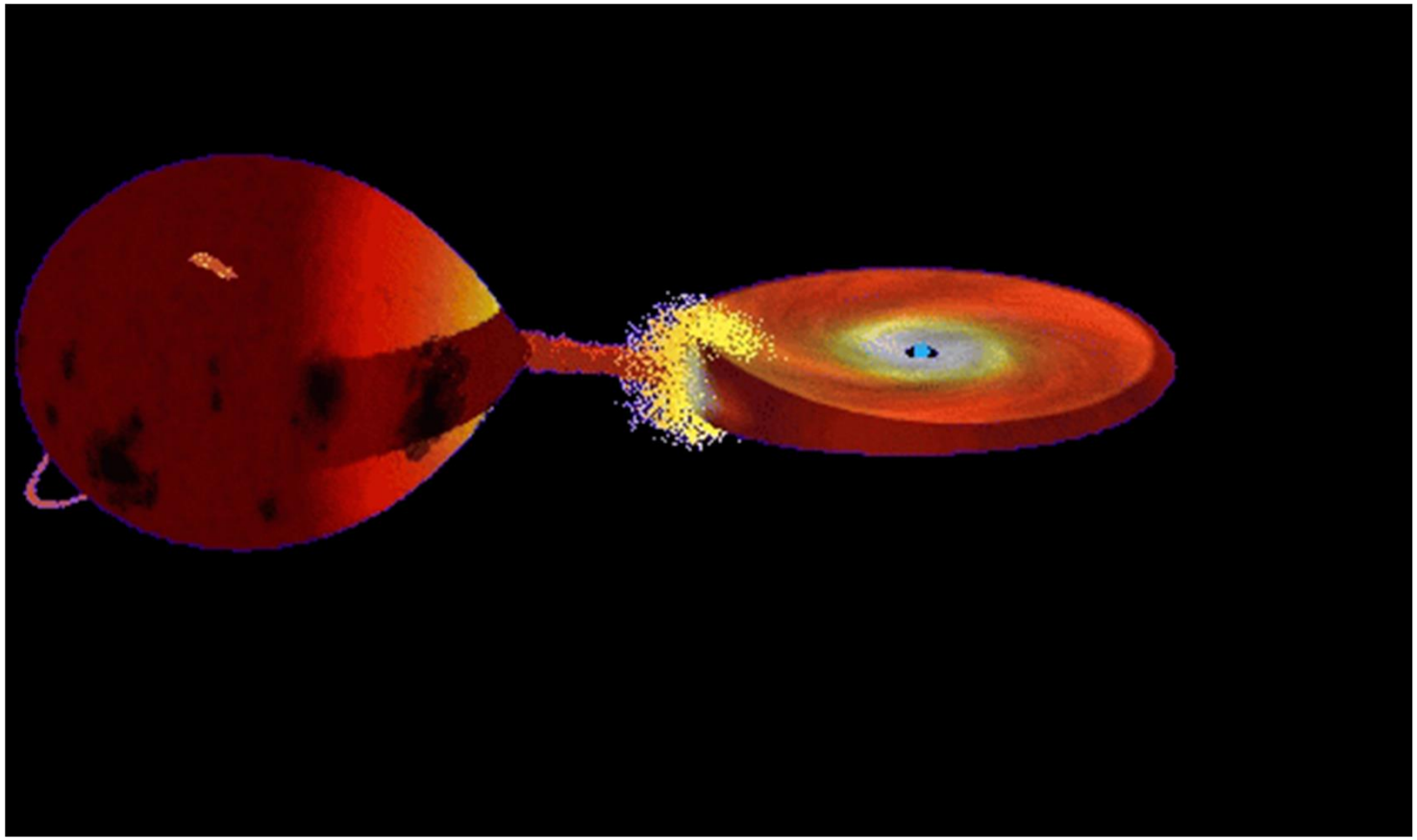
Department of Physics & Astronomy

The Menagerie of CVs

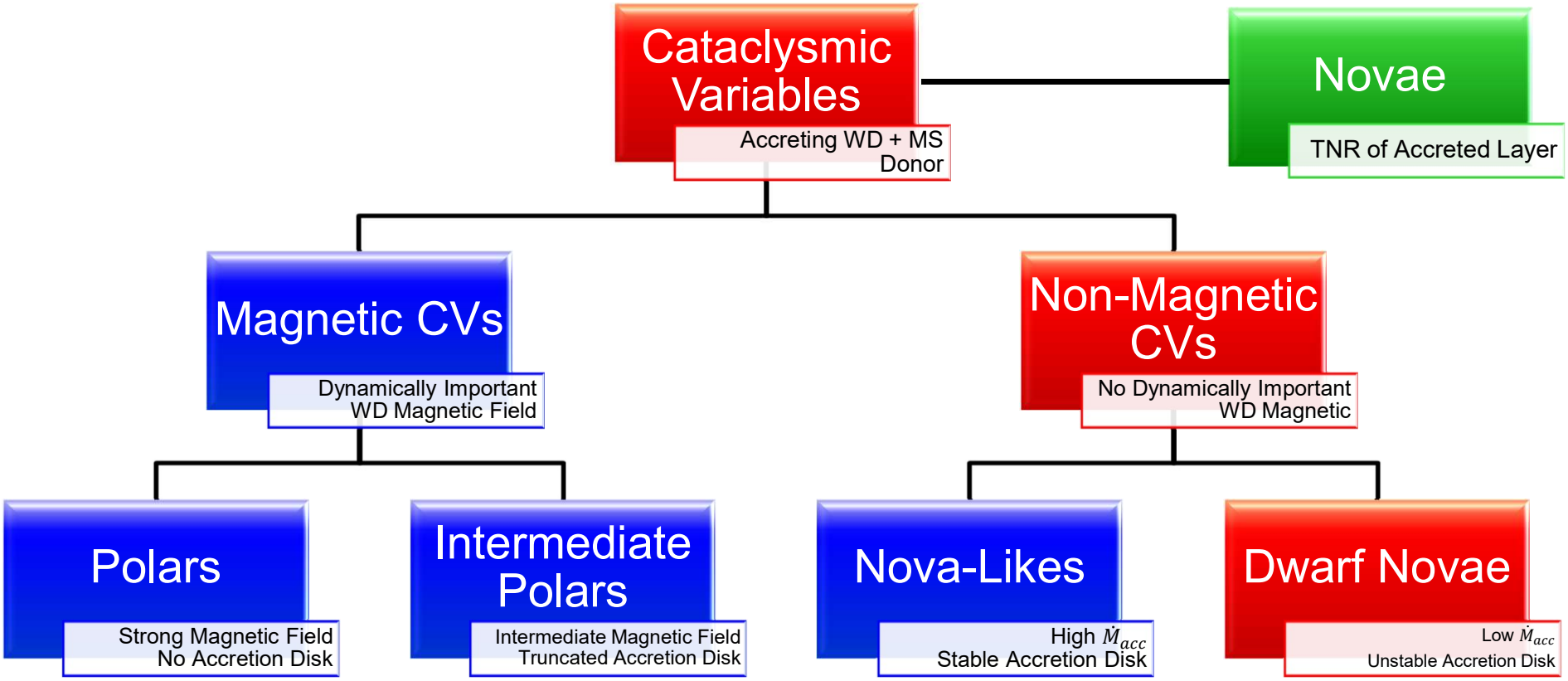


The Menagerie of CVs

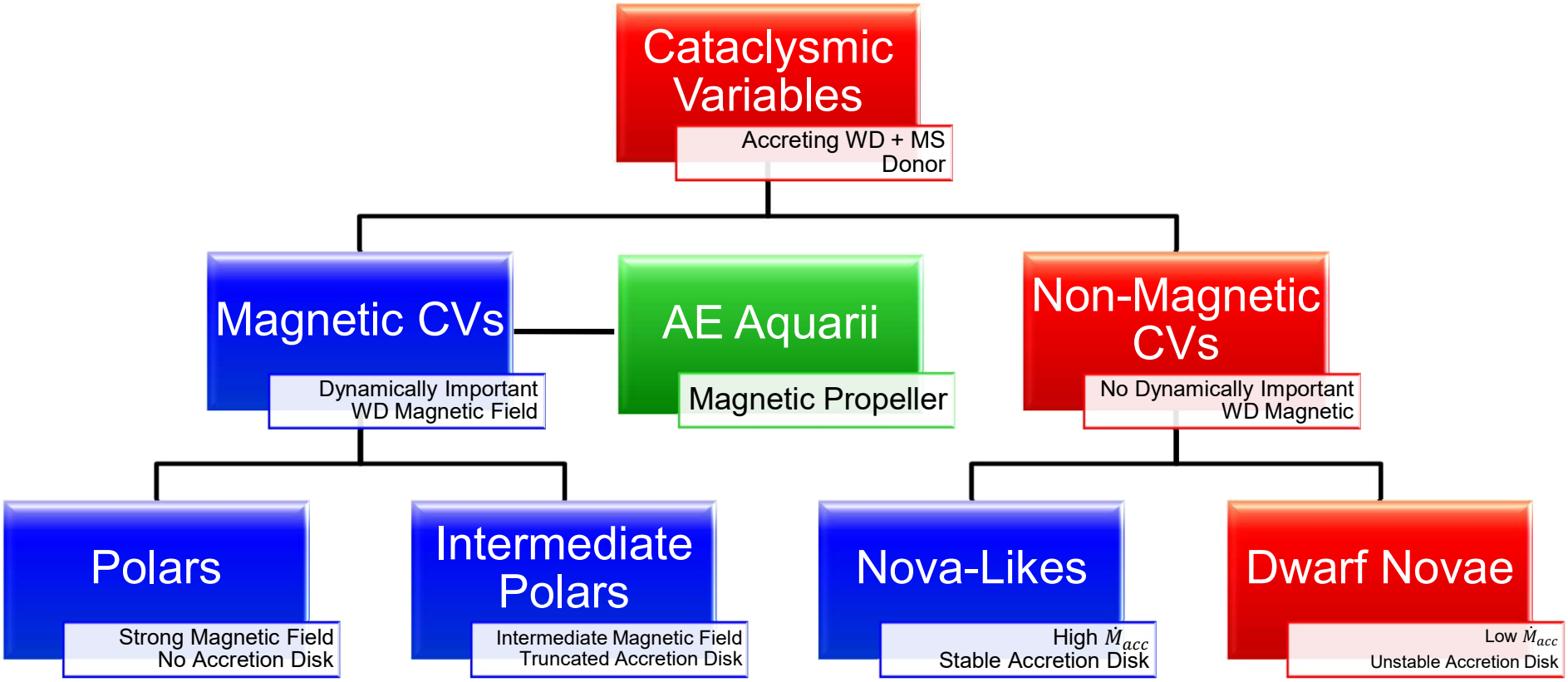
Nova-likes and Dwarf Novae



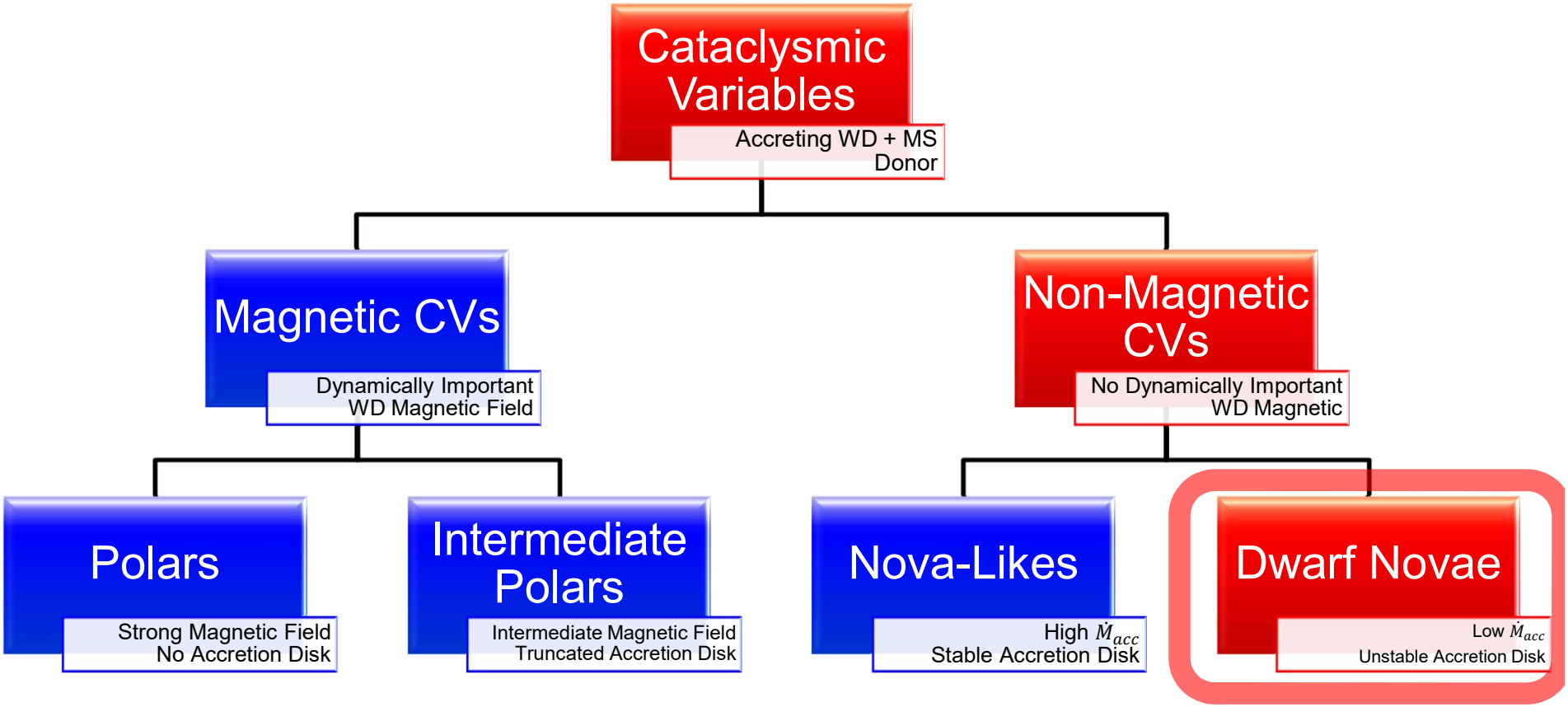
The Menagerie of CVs



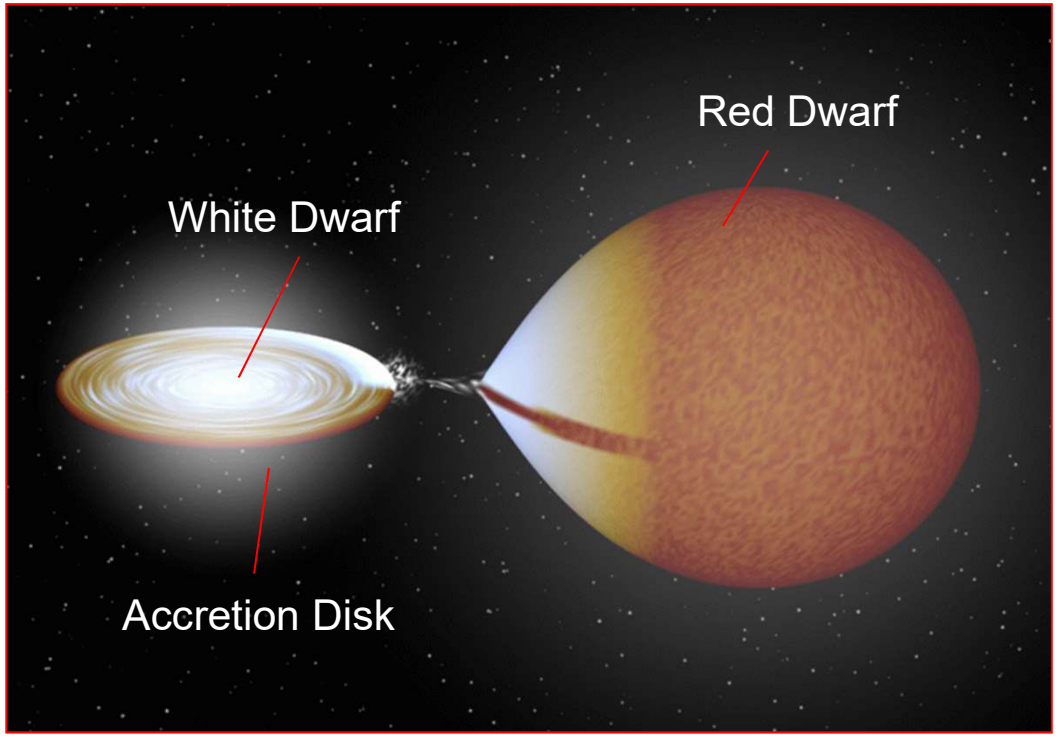
The Menagerie of CVs



The Menagerie of CVs



The Physical Structure of Non-Magnetic CVs

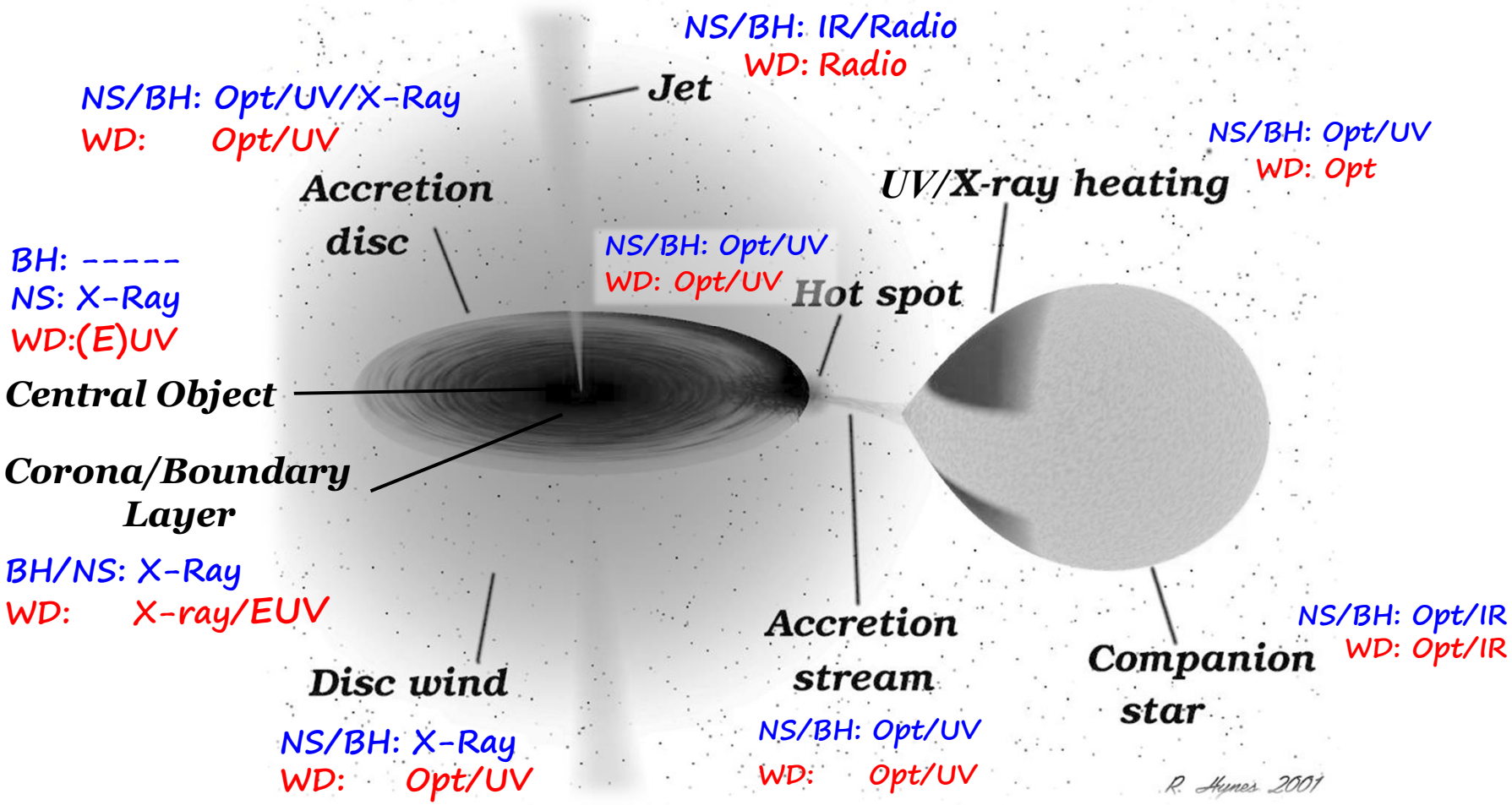


Credit: Rob Hynes

- White dwarf primary
- MS secondary
- 75 mins < P_{orb} < 6 hrs
- Accretion via a disk
- Bright, nearby, numerous

Accreting White Dwarfs vs Neutron Stars and Black Holes

