Exploring the Shock-Driven High-Energy Emission of Classical Novae with NuSTAR

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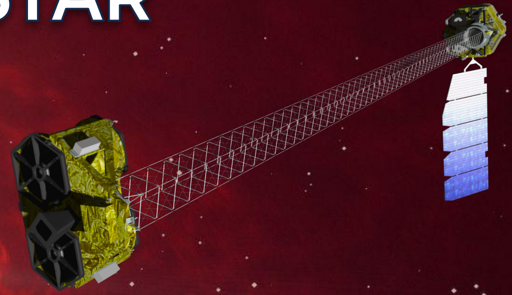

in collaboration with
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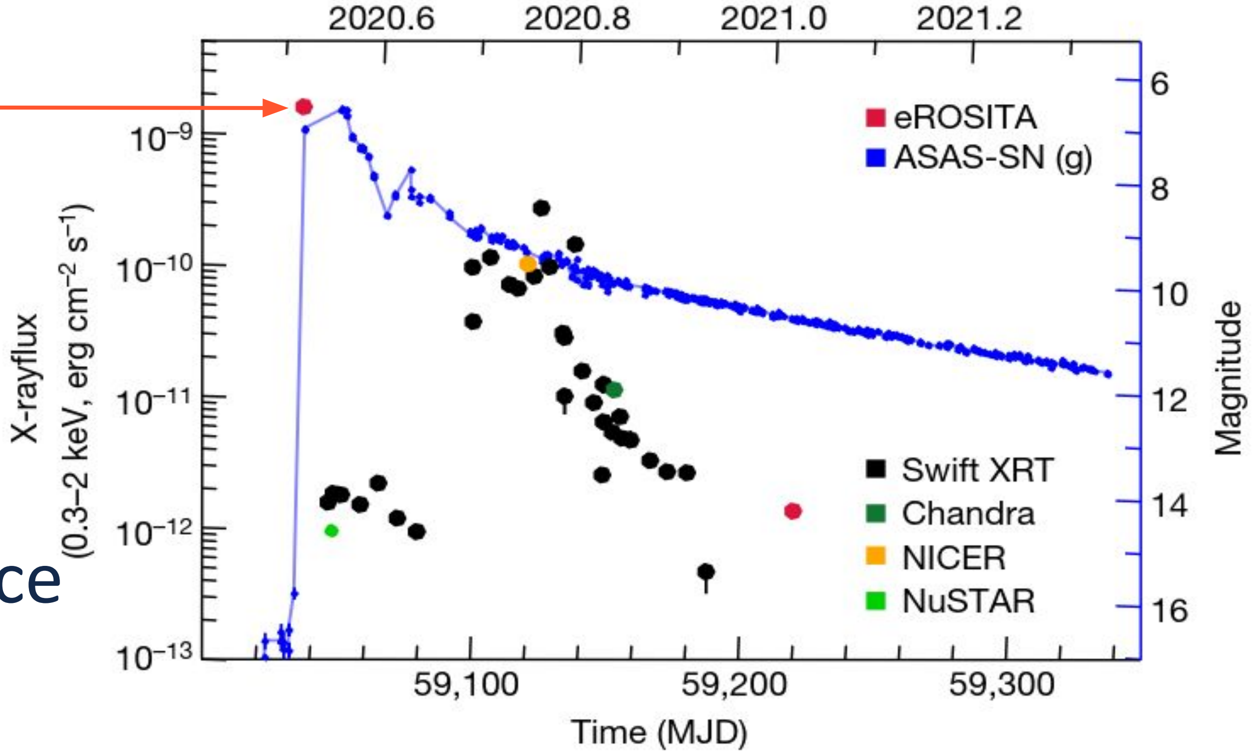
Pierre Jean *(Toulouse)*, Tyrel Johnson *(GMU)*,
Konstantin Malanchev (*Carnegie Mellon)*

Images:
NASA/NuSTAR and
artist's impression of RS Oph
(DESY/H.E.S.S., Sci. Comm. Lab)

X-ray lightcurve of a nova

1. Fireball
2. Shocks
3. Super-Soft Source
4. Accretion

X-ray and optical lightcurve of nova **YZ Ret**
(Konig et al. 2022, Nature, V.605, I.7909, p.248)



NuSTAR - best for nova shocks

Focusing X-rays in **3-78 keV** range

- **Sensitive** (compared to coded mask)
- Can **penetrate through** a lot of **absorption**
- **No optical loading** (good for nova at peak)

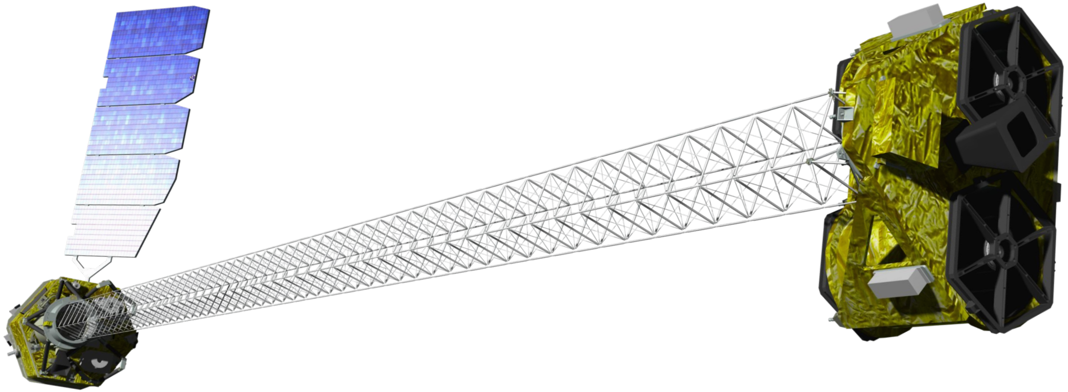


Image:
artist's concept of NuSTAR in orbit.
NASA/JPL-Caltech via [Wikipedia]