The Multi-Wavelength Perspective



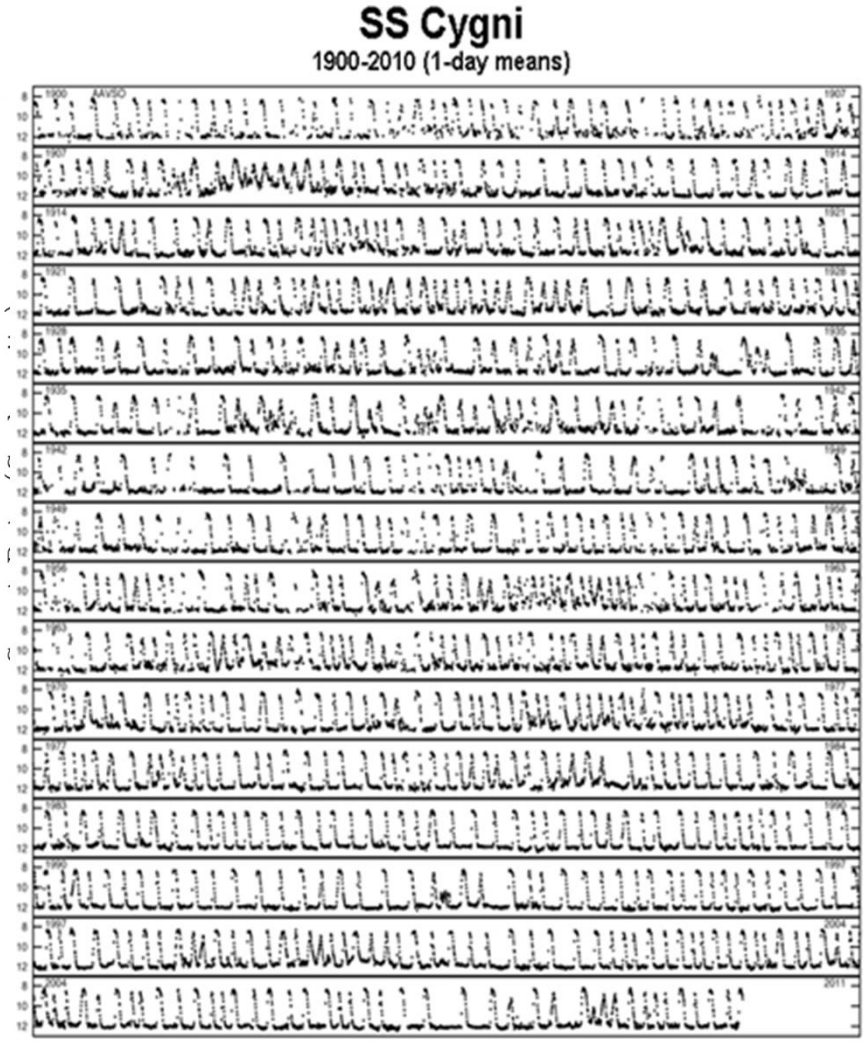
Cataclysmic Variables as Universal Accretion Disk Laboratories

From phenomenology to physics

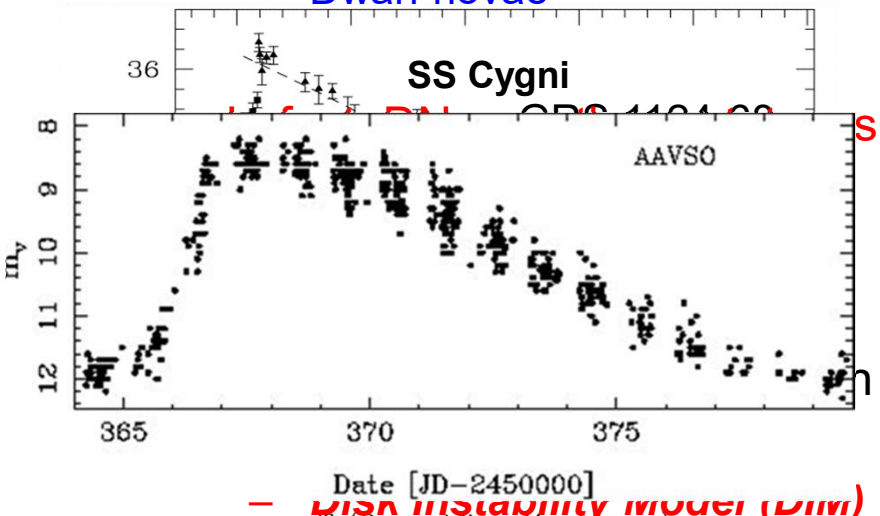
Christian

Department of Physics & Astronomy

Outbursts

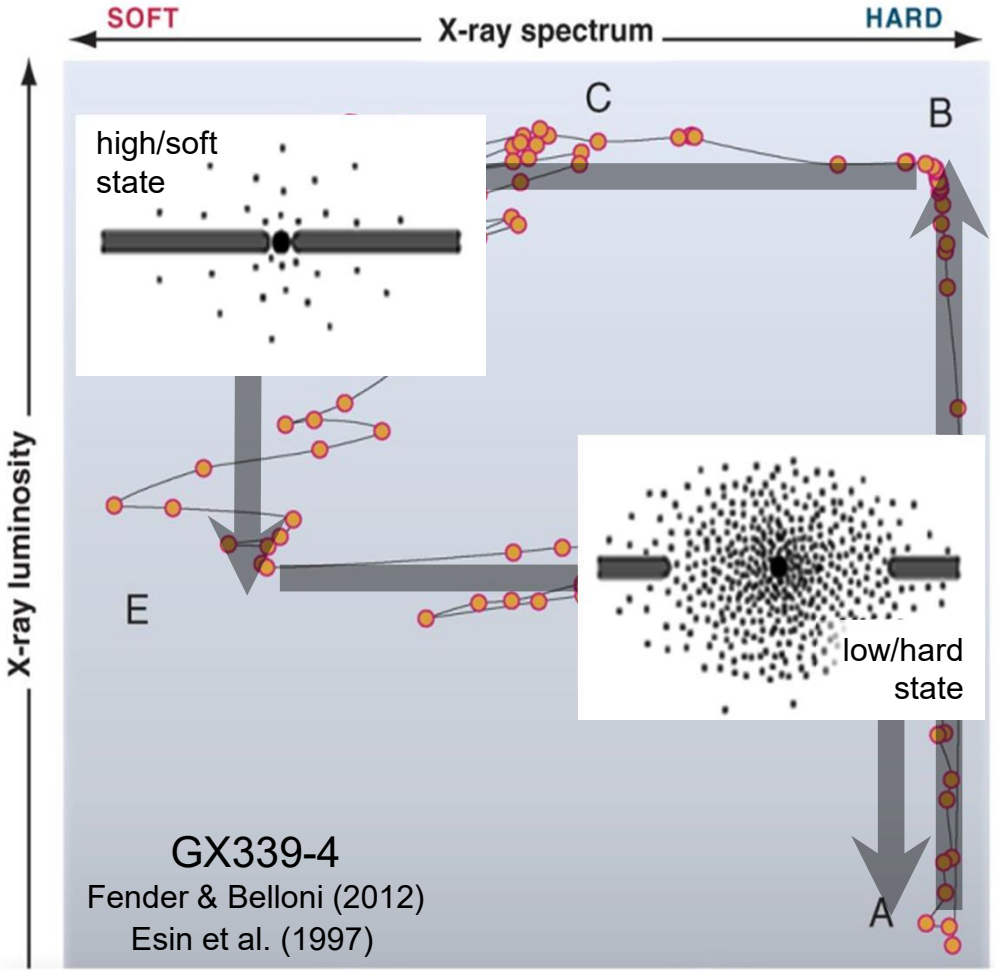


- Many accreting compact binaries exhibit outbursts
  - e.g. black hole and neutron star X-ray transients
- Most accreting white dwarfs do the same
  - Dwarf novae



  - ***Disk instability model (DIM)***
  - ***Viscous-thermal instability***

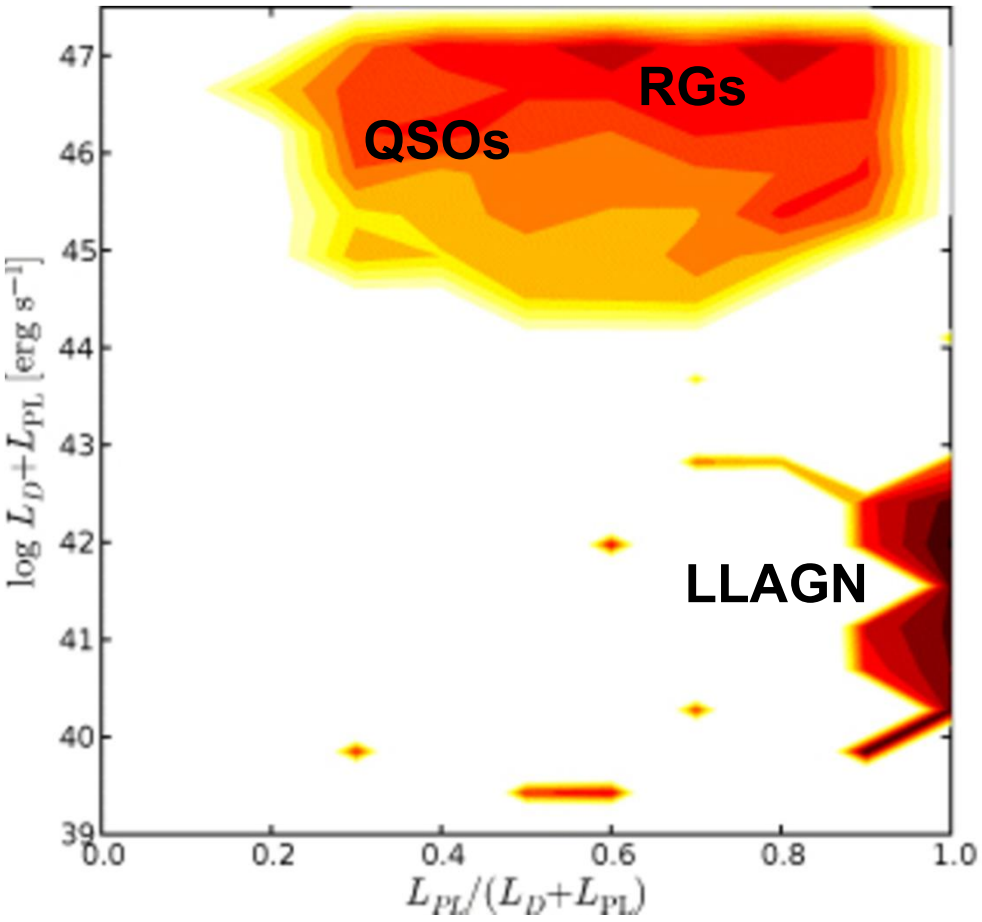
The Phenomenology of Transient Accretion: Neutron Stars and Black Holes



- Recent insights from NSs and BHs
  (Fender, Belloni & Gallo 2004)
  - X-ray transients execute a q-shaped path in the X-ray hardness vs intensity plane

→ **Hysteresis**

The Phenomenology of Transient Accretion:
Neutron Stars and Black Holes



- Recent insights from NSs and BHs
  (Fender, Belloni & Gallo 2004)
  - X-ray transients execute a q-shaped path in the X-ray hardness vs intensity plane

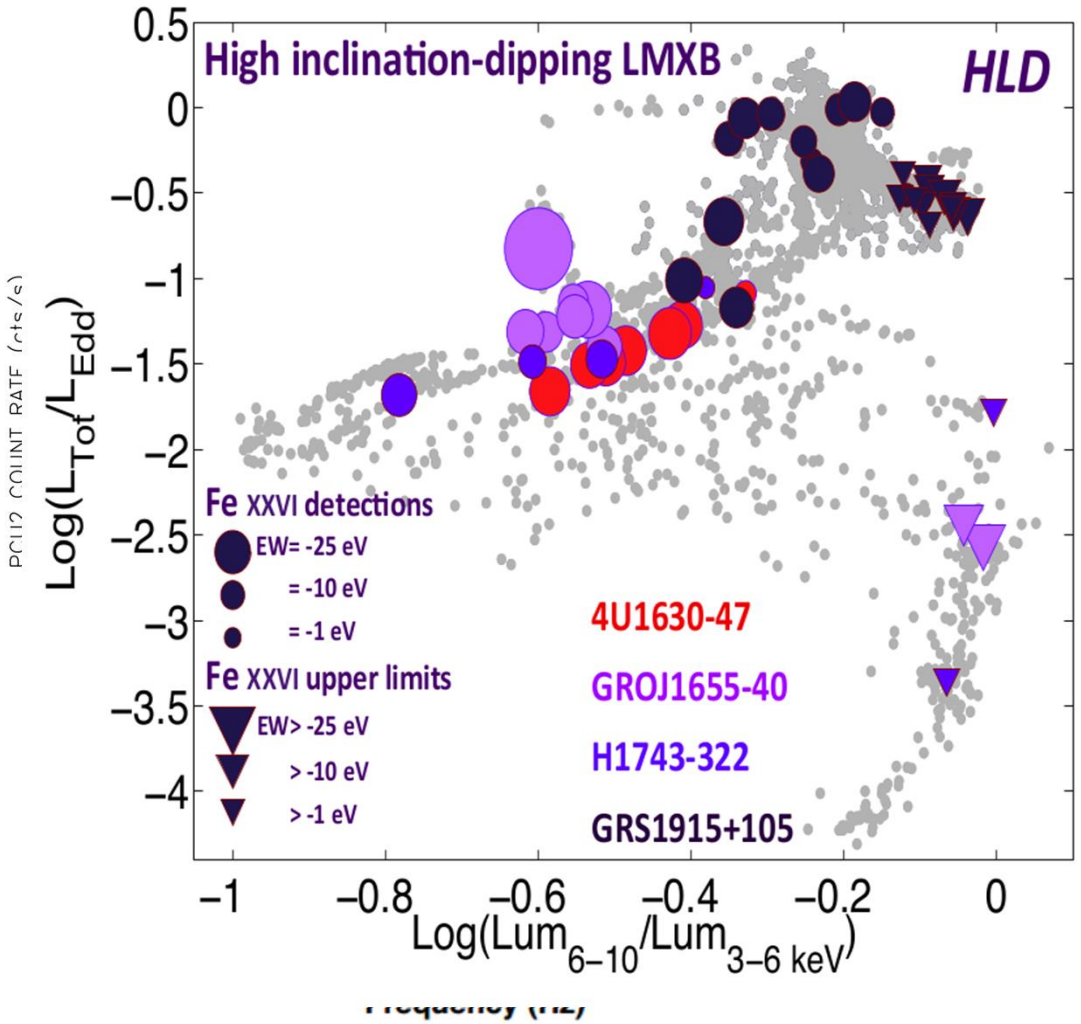
    → **Hysteresis**
  - Generalized “disk-fraction/luminosity” diagram (DFLD) may also apply to AGN
    (Koerding, Jester & Fender 2006)

The Phenomenology of Transient Accretion:

Neutron Stars and Black Holes

Remillard & McClintock (2(

Ponti et al. (2012)



Recent insights from NSs and BHs

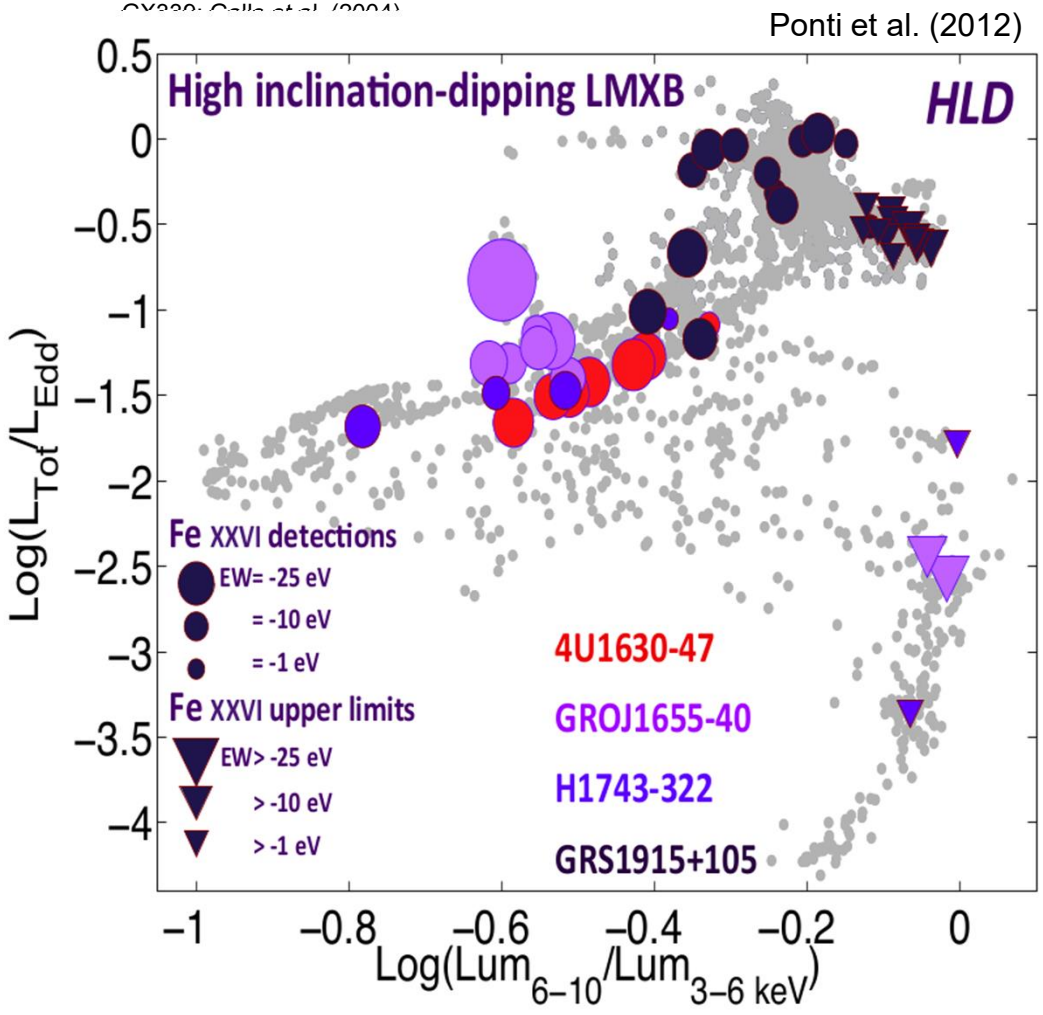
(Fender, Belloni & Gallo 2004)

– *All properties of the accretion flow correlate with spectral state!*

- **Variability**
- **Radio Jets**
- **Disk Winds**

The Phenomenology of Transient Accretion:
Neutron Stars and Black Holes

Ponti et al. (2012)



- Recent insights from NSs and BHs
  (Fender, Belloni & Gallo 2004)

  – *All properties of the accretion flow correlate with spectral state*

  - **Variability**
  - **Radio Jets**
  - **Disk Winds**

The Phenomenology of Transient Accretion: White Dwarfs

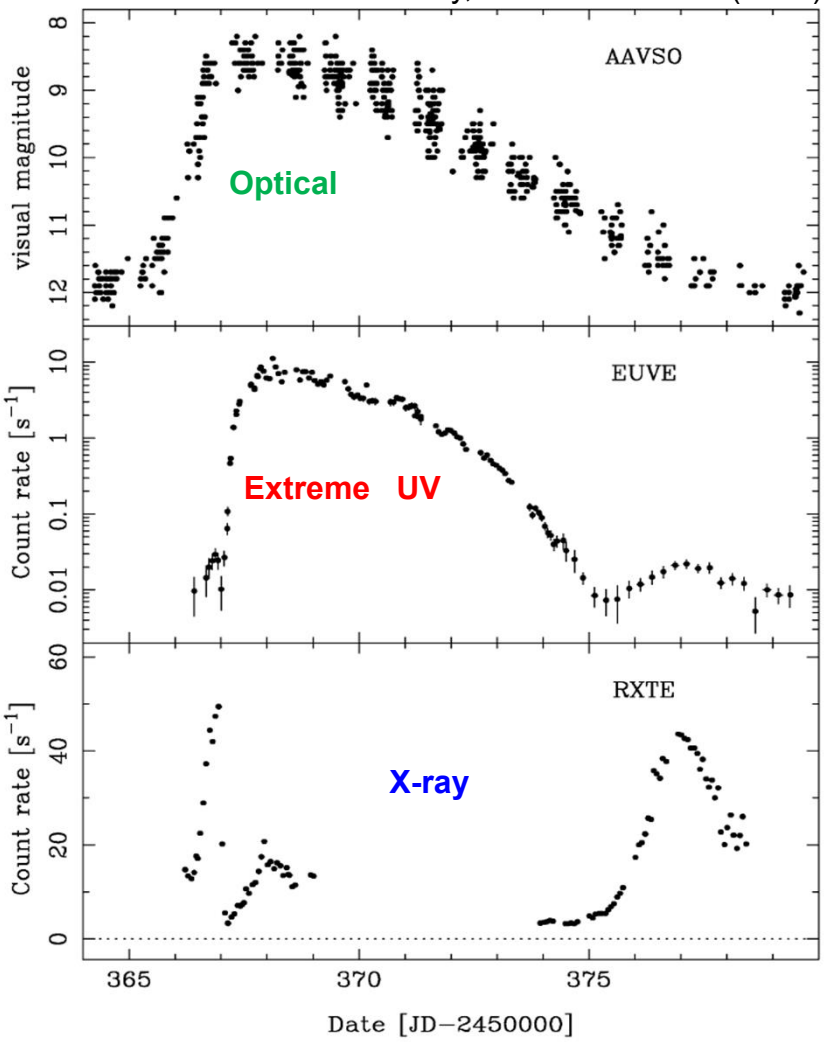
- How do we turn this phenomenology into physics?
  - Can we use accreting WDs as *universal* accretion laboratories?

- Do they display the full range of behaviour seen in neutron star and black hole systems?

White Dwarfs as Universal Accretion Laboratories

I: Hysteresis

Wheatley, Mauche & Mattei (2003)

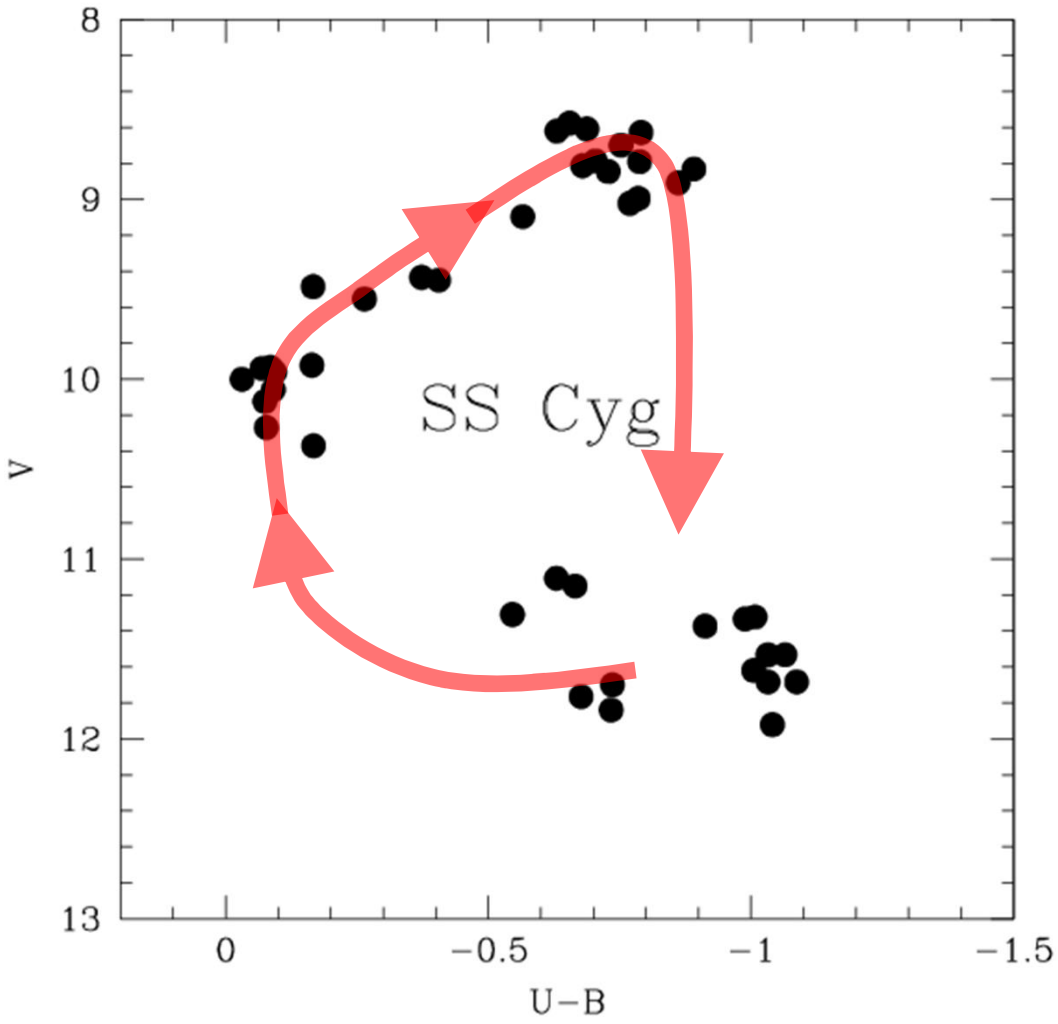


- Do transient accreting WDs – i.e. dwarf novae -- show hysteresis?
  - Remarkably few simultaneous multi-wavelength observations!
  - **Best available data set: SS Cyg**
  - Multi-wavelength coverage matters!
    - Disk: UV / Opt
    - Corona / BL($\tau < 1$): X-ray
    - BL ($\tau > 1$): EUV / X-ray

Let's take a look at the behaviour in different bands….