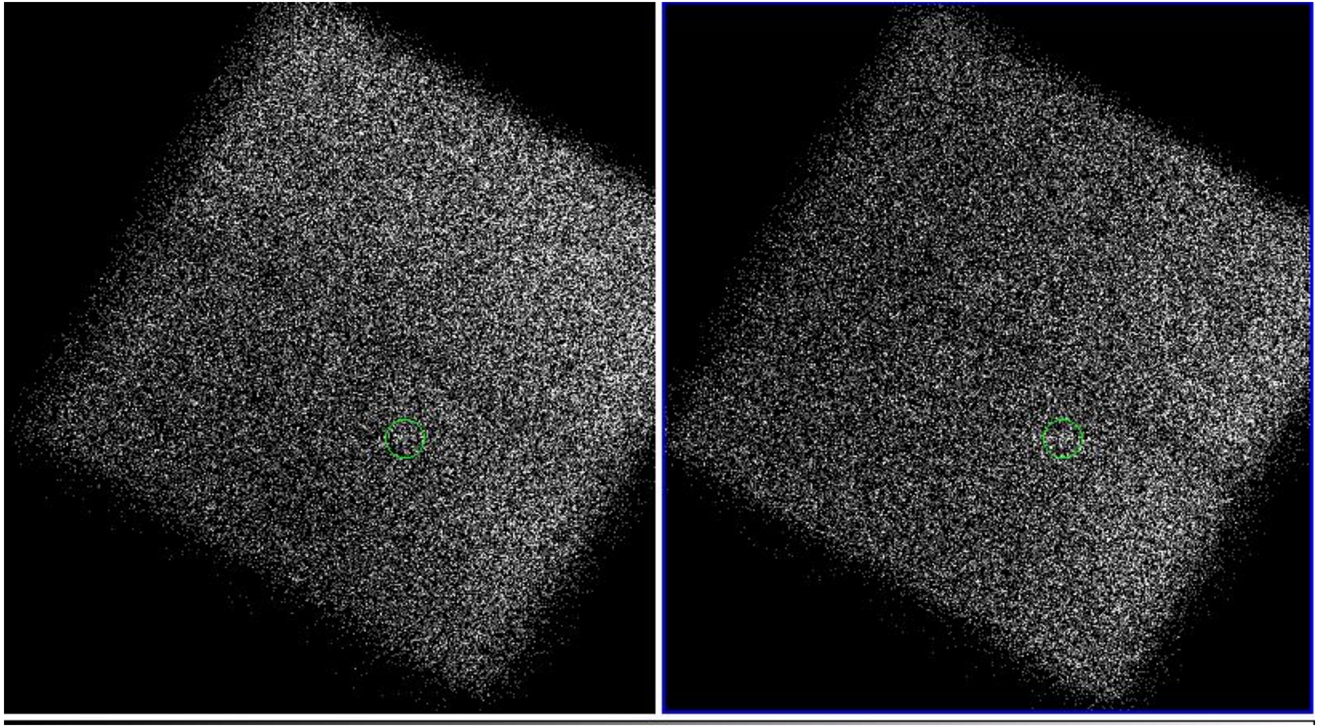
Classical novae with NuSTAR

9 observed, 7 detected (4 while being GeV-bright*)

Nova name	*T_0 +*	*Exp.*	*Detected*	*Reference*
V339 Del	9 d	24 ks	**No**	Vurm & Metzger (2018, ApJ, 852, 62)
V5668 Sgr	13 d	52 ks	**No**	Vurm & Metzger (2018, ApJ, 852, 62)
V5855 Sgr*	13 d	51 ks	**Yes**	Nelson et al. (2019, ApJ, 872, 86)
V906 Car*	36 d + 57 d	50 ks + 50 ks	**Yes + Yes**	Sokolovsky et al. (2020, MNRAS, 497, 2569)
YZ Ret*	10 d	65 ks	**Yes**	Sokolovsky et al. (2022, MNRAS, 514, 2239)
V1405 Cas	3 d	40 ks	**Yes**	ATel #14530 (publication in prep.)
V1674 Her	12 d	39 ks	**Yes**	Sokolovsky et al. (2023, MNRAS, 521, 5453)
V1716 Sco*	2 d	70 ks	**Yes**	ATel #16018 Sokolovsky et al. (in prep.)
V1723 Sco?	2 d + 47 d	63 ks + 22 ks	**No + Yes**	ATel #16444 Fauverge et al. (in prep.)

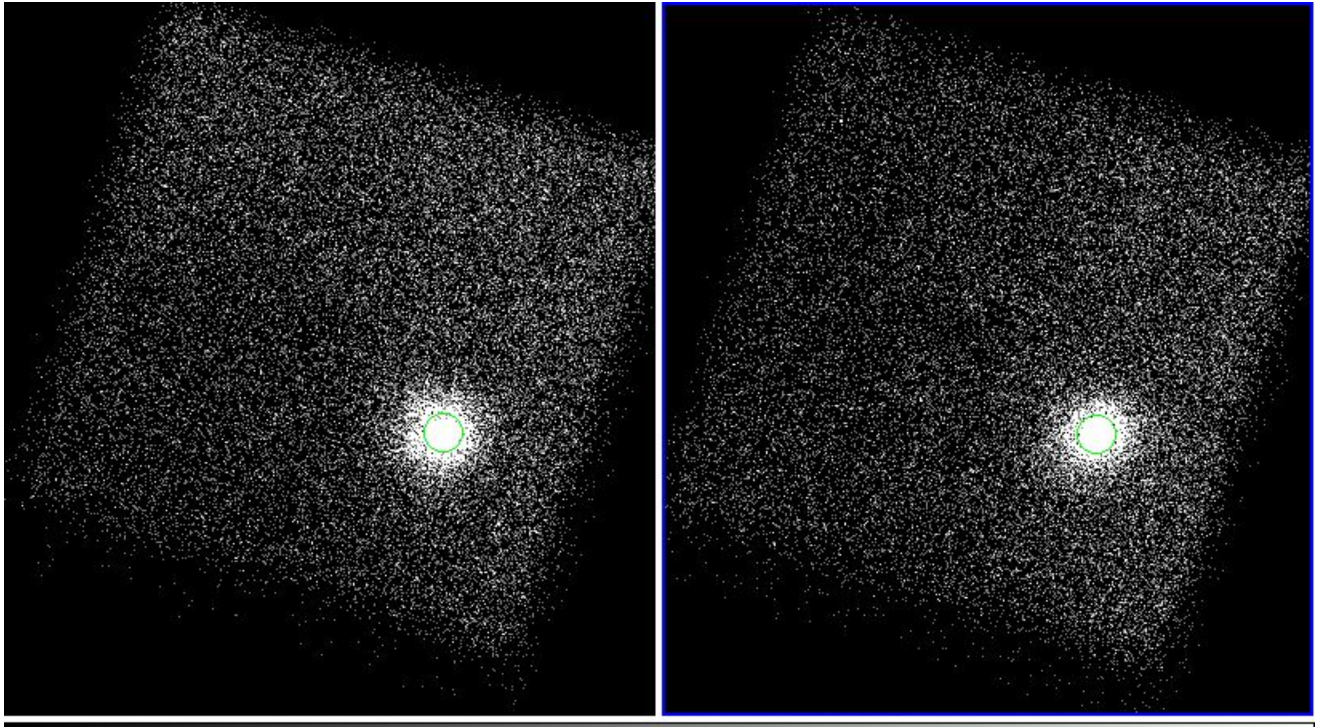
V1723 Sco (2024) eruption + 2 days

63 ks, non-detection <0.002 cts/s (2 focal plane modules)