White Dwarfs as Universal Accretion Laboratories

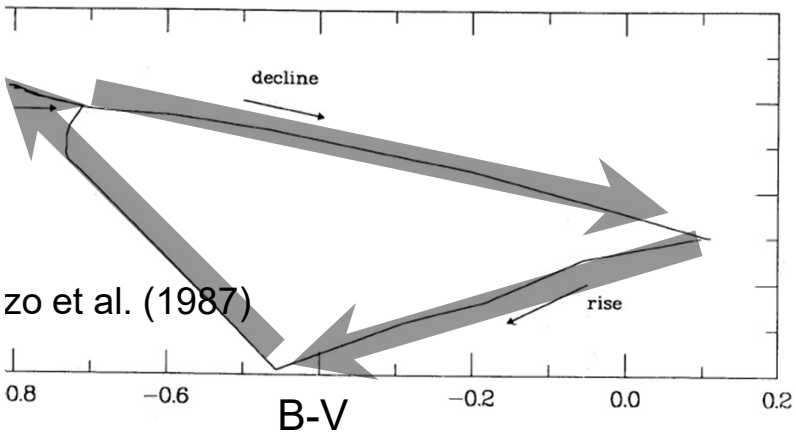
I: Hysteresis



Do transient accreting WDs – i.e. dwarf novae -- show hysteresis?

– Optical colours do!
(Bailey 1980, Echevaria & Jones 1983)

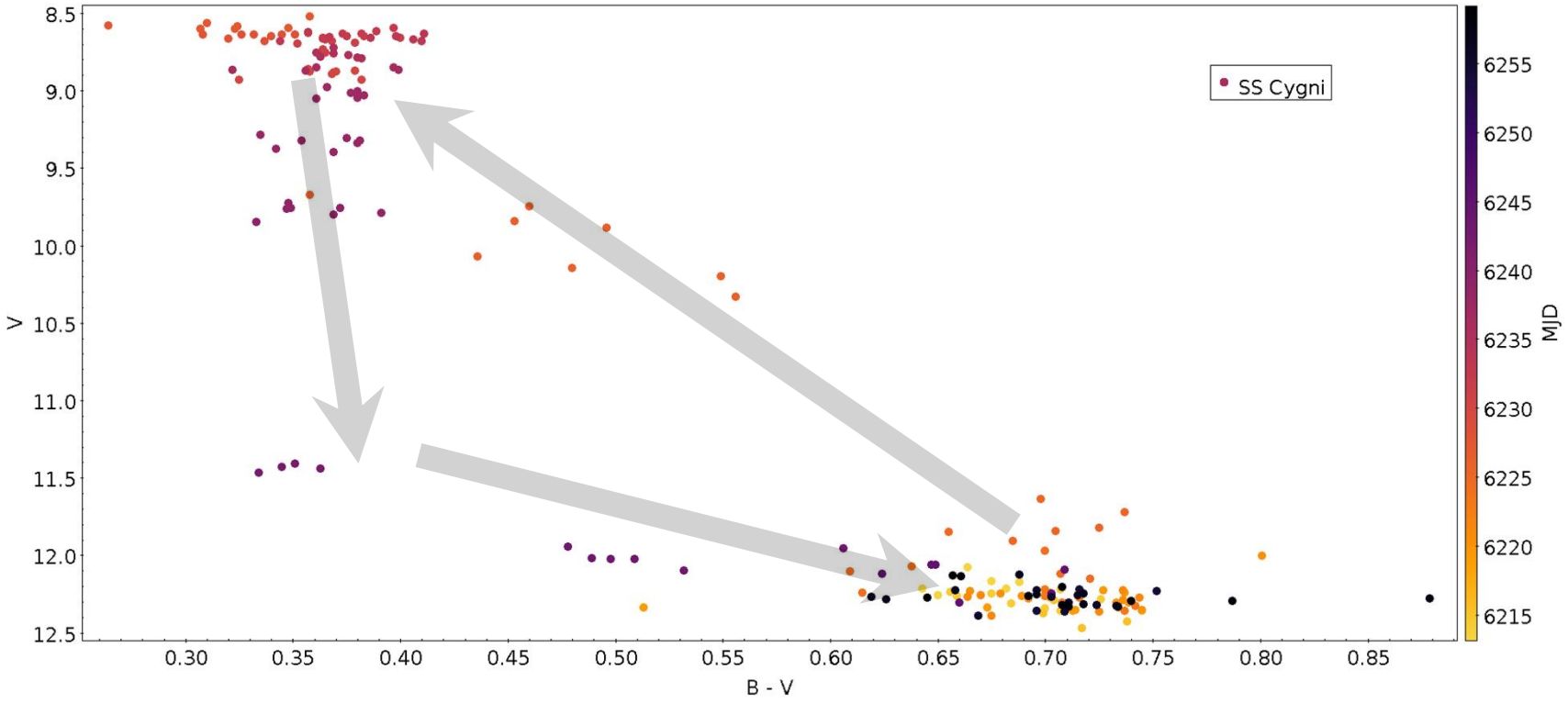
- Opposite sense to HID in XRBs
- Broadly consistent with DIM



zo et al. (1987)

Aside: Colour evolution during a DN outburst provides a great test of accretion disk theory!

So, obviously, we must have ***much*** better data available for such a test now….

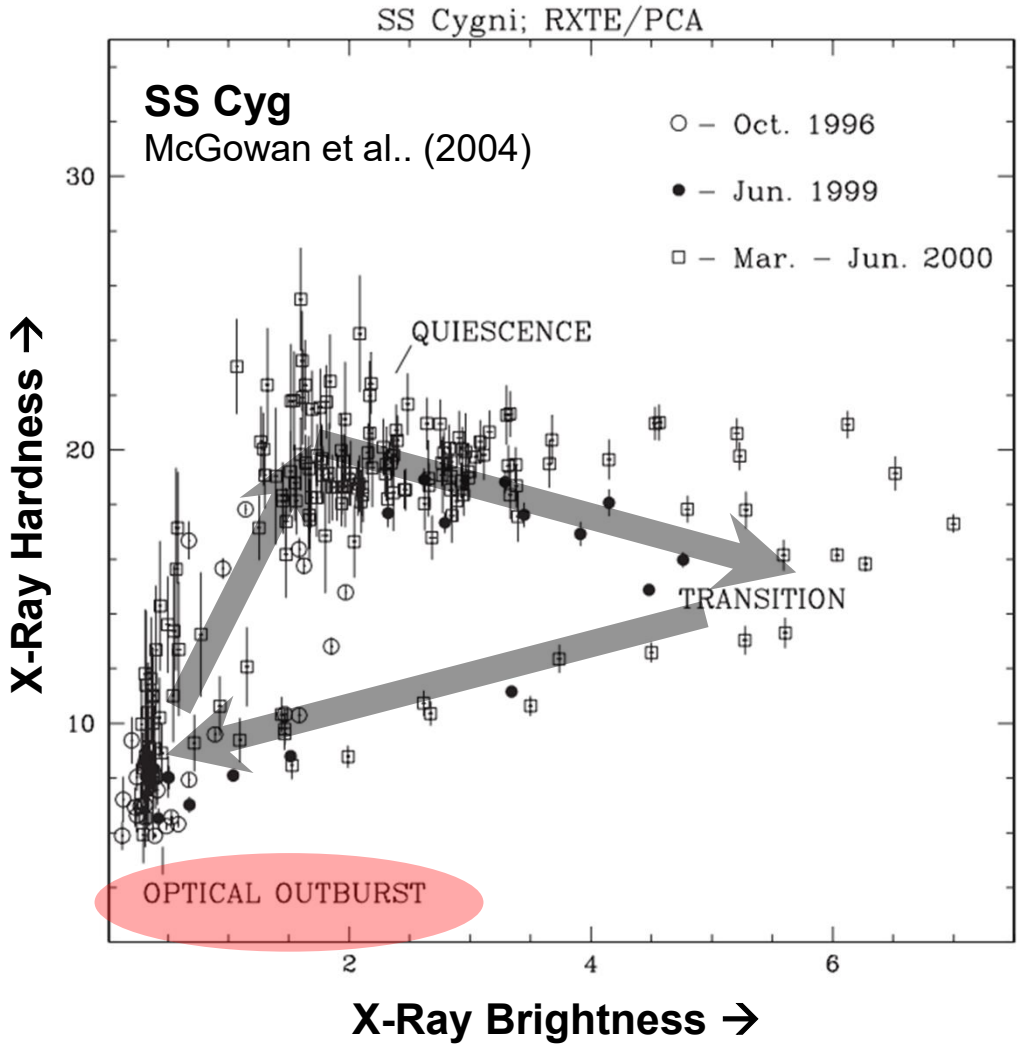


NO: Huge opportunity for amateur astronomers to make a significant contribution!

We'll come back to this…

White Dwarfs as Universal Accretion Laboratories

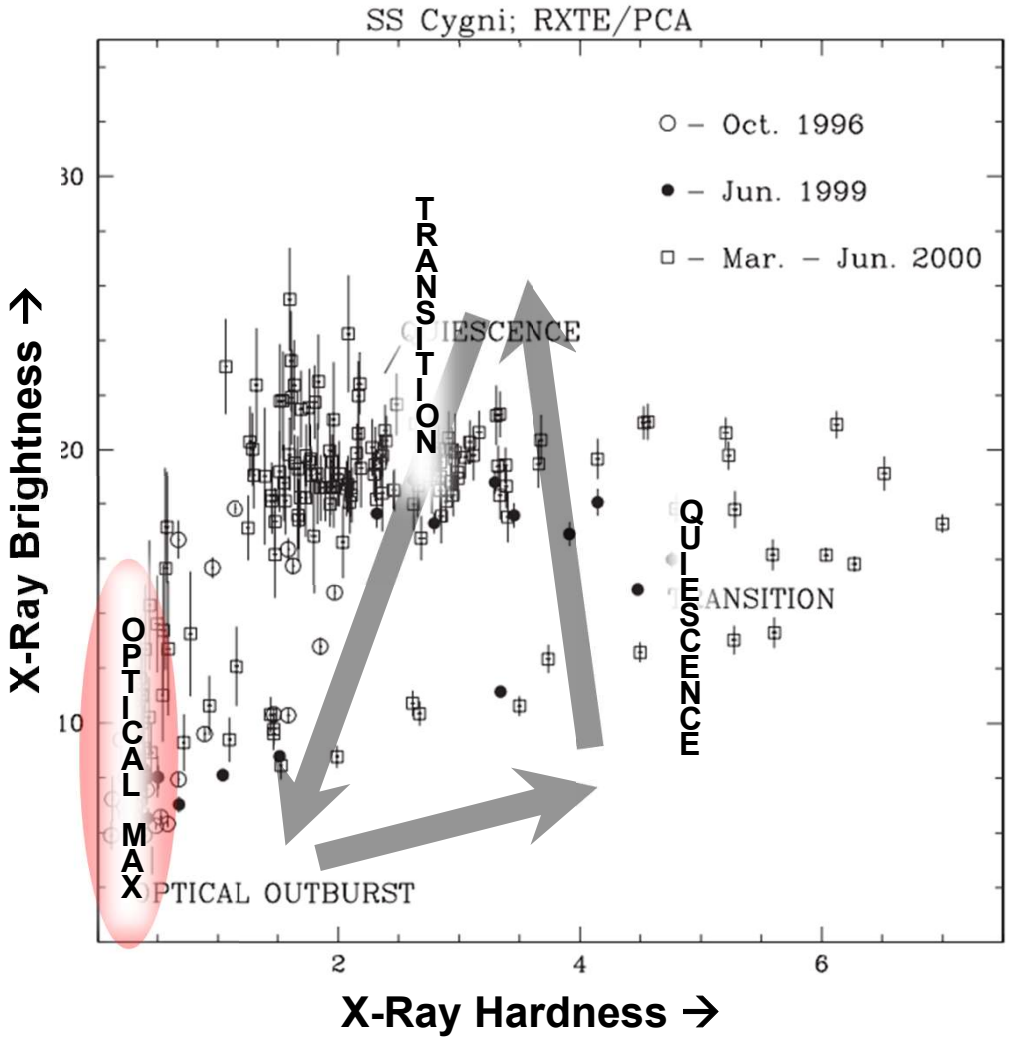
I: Hysteresis



- Do transient accreting WDs – i.e. dwarf novae -- show hysteresis?
  - X-rays do as well! (McGowan et al. 2004)

White Dwarfs as Universal Accretion Laboratories

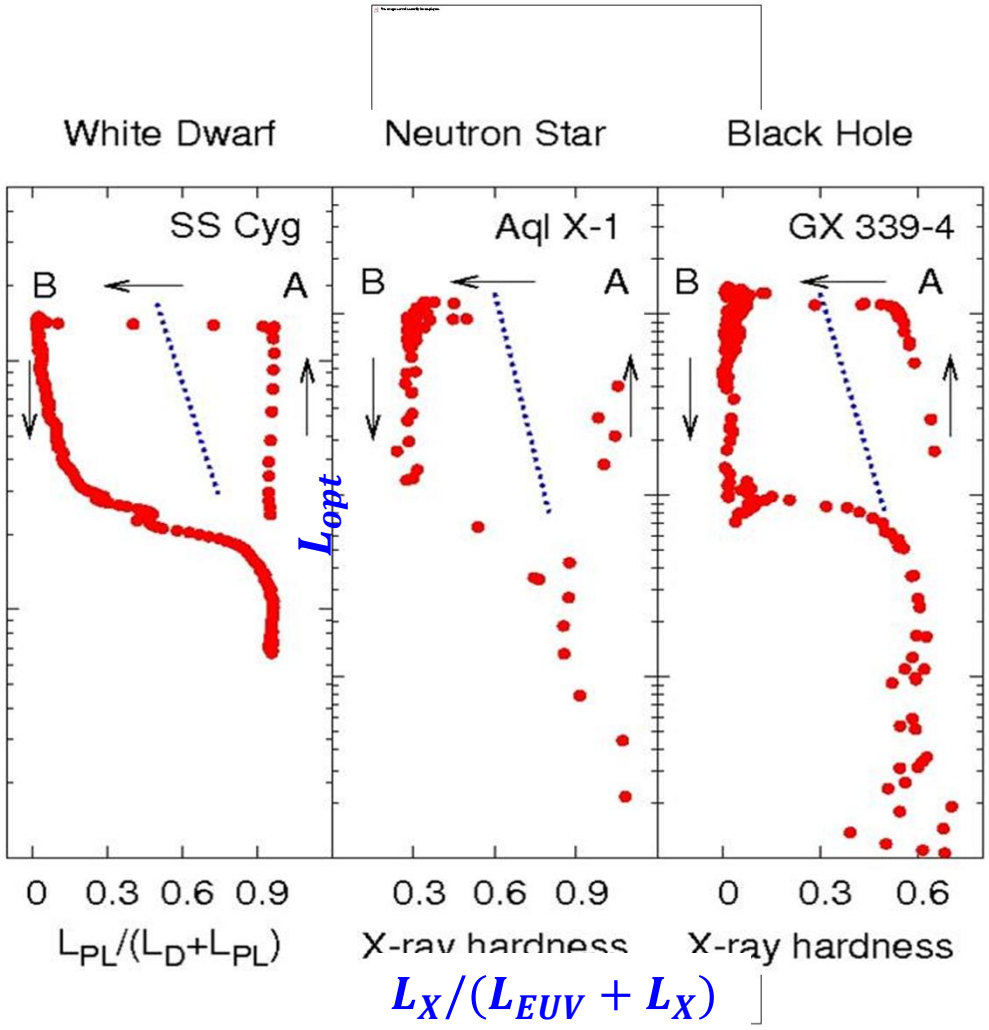
I: Hysteresis



- Do transient accreting WDs – i.e. dwarf novae -- show hysteresis?
  - X-rays do as well! (McGowan et al. 2004)
    - Same sense as HID in XRBs
- But what is the "right" diagram for comparison to XRBs?

White Dwarfs as Universal Accretion Laboratories

I: Hysteresis



- Only one attempt to construct a multi-λ DFLD for accreting WDs (Koerding et al. 2008, Science)

  – **Remarkably similar to NS/BH XRBs**

White Dwarfs as Universal Accretion Laboratories

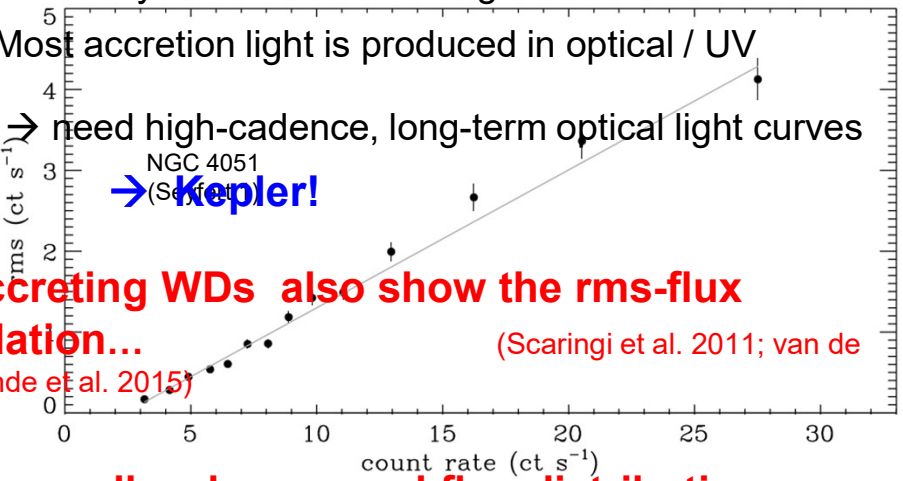
II: Variability

- All types of accreting systems display aperiodic variability ("flickering")?
  - ***Can you spot the accreting WD?***
- Key discovery in XRBs and AGN: **"rms-flux relation"**
  - Rules out "additive" (e.g. shot-noise) models
  - Applies on all time-scales → log-normal flux distribution
- **What about CVs?**
  - Variability time-scales are longer
  - Most accretion light is produced in optical / UV

    → need high-cadence, long-term optical light curves

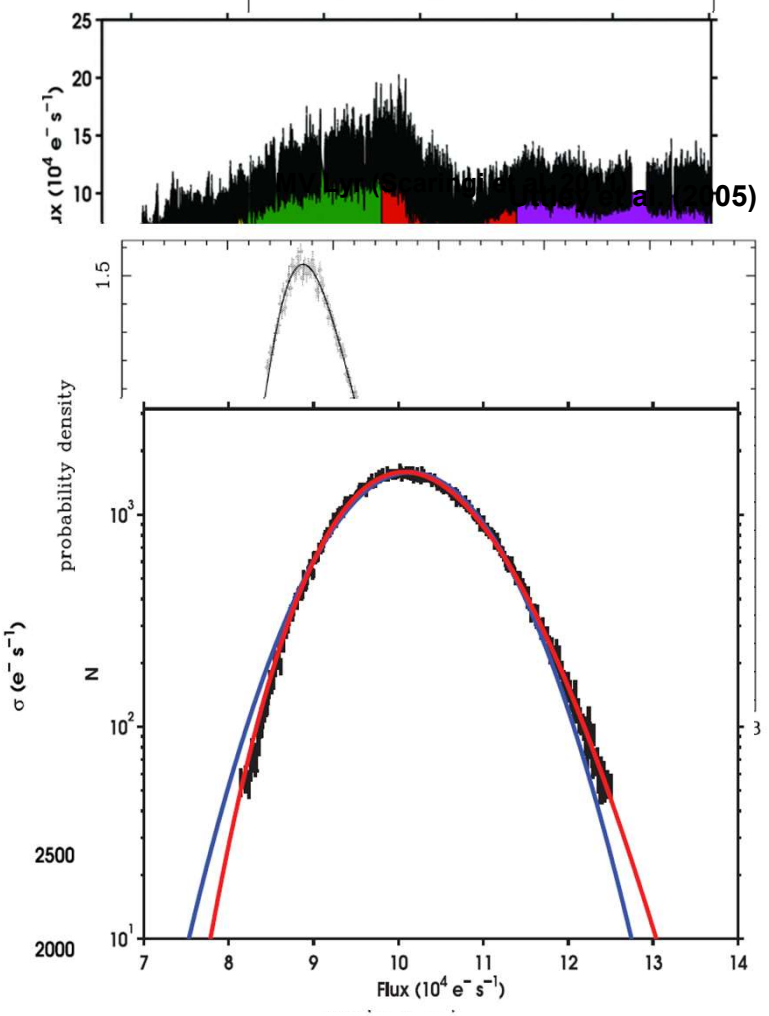
    → **Kepler!**

AGN (Vaughan et al. 2011)



- **Accreting WDs also show the rms-flux relation…** (Scaringi et al. 2011; van de Sande et al. 2015)
- **…as well as log-normal flux distributions** (Scaringi et al. 2011)

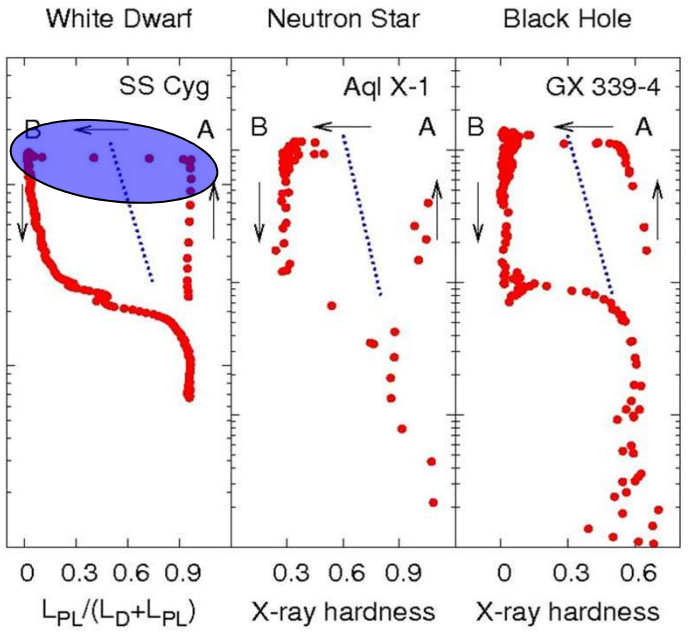
Black Hole XRB (Uttley & McHardy 2001)
MV Lyr (Scaringi et al. 2011)



White Dwarfs as Universal Accretion Laboratories

III: Jets

- **Are CVs also capable of launching jets?**
  - Strong implications for jet formation theories (Livio 1999)
  - Early searches negative, but focused on high-state systems
  - **If analogous to NSs/BHs, should focus on the hard-to-soft transition during outburst!**

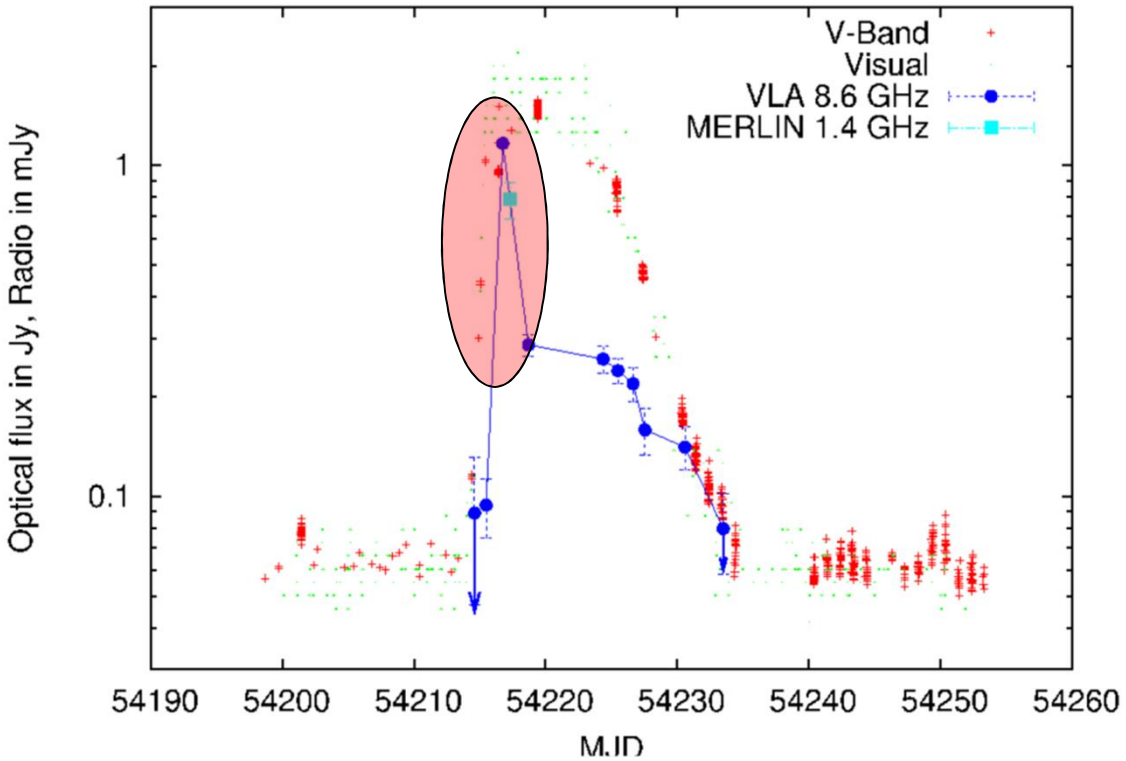


Koerding et al. (2008)

White Dwarfs as Universal Accretion Laboratories

III: Jets

- First attempt: the proto-typical dwarf nova SS Cygni
  - **Disovery of the first jet in a CV via detection of a radio flare**
    (Koerding, Rupen, Knigge, Fender et al. 2008, Science)



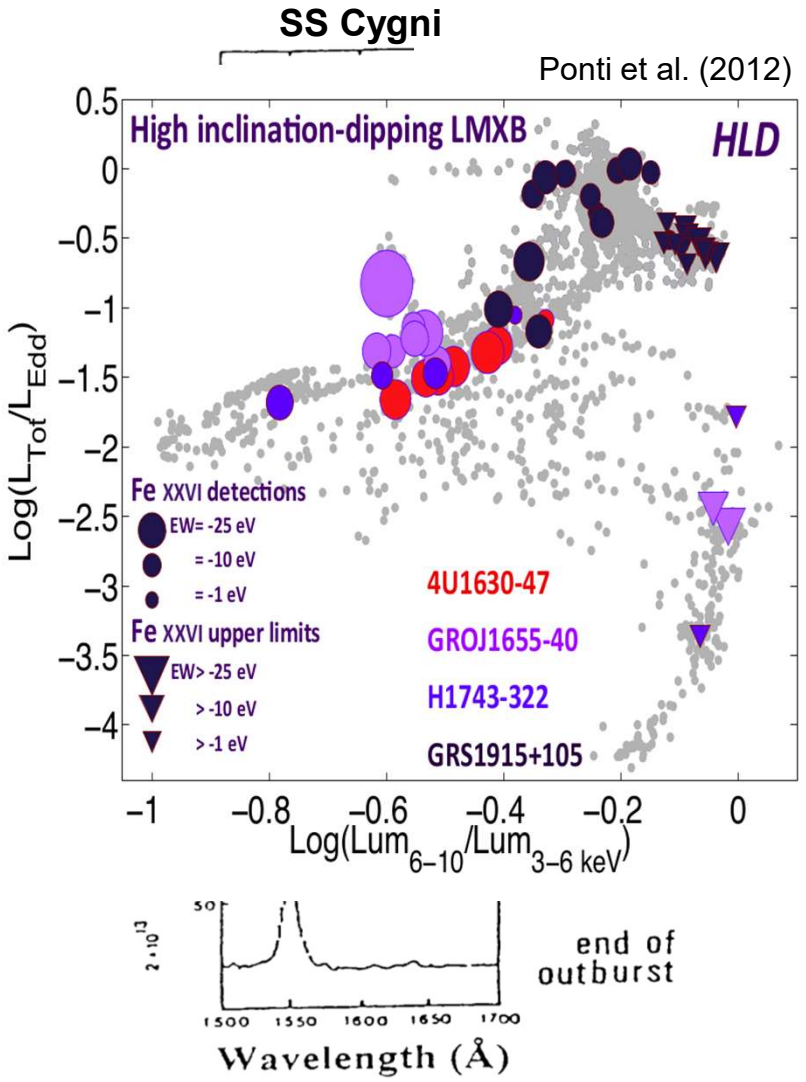
This campaign would have been impossible without the patient, careful and high-cadence optical monitoring that was provided by amateur astronomers and coordinated by the AAVSO!

White Dwarfs as Universal Accretion Laboratories

IV: Disk Winds

- Recent insights from BH XRBs (Ponti et al. 2012)
  - High-inclincation LMXBs show blue-shifted X-ray absorption lines, but only in high/soft(ish) states
    - Never in hard/jet states
    - ***Hard-to-soft transition accompanied (caused?) by switch from collimated jet → disk wind***
- Relation to accreting white dwarfs?
  - Disk winds are present in all high-$\dot{M}$ CVs !
    - blue-shifted UV absorption lines in low-i systems
    - uneclipsed UV emission lines in high-i systems
  - In DNe, wind-formed blue-shifted UV absorption only develops near outburst maximum

→ analogous to XRBs?



From Phenomenology to Physics:

A Sketch of a Coordinated Multi-Wavelength DN Outburst Campaign

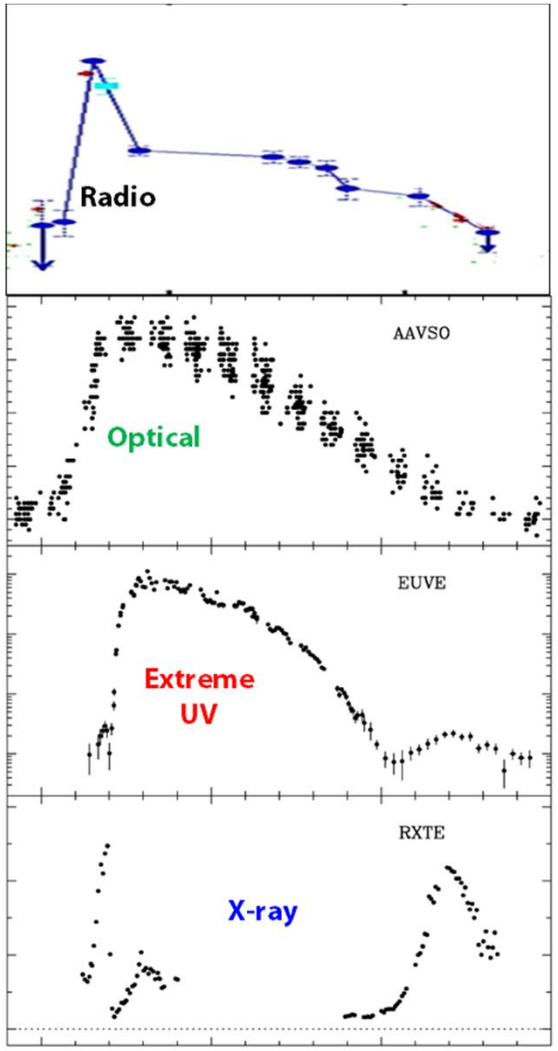
Christian

Department of Physics & Astronomy
University of Southampton

Anatomy of an Erupting Accretion Disk

Dissecting a Dwarf Nova Outburst

- Disk annulus becomes unstable, sending a heating wave inwards
  - **Optical** monitoring allows approximate timing to be predicted
    (AAVSO, BAA, CBA)
- Flickering and DNOs strengthen and speed up as disk moves inwards
  - High-speed **optical**, **UV** and **X-ray** photometry
    (ULTRACAM, HST, Swift, XMM, Chandra)
- X-rays from BL/corona brighten as onto WD increases
  - Time-resolved **X-ray** photometry/spectroscopy
    (Chandra, XMM, NuSTAR, INTEGRAL, Swift)
- Disk wind is launched once disk is sufficiently hot and bright
  - Time-resolved **EUV**, **UV** and **optical** spectroscopy
    (Chandra, HST, Swift, ground-based)
- Strong radio flare due to jet ejection when inner disk reaches centre
  - **Radio** and **infrared** monitoring
    (VLA, ground-based)
- DNOs are quenched as magnetosphere is crushed onto WD
  - High-speed **optical**, **UV** and **X-ray** photometry
    (ULTRACAM, HST, Swift, XMM, Chandra)
- BL emission switches from X-ray to EUV as it becomes optically thick
  - Time-resolved **X-ray** and **EUV** spectroscopy
    (Chandra, XMM, NuSTAR, INTEGRAL, Swift)



What would this answer?