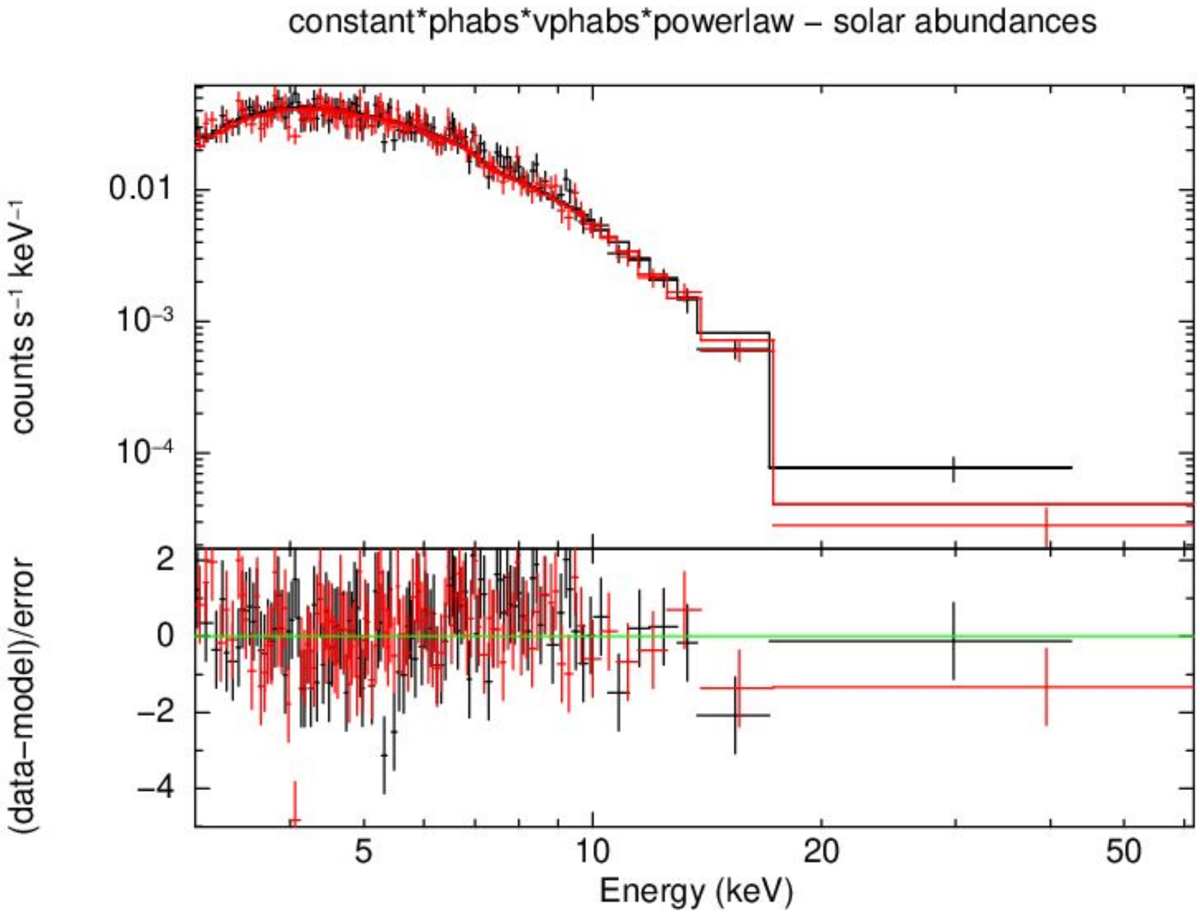


V1723 Sco (2024)   eruption + 47 days

22 ks, clear detection 1.0 cts/s (2 focal plane modules)



V1723 Sco (2024) NuSTAR spectrum



Concave and mostly **featureless**

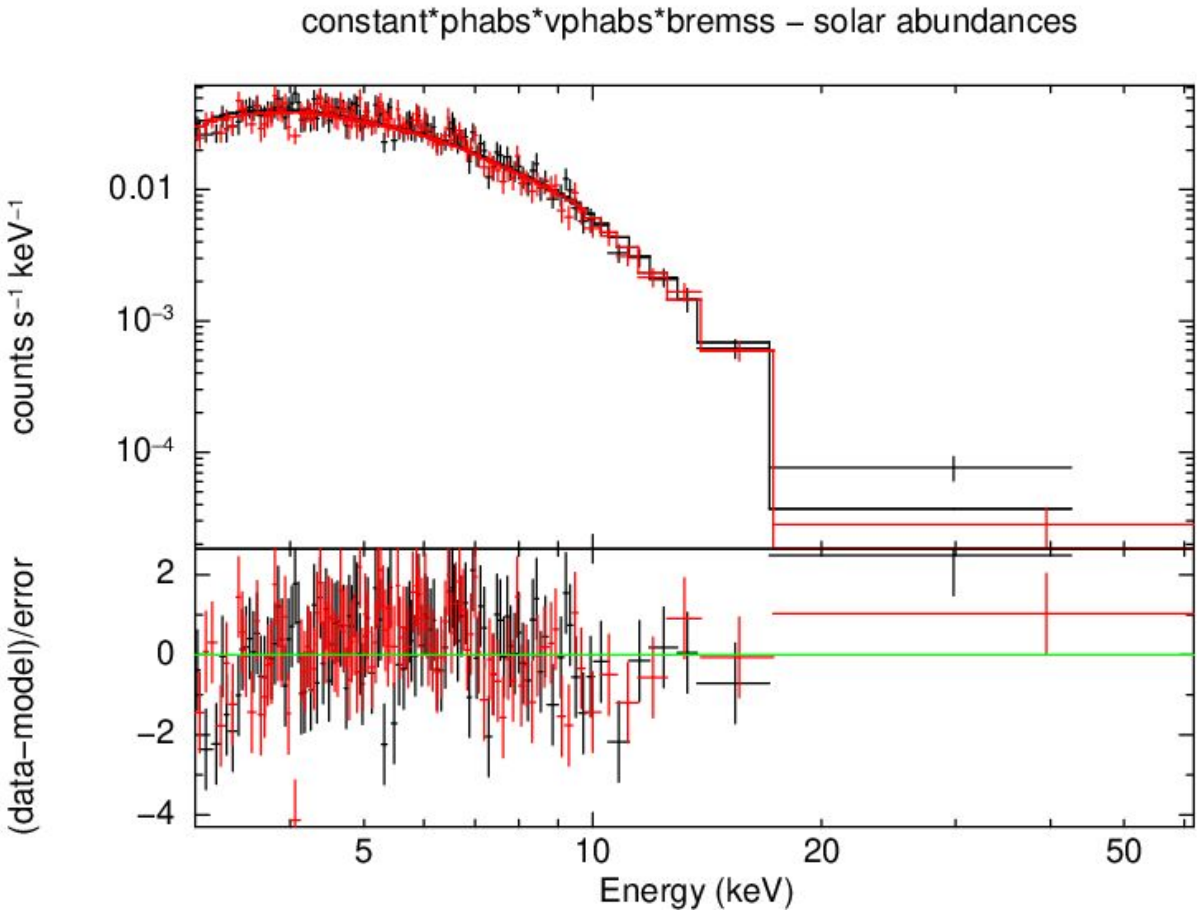
Power law fit:

γ= 3.74+/-0.06

N$_H$ = 1.57 +/-0.01 x**10^{23}** cm^{-2}

X^2_{red}= 236/235

V1723 Sco (2024) NuSTAR spectrum



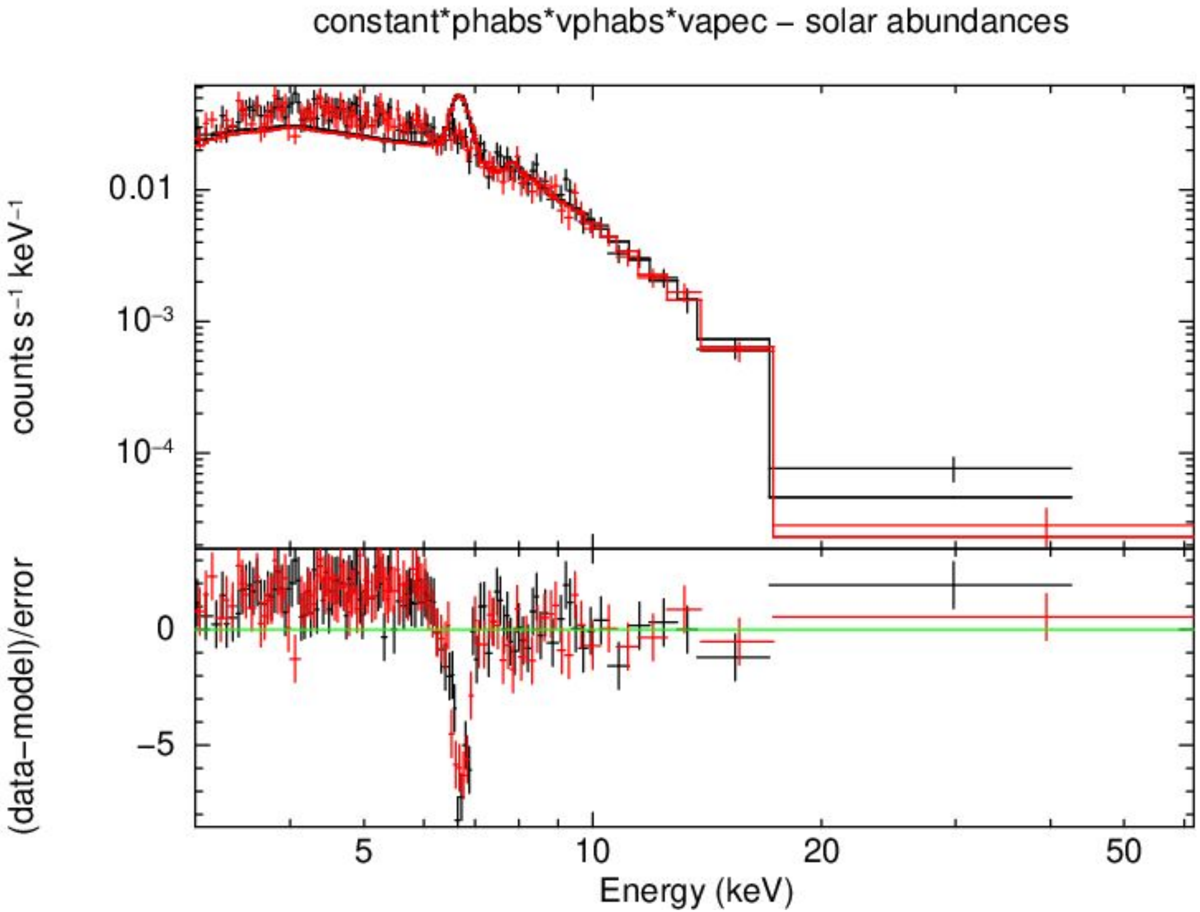
Concave and mostly **featureless**

Thermal bremsstrahlung fit: **kT = 4.4**3+/-0.09 keV

N_H = 0 cm^{-2} (no excess over the assumed Galactic value)

χ^2_{red} = 254/235

V1723 Sco (2024) NuSTAR spectrum



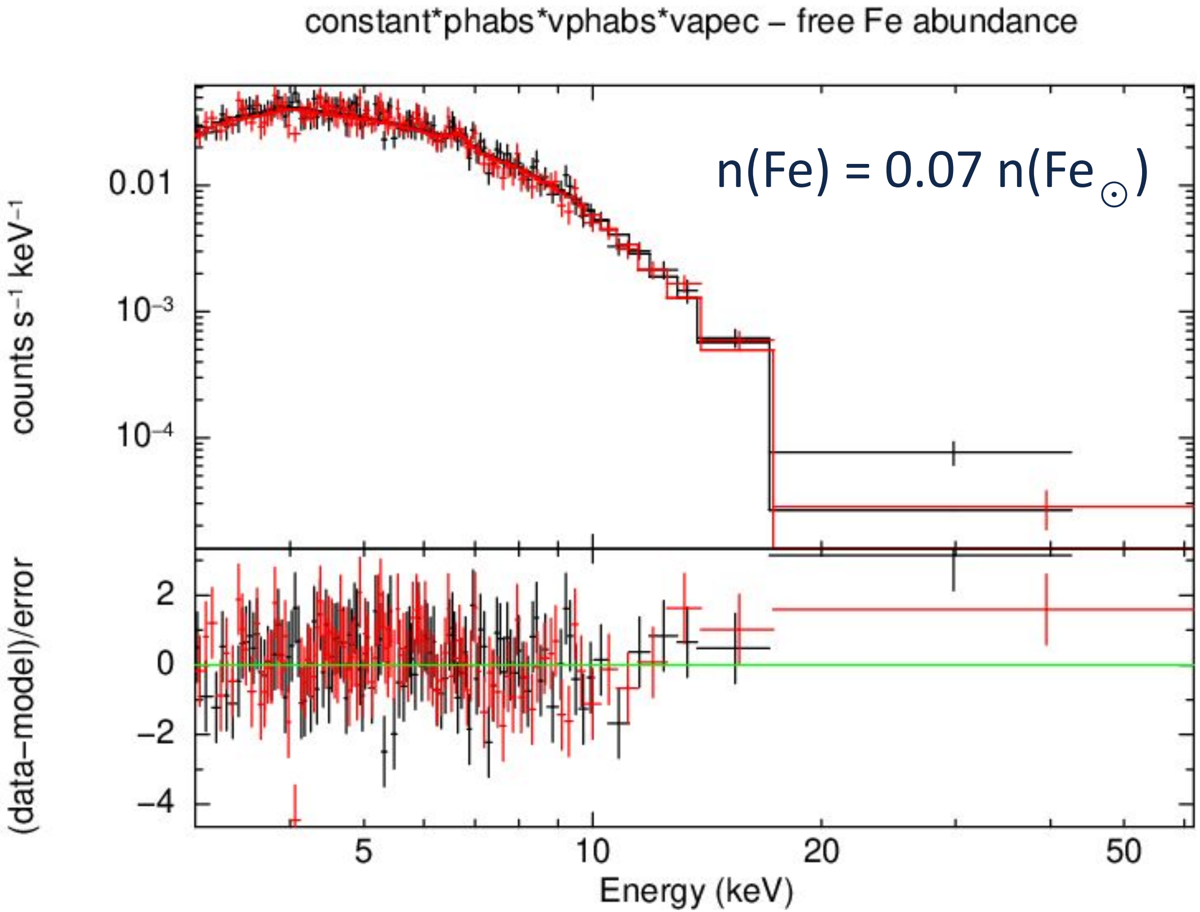
Concave and mostly **featureless**

Thermal plasma fit:
kT = 4.97 keV

N_H = 0 cm^{-2} (no excess over the assumed Galactic value)