Predictions and Open Questions

- Are jets and disk winds causally connected?
  - Do radio flares precede or follow the development of UV wind lines?
- Do jet ejection and oscillation quenching signal the disk reaching WD
  - Does DNO quenching coincide with radio flares?
- Does the BL become optically thick at the same point?
  - Does the X-ray → EUV switch coincide with radio flares or DNO quenching?
- Is there still a hot corona after the swich?
  - Are there residual hard X-rays in outburst?
- Is flickering PSD a good tracer of the inner disk edge?
- How does the rms-flux relation evolve?
- Are there lags between variability in different wavebands?
- Do disk winds signatures dominate UV and optical spectra?
- When and how do disk winds turn off?
- What is the total amount of accreted and ejected material?

We can actually do this!

- Requires roughly 1 week ~ 600 ksec ~ 100 HST orbits
  - Big, but not ridiculous
- Coordinated observations from radio to X-ray

  Optical **(crucial role for amateur astronomers!)**, VLA, HST, Swift, Chandra, XMM, NICER...
- Can probably be scheduled as non-disruptive ToO
  - several weeks notice
- Can we get critical mass in the professional **and amateur** communities?
- Are observatories willing and able to try this?
  - How do you propose for such a campaign?
  - Coordinated planning of observations
  - Triggering and continuous monitoring
    - **Only** possible through close collaboration between professional and amateur communities
    - Requires dedicated effort by amateur community

In the meantime…

- Carefully designed pro-am collaborations will always yield great – and sometimes surprising – results!

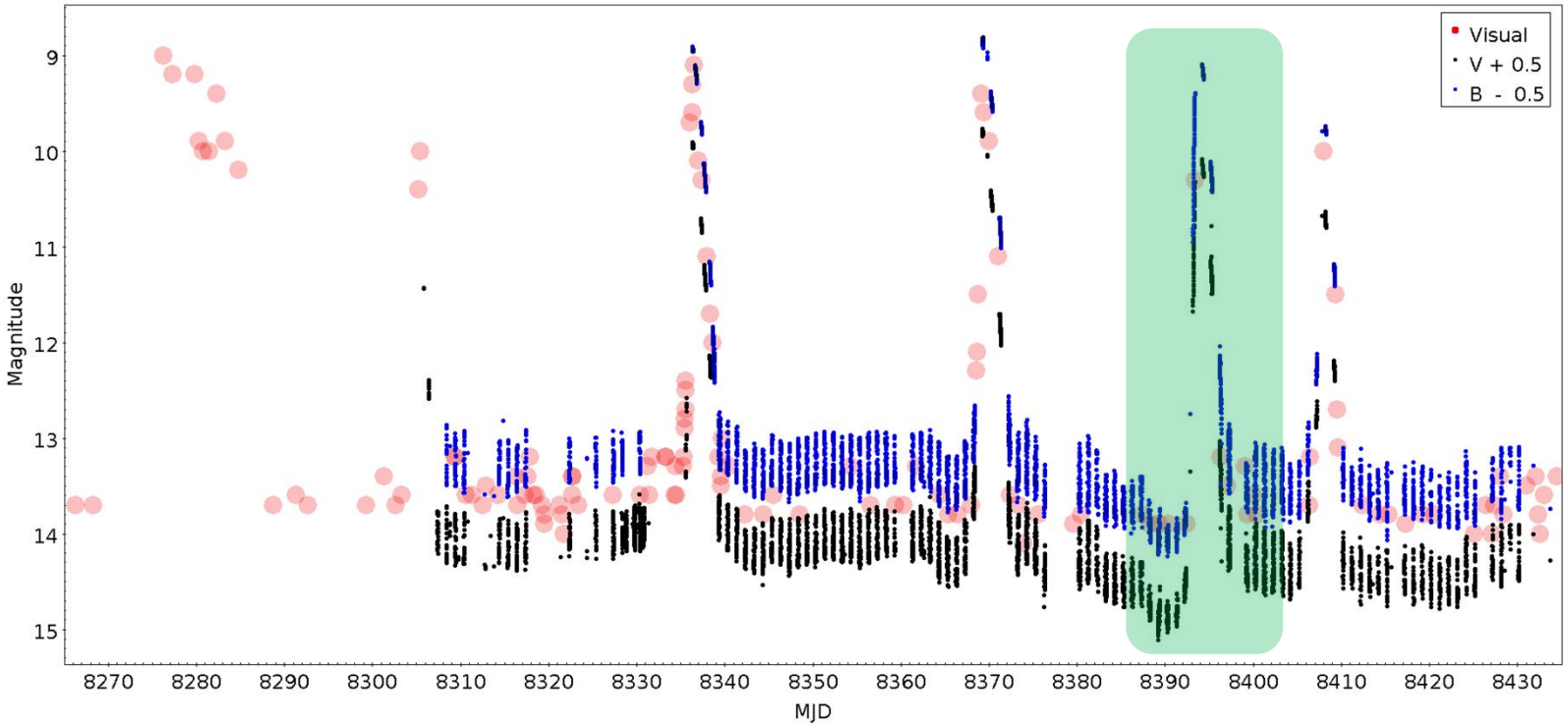
- Two recent examples:

  – VW Hyi
    - Great results from just a pilot multi-wavelength campaign

  – TCP J21040470+4631129
    - A new 9th magnitude DN !
    - Discovered by an amateur (Hideo Nishimura)

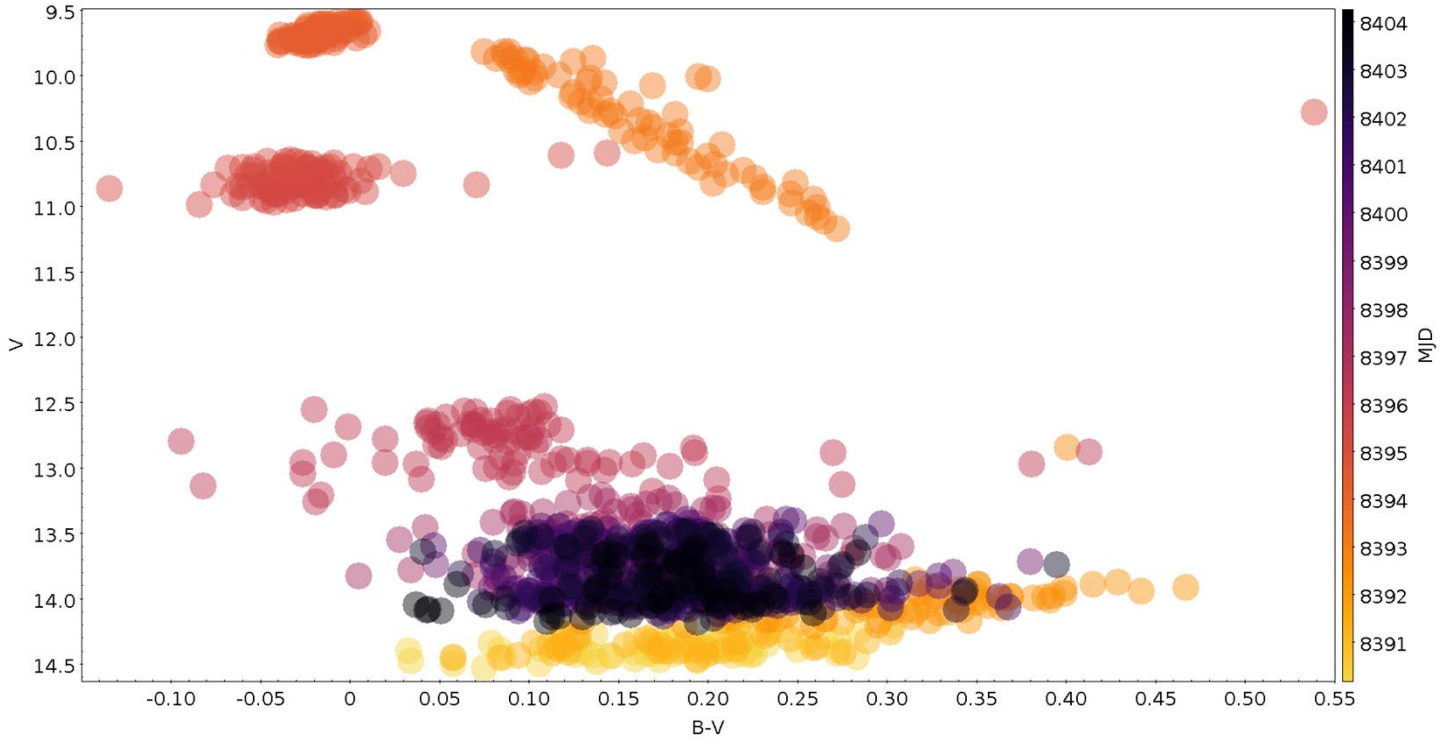
VW Hyi

Castro Segura et al. (in prep)



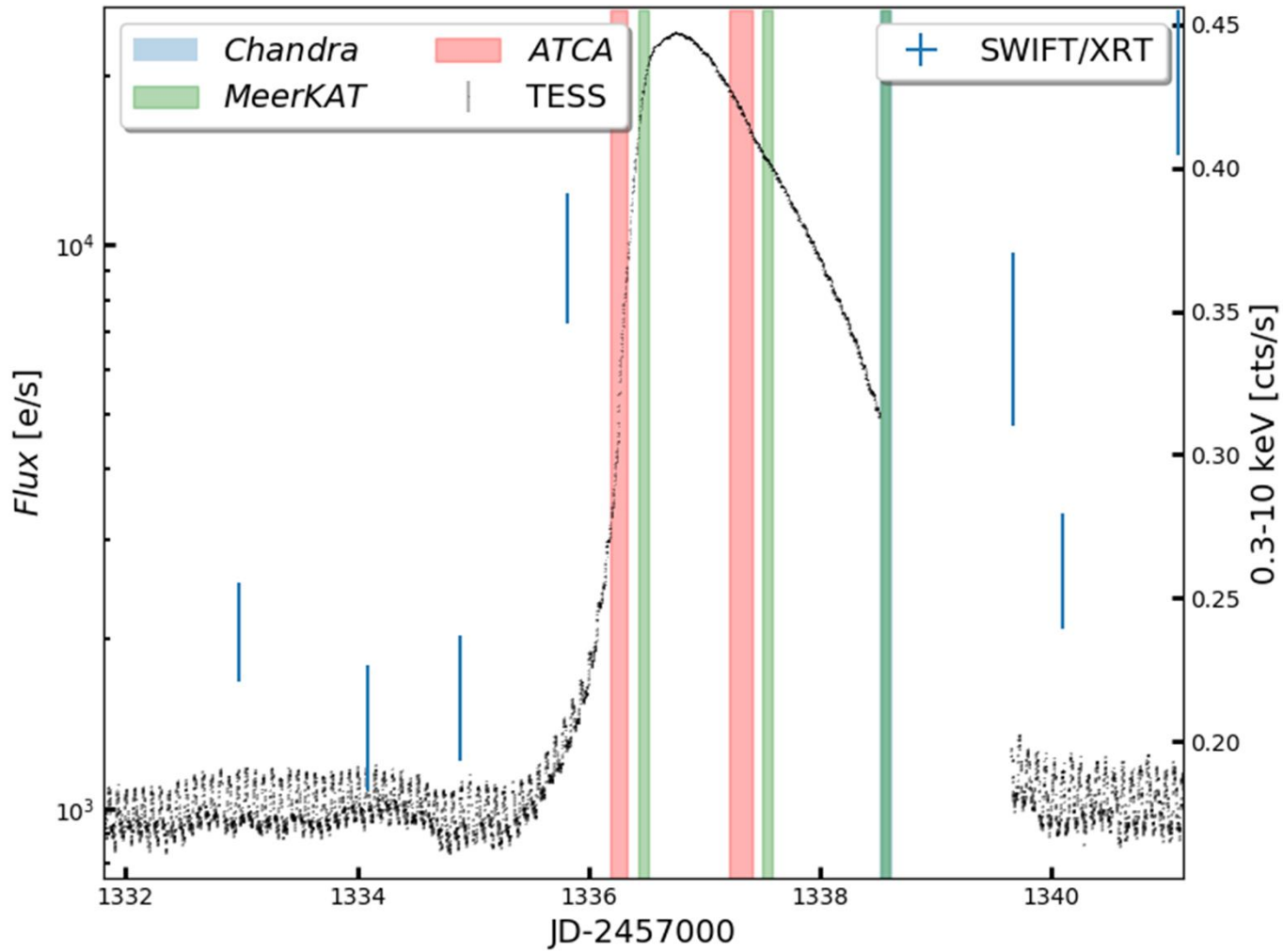
Best data set for DN colour evolution yet...

Castro Segura et al. (in prep)



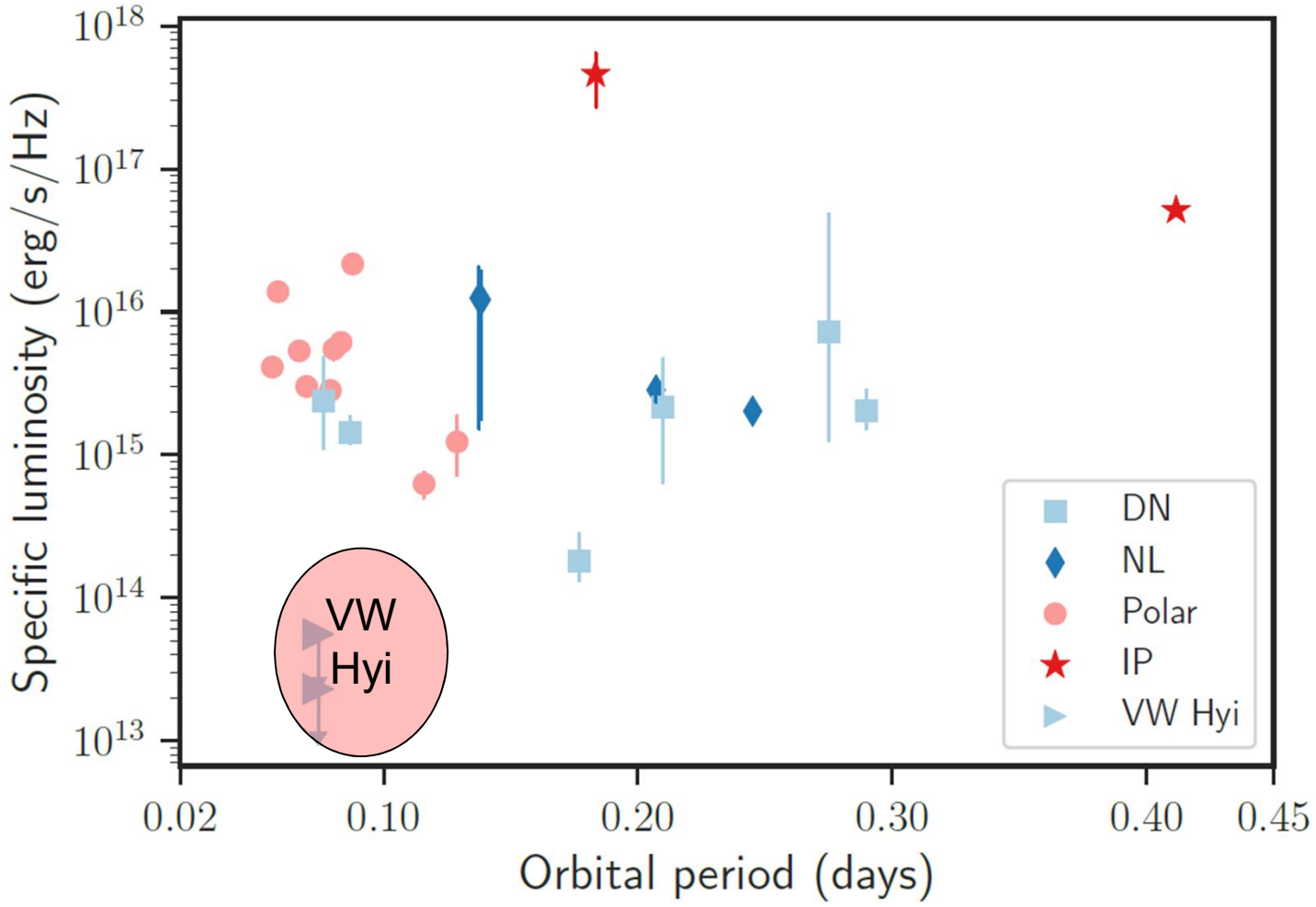
Great Multiwavelength Coverage

Castro Segura et al. (in prep)

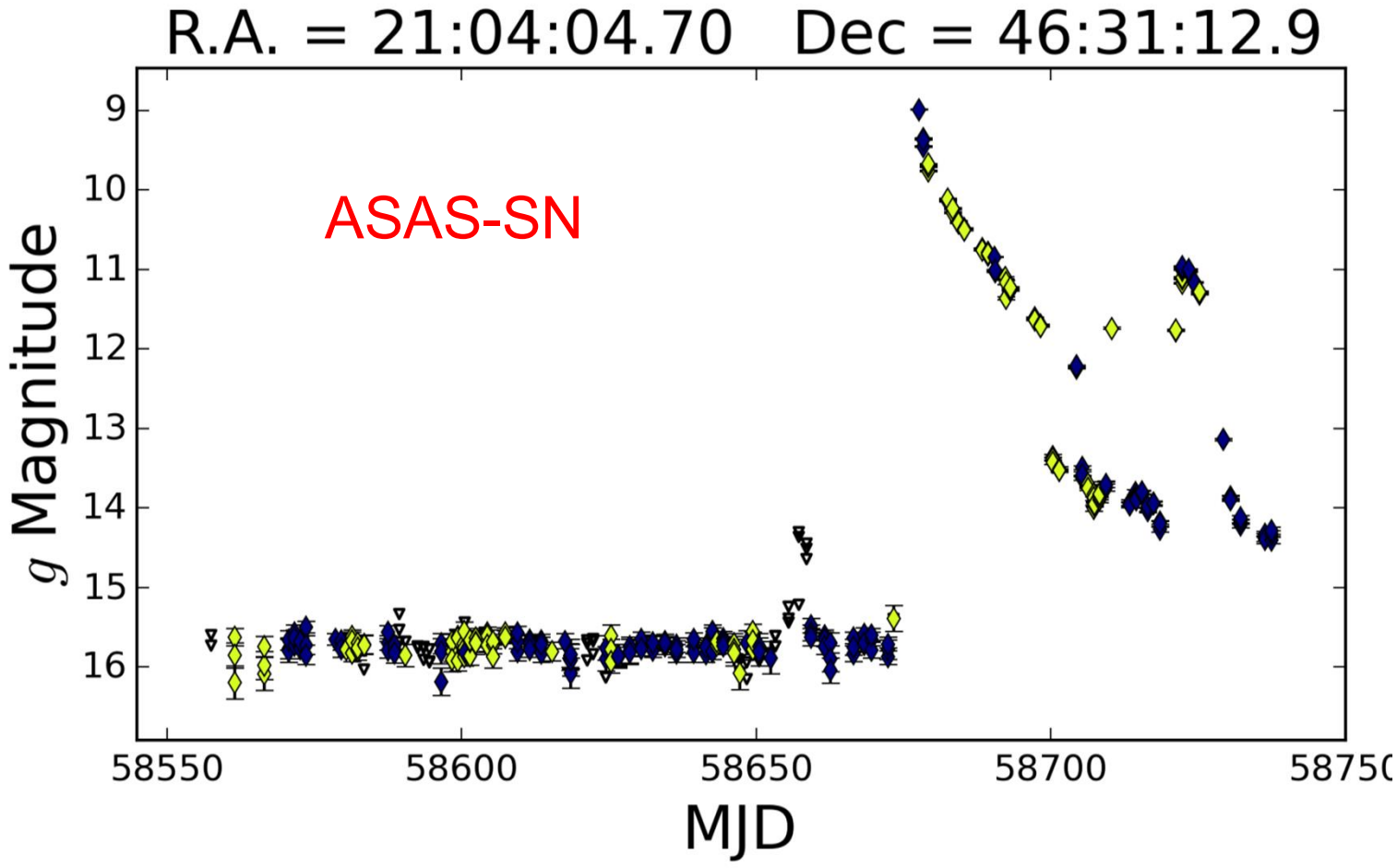


No Radio Detection: Where is the jet???

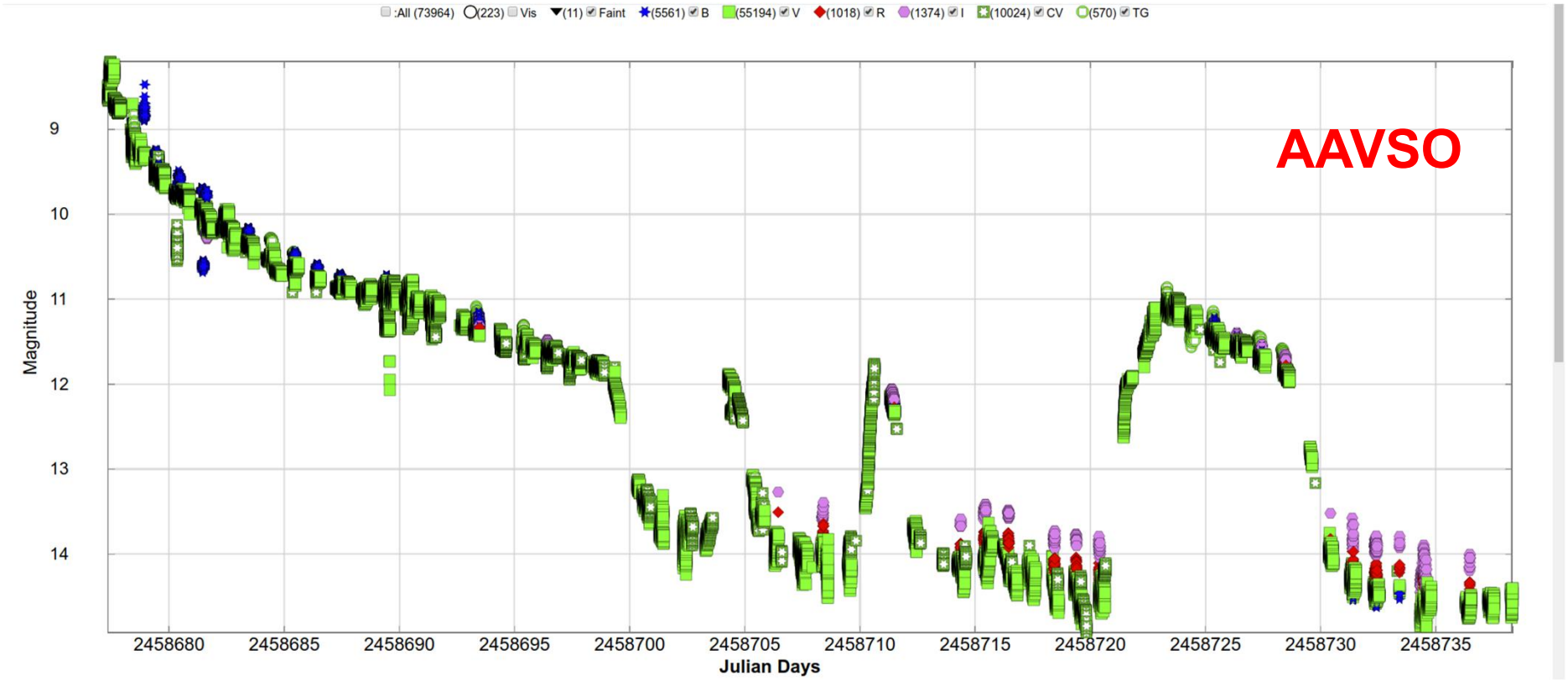
Castro Segura et al. (in prep)



TCP 21+46

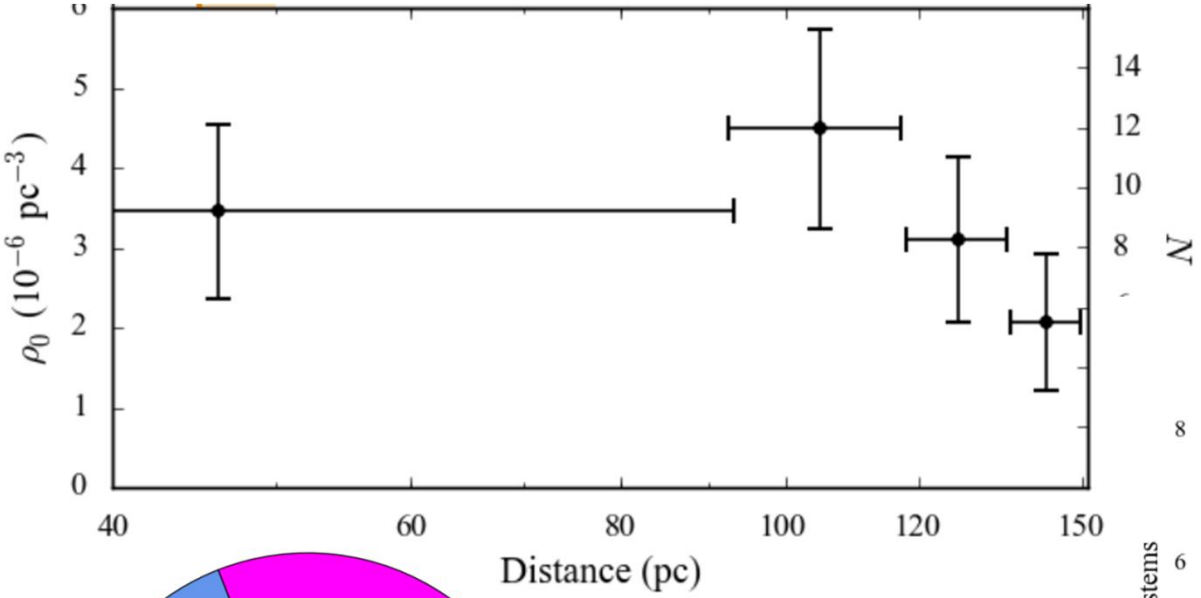

R.A. = 21:04:04.70 Dec = 46:31:12.9
ASAS-SN
g Magnitude
9
10
11
12
13
14
15
16
58550
58600
58650
58700
58750
MJD

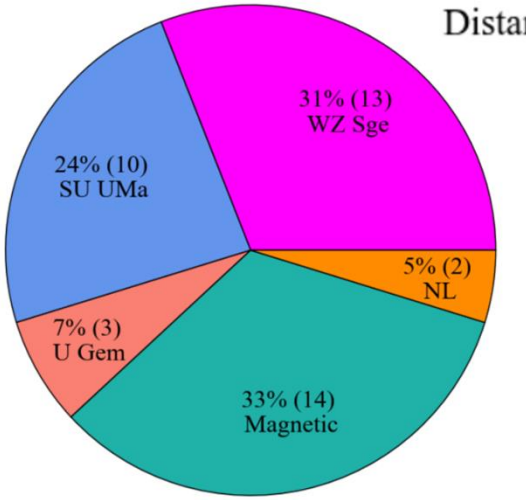
TCP 21+46


:All (73964)
(223)
Vis
(11)
Faint
(5561)
B
(55194)
V
(1018)
R
(1374)
I
(10024)
CV
(570)
TG
AAVSO
Magnitude
9
10
11
12
13
14
2458680
2458685
2458690
2458695
2458700
2458705
2458710
2458715
2458720
2458725
2458730
2458735
Julian Days

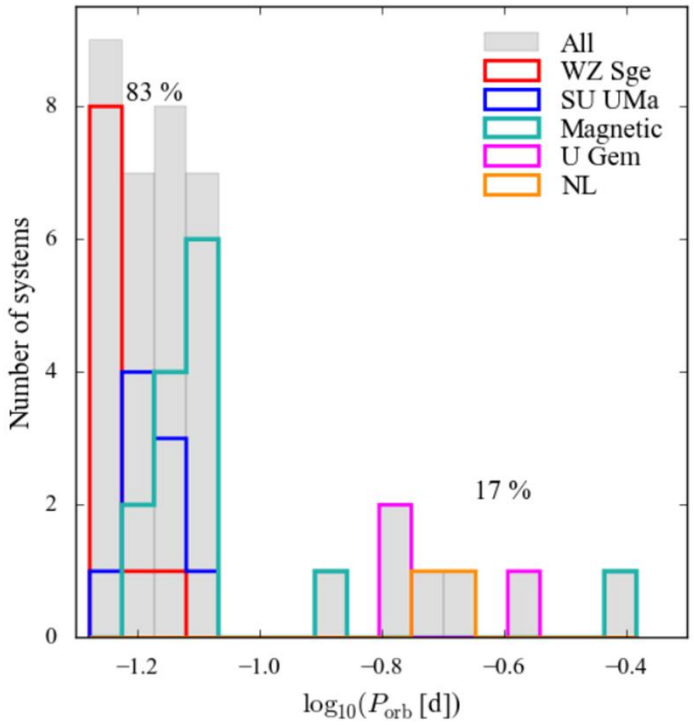
The Space Density of CVs from Gaia DR2

Maybe we actually know all CVs out to ≈150pc





Pala et al. 2019



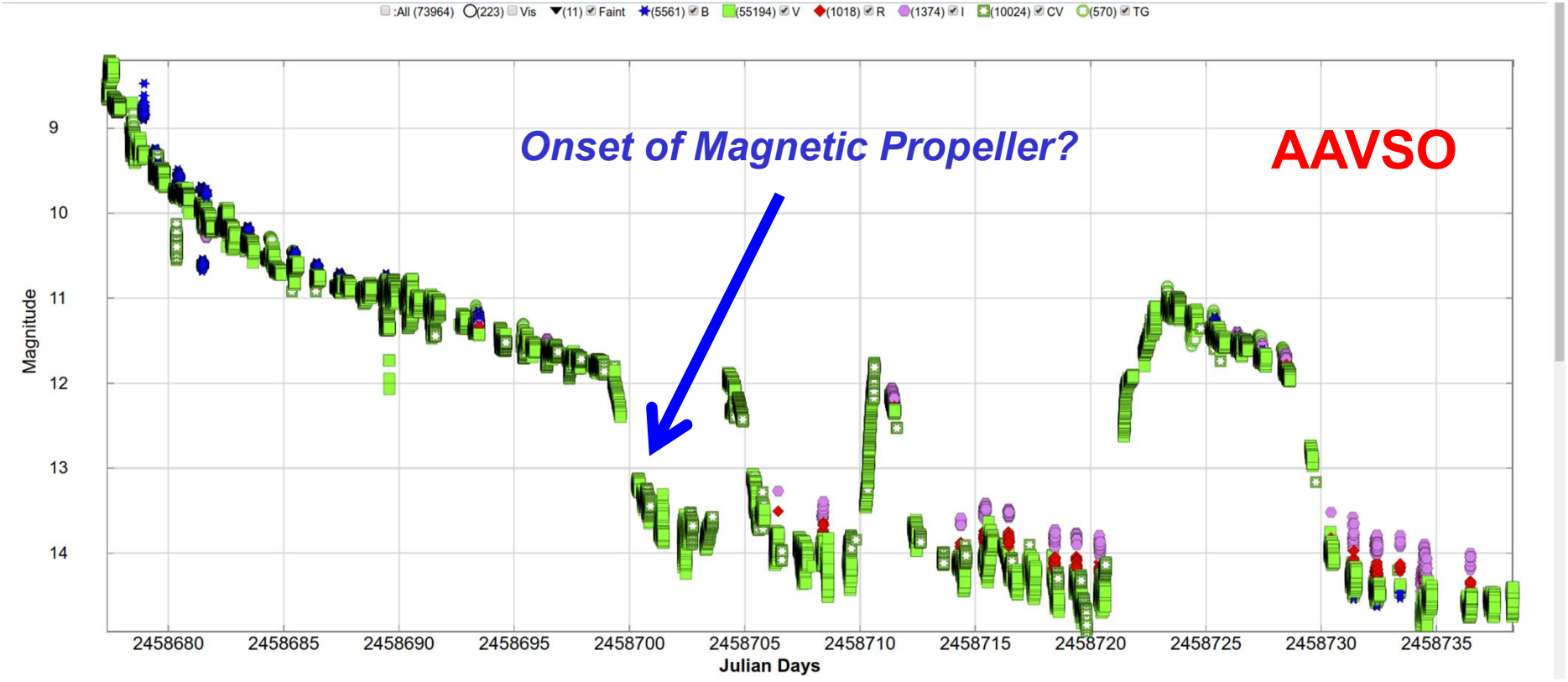
What else are we missing?