X^2_{red}= 853/235 (bad)

V1723 Sco (2024) NuSTAR spectrum



Concave and mostly **featureless**

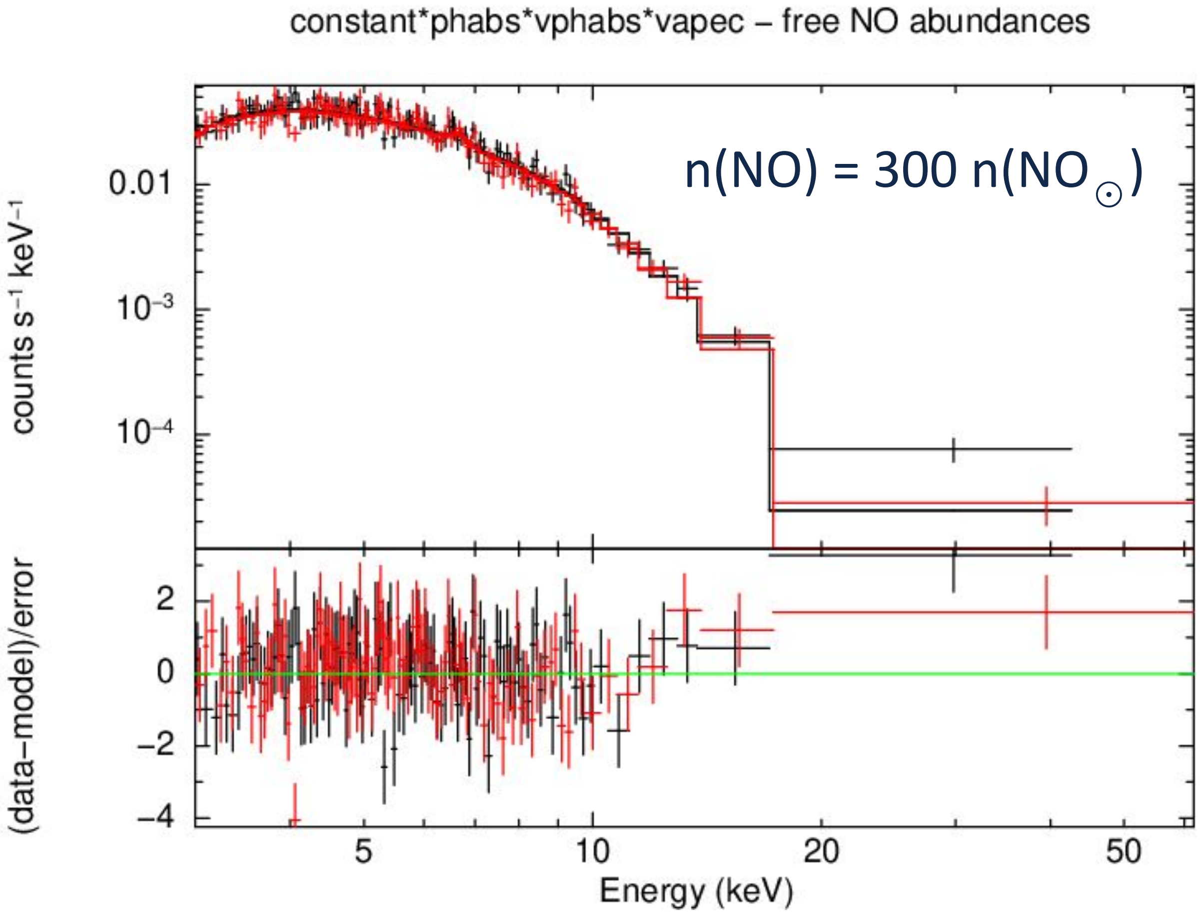
Thermal plasma fit:

kT = 3.84+/-0.12 keV

N$_H$ = 4.48 +/-0.98 x**10^{22}** cm^{-2}

X^2_{red}= 227/234

V1723 Sco (2024) NuSTAR spectrum



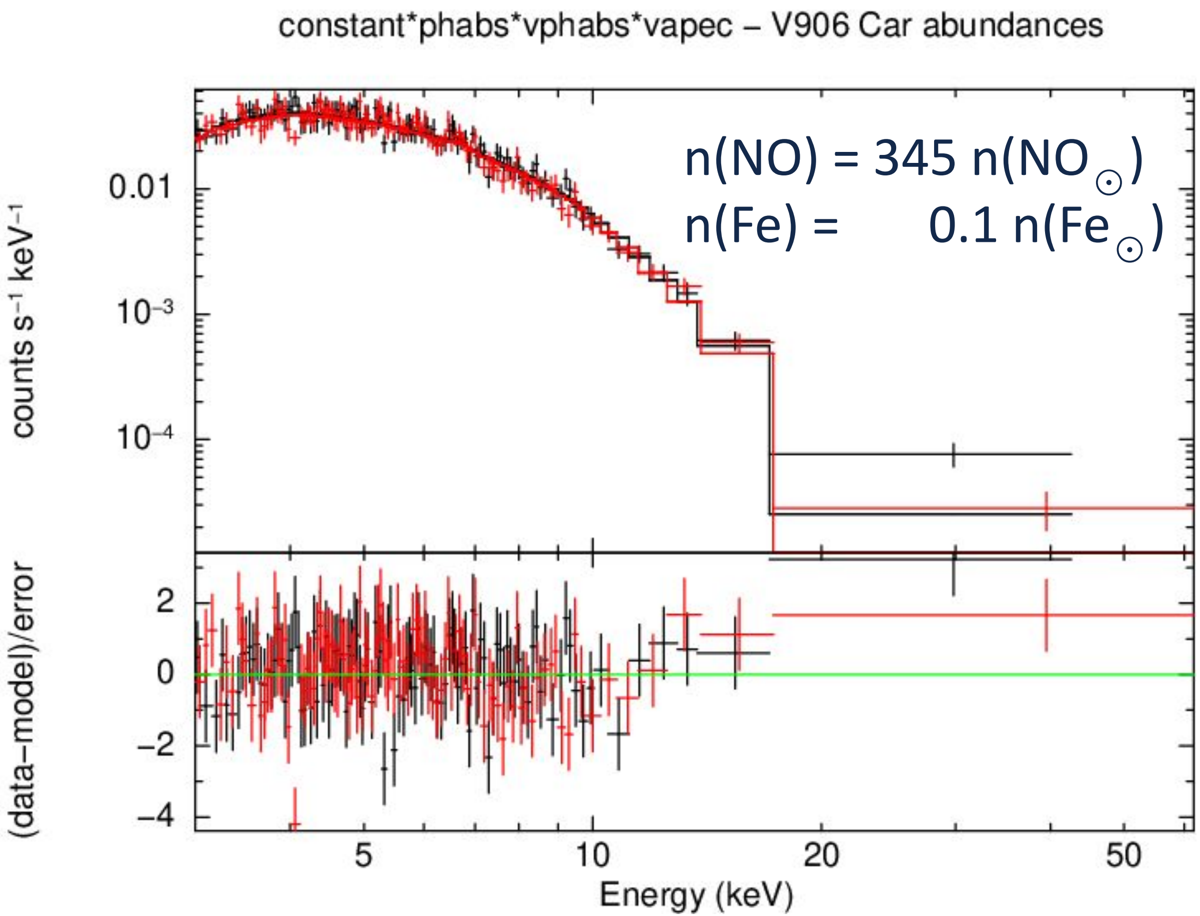
Concave and mostly **featureless**

Thermal plasma fit:
kT = 3.62+/-0.11 keV

N_H = 3 +/-1 x**10^{20}** cm^{-2}

X^2_{red}= 225/234

V1723 Sco (2024) NuSTAR spectrum



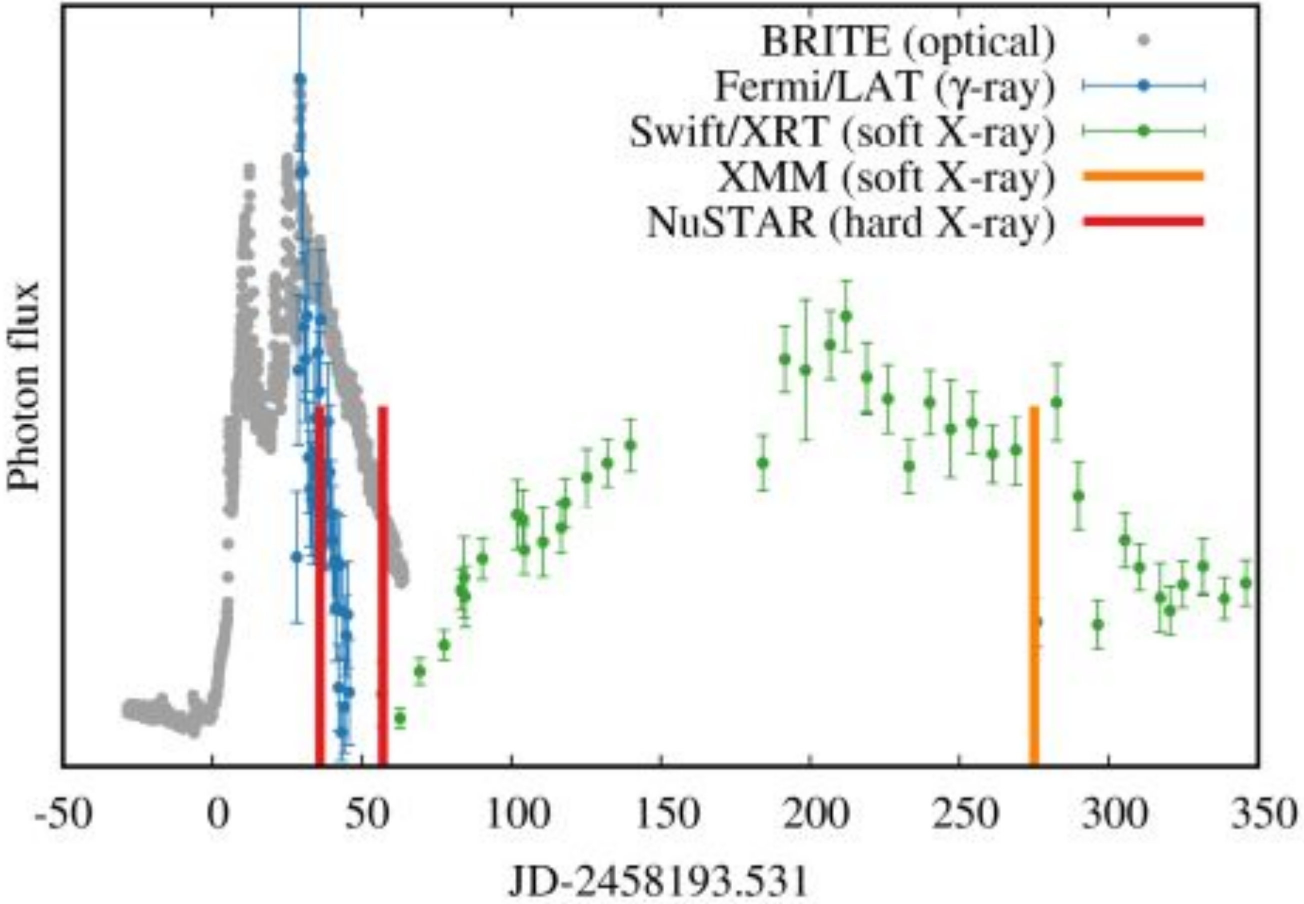
abundances from a totally different nova V906 Car

Thermal plasma fit:
kT = 3.67+/-0.10 keV

N$_H$ = 2.1 +/-0.1 x**10**^{21} cm^{-2}

X^2_{red}= 227/235

Optical/GeV/X-ray lightcurve of V906 Car



V906 Car: X-ray grating spectroscopy XMM/RGS

275 days after eruption, still shock-dominated

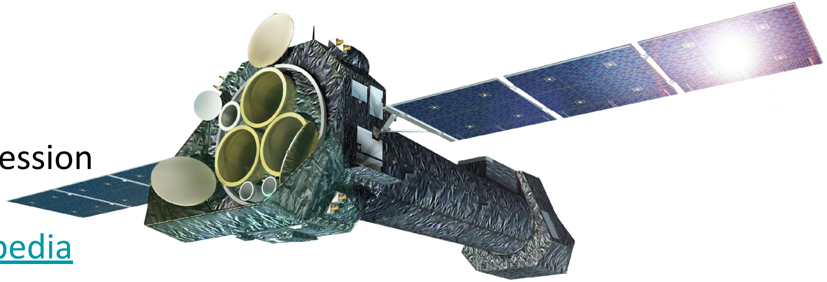
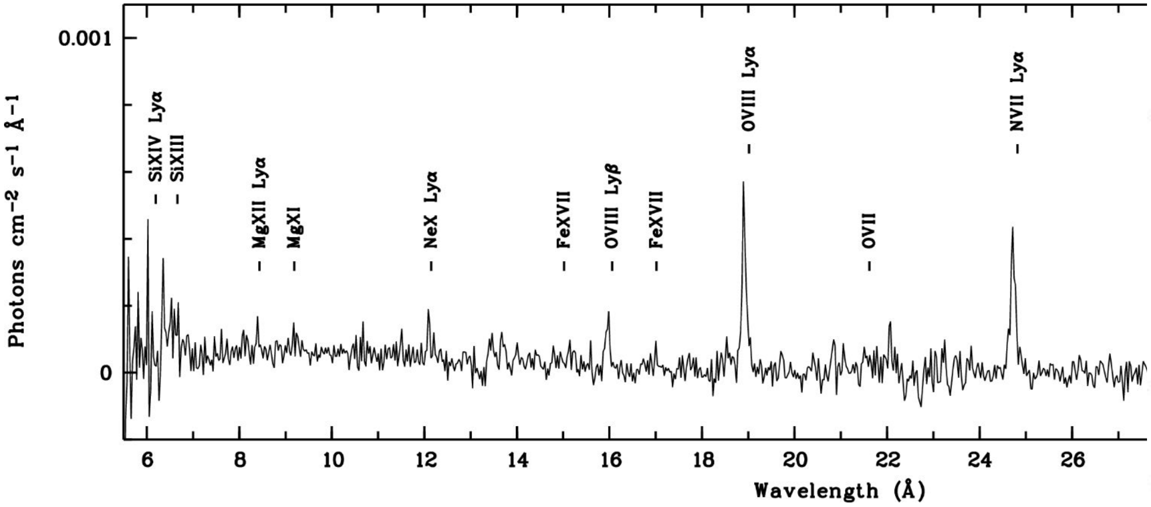


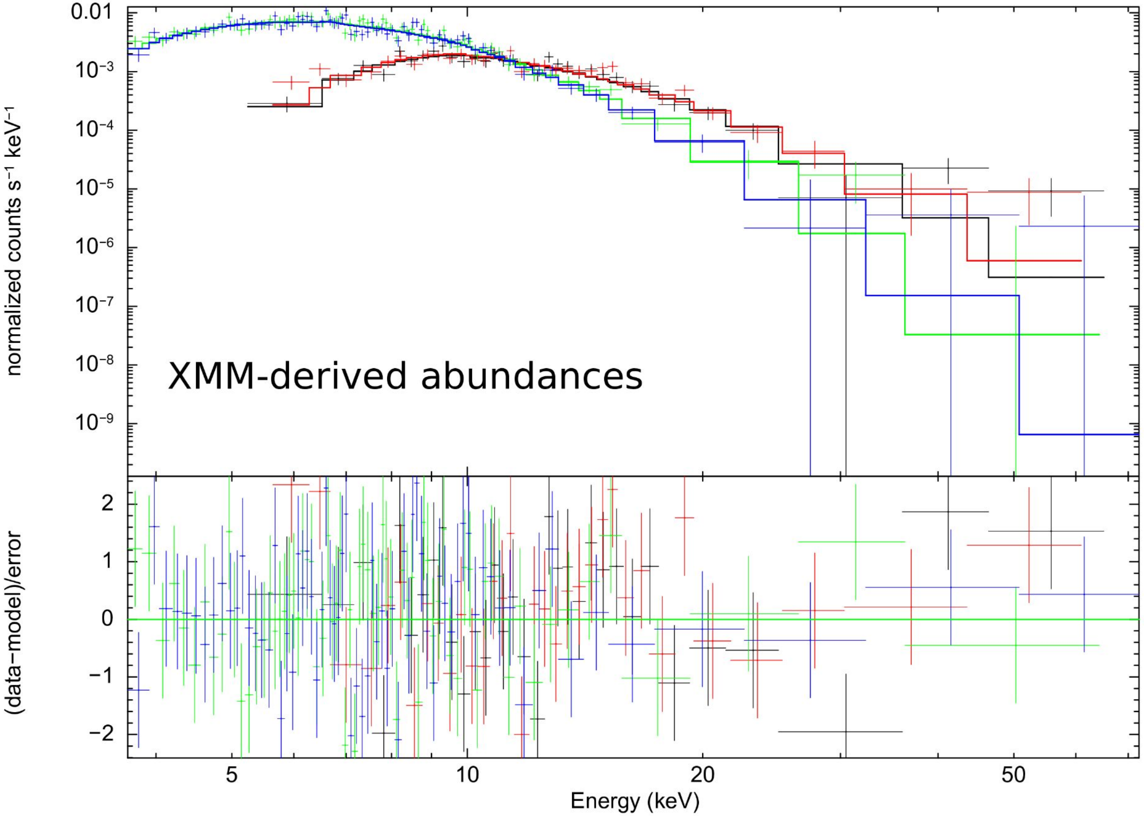
Image: artist's impression of XMM-Newton ESA/NASA via Wikipedia



Parameter	Value	Comment
phabs		
N_H ($\times 10^{21}$ cm^{-2})	$2.4^{+0.4}_{-0.3}$	
vphabs		
N_H ($\times 10^{21}$ cm^{-2})	$0.12^{+0.03}_{-0.03}$	
bvapec		
kT (keV)	$1.07^{+0.04}_{-0.01}$	
redshift	-2.9×10^{-3}	fixed
velocity (km s^{-1})	378	fixed
$N/N_\odot$	345^{+93}_{-70}	
$O/O_\odot$	29^{+7}_{-5}	
$Ne/Ne_\odot$	$2.2^{+0.6}_{-0.5}$	
$Mg/Mg_\odot$	$0.6^{+0.2}_{-0.1}$	
$Si/Si_\odot$	$1.1^{+0.2}_{-0.2}$	
$Fe/Fe_\odot$	<0.1	
χ^2_ν	1.15	
d.o.f.	1837	

Sokolovsky et al. (2020, MNRAS, 497, 2569)