However, we cannot exclude that some WZ Sge systems, nova-like CVs and polars within 150 pc remain to be identified: ASASSN-14dx, a WZ Sge star located at $d = 81.0 \pm 0.3$ pc with a quiescent magnitude of $V \simeq 16.2$ mag (Thorstensen et al. 2016), and TCP J21040470+4631129, another WZ Sge-type CV located at $d = 109 \pm 2$ pc with a quiescent magnitude of $V \simeq 17.7$ mag (Atel #12936), have only been discovered in 2014 and 2019, respectively, following a dwarf nova outburst.

Pala et al. 2019

TCP 21+46

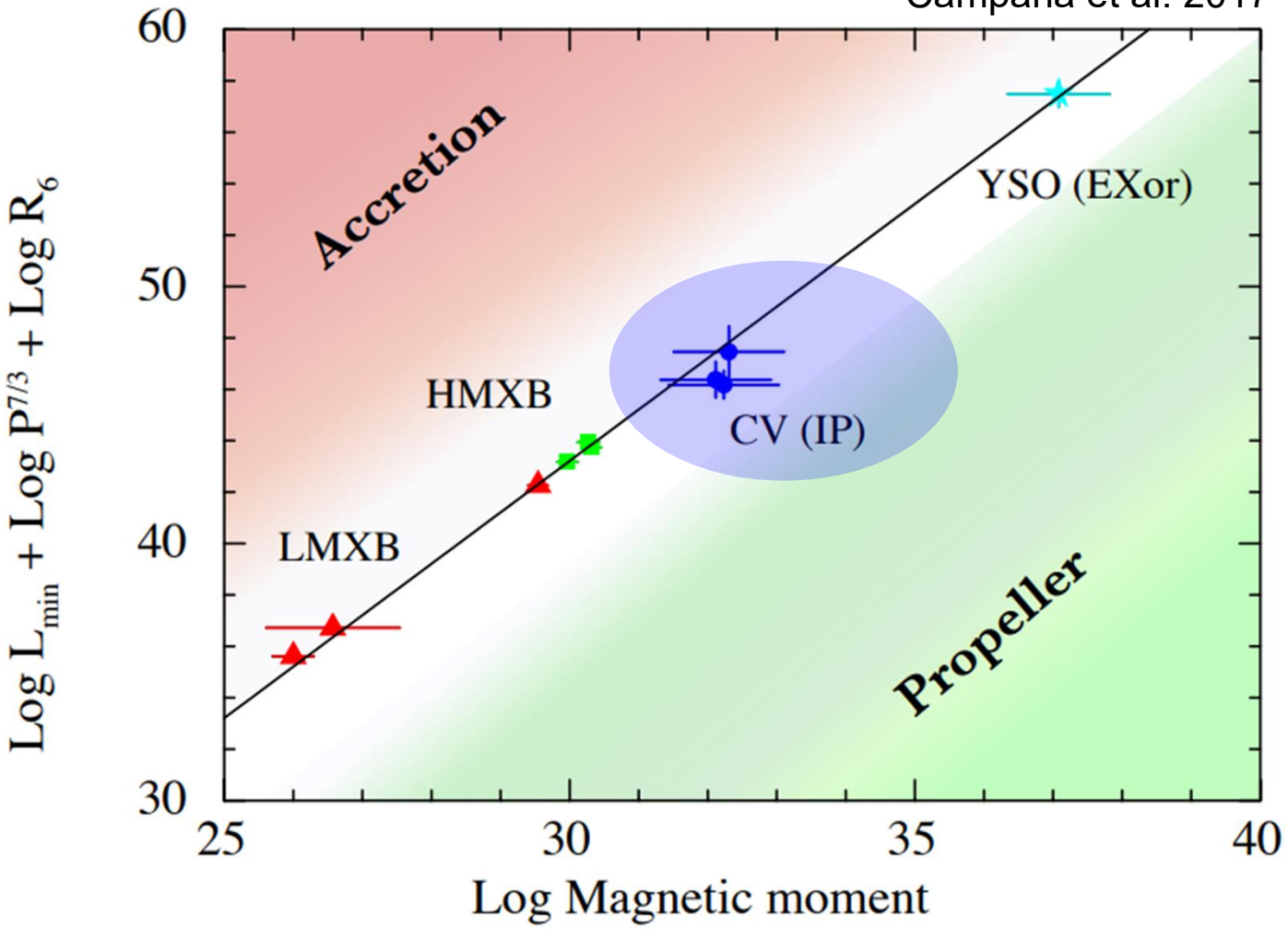
A(nother) WZ Sge Magnetic Propeller?



TCP 21+46

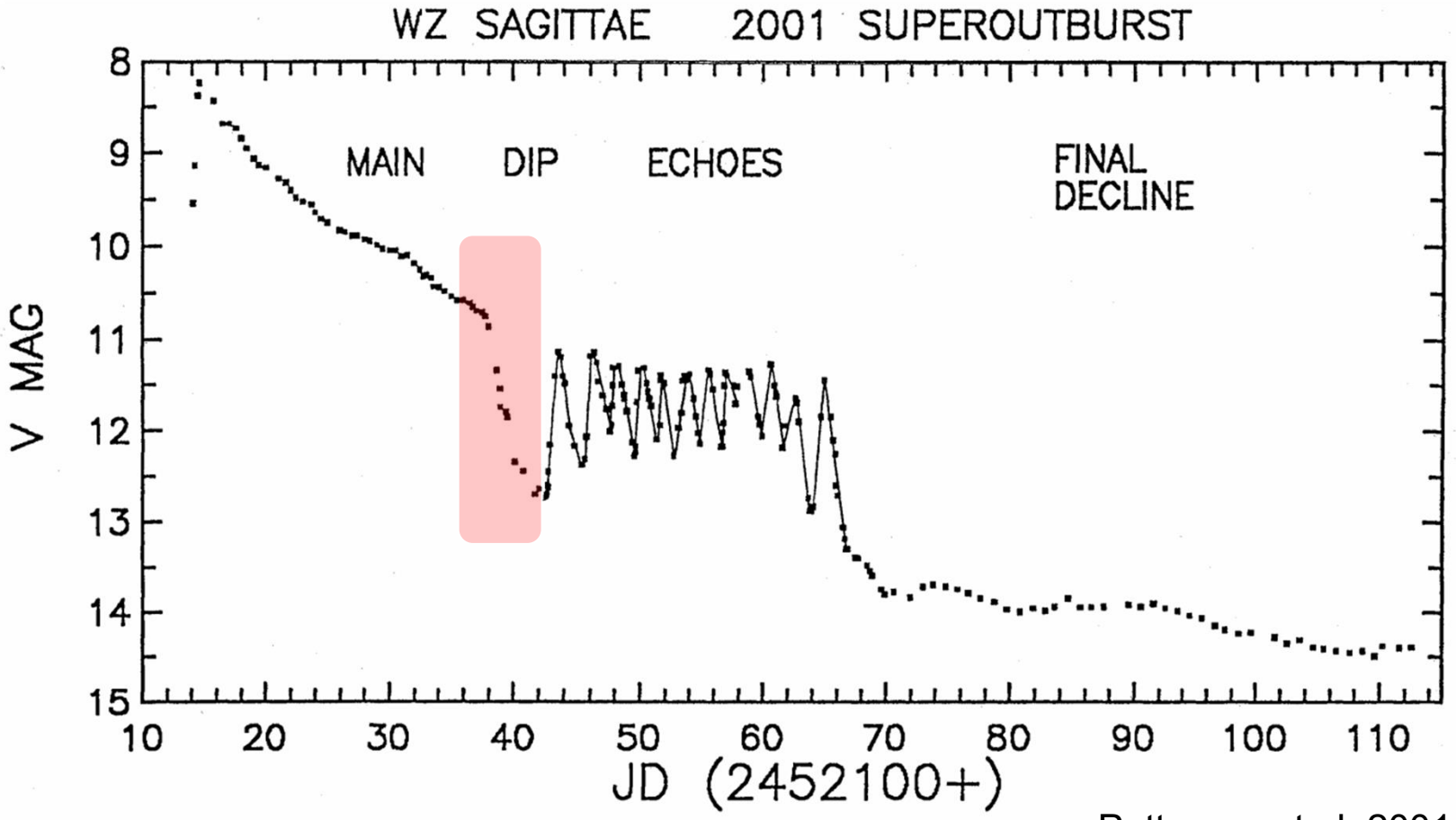
A(nother) WZ Sge Magnetic Propeller?

Campana et al. 2017



"Dips" are common in WZ Sge stars…

…and not understood at all!

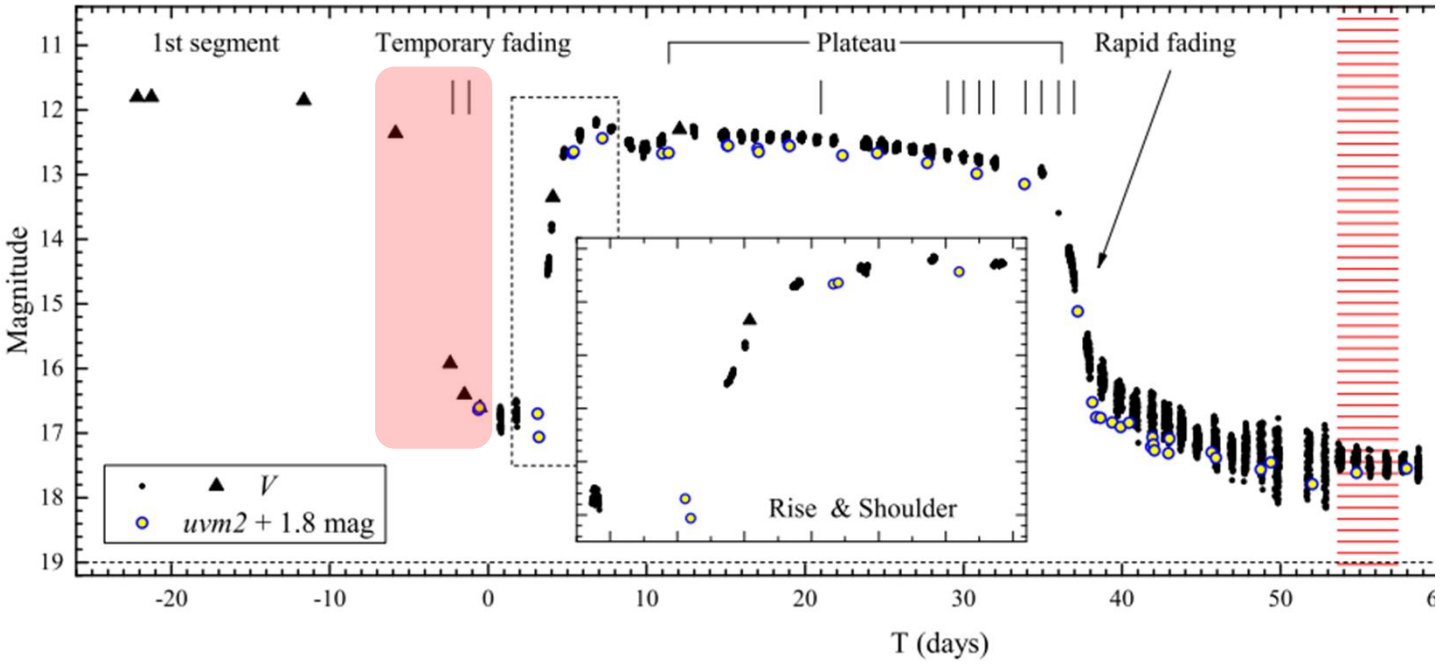


Patterson et al. 2001

"Dips" are common in WZ Sge stars…

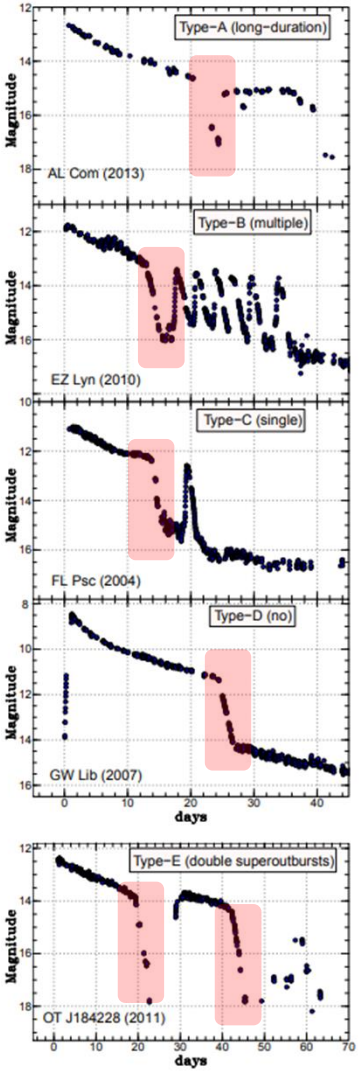
…and not understood at all!

Neustroev et al. 2017



Could WZ Sge stars have been hiding a completely unexpected transition between disk and propeller accretion in plain sight?

Kimura et al. 2016



Summary

- Disk-accreting systems – ***including CVs*** – exhibit remarkable similarities
  - Outbursts associated with disk instabilities
  - Hysteresis associated with these outbursts
  - Radio jets (particularly associated with state transitions during outbursts)
  - Disk winds (only in high/soft states)
  - Flickering that produces linear RMS-flux relations

  → Much of accretion physics seems to be universal…

- *CVs are the perfect laboratories for discovering turning this phenomenology into physics…*
- *Pro-am collaborations are the perfect teams to make it happen!*

We better get started, because there is a lot left to be discovered and understood!