V906 Car: NuSTAR spectra at 36 and 57 days



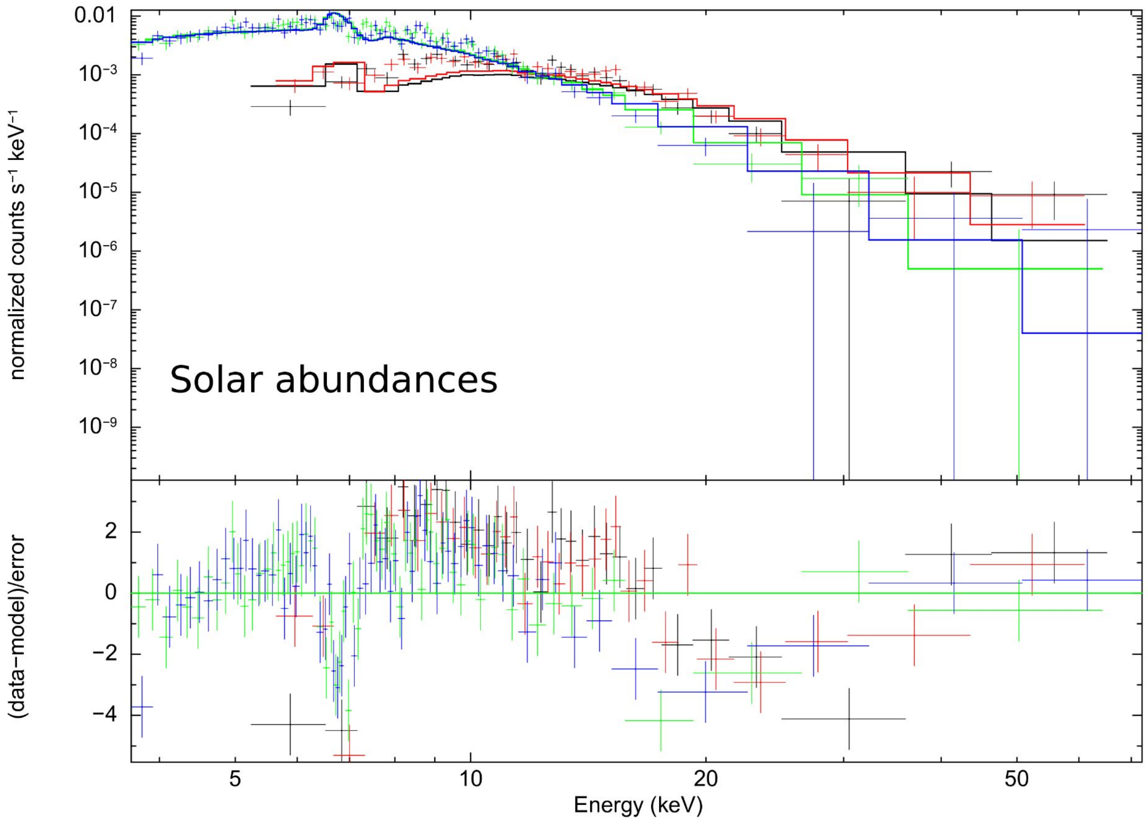
kT_1 = **8.6**+/-0.8 keV
N_{H1} = 1.9 +/-0.1 x**10**^{23} cm^{-2}

kT_2 = **4.3**+/-0.2 keV
N_{H2} = 2.6 +/-0.2 x**10**^{22} cm^{-2}

χ^2_{red}= 211/200

Sokolovsky et al. (2020, MNRAS, 497, 2569)

V906 Car: NuSTAR spectra at 36 and 57 days



kT_1 = 13.7 keV
N_{H1} = 1.6
x**10^{24}** cm^{-2}

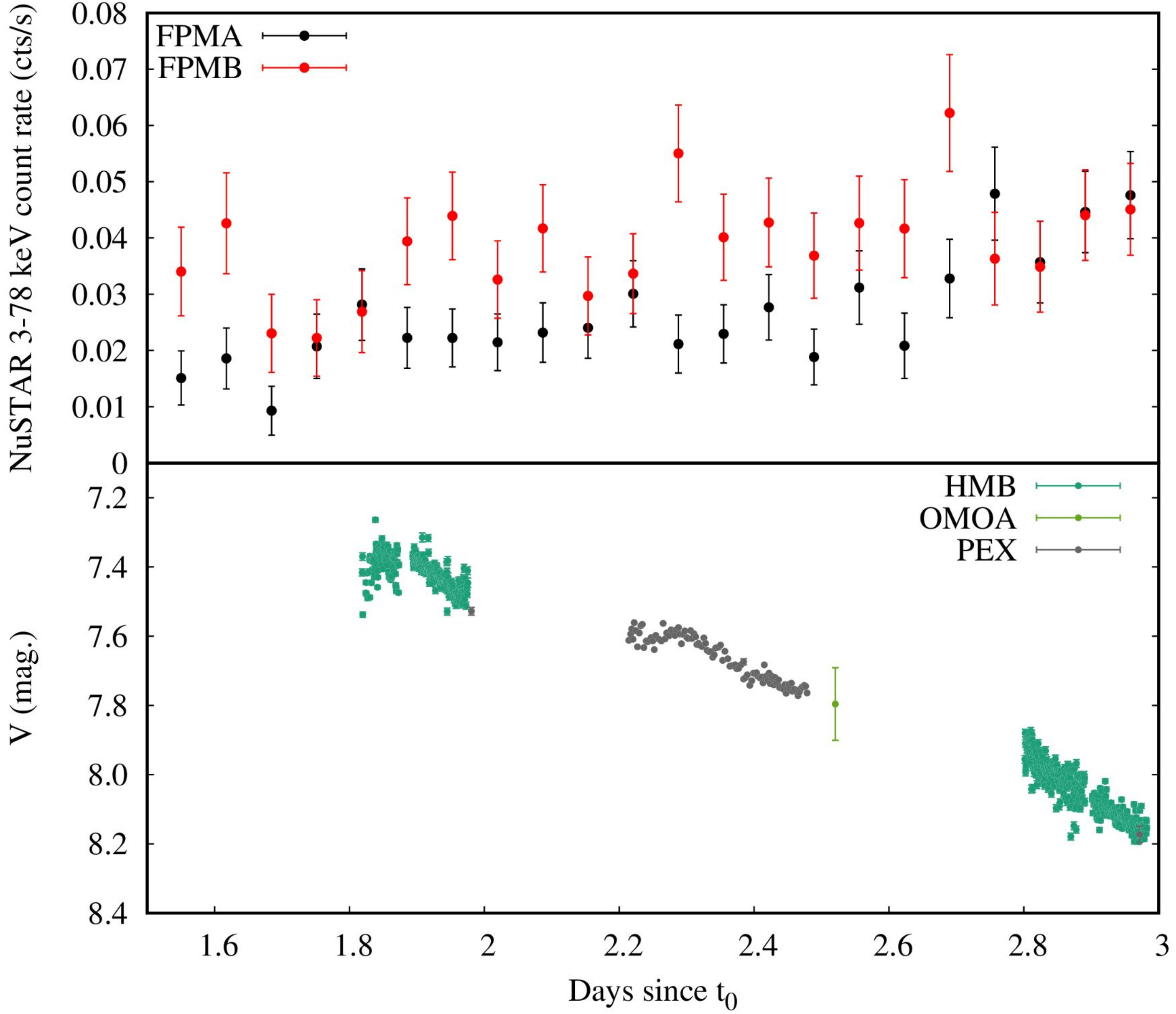
kT_2 = 4.3+/-0.2 keV
N_{H2} = 1.6
x**10^{23}** cm^{-2}

χ^2_{red}= 621/200 (bad)

Sokolovsky et al. (2020, MNRAS, 497, 2569)

NuSTAR spectra summary

- **Single-temperature** thermal
- kT > 1 keV suggests **shock heating**
- **No power law** component *(no MeV line comptonization/GeV emission tail in NuSTAR band)*
- **Non-solar abundances** imply WD ablation
- **kT and N_H decrease over time**



NuSTAR

X-ray 3-30 keV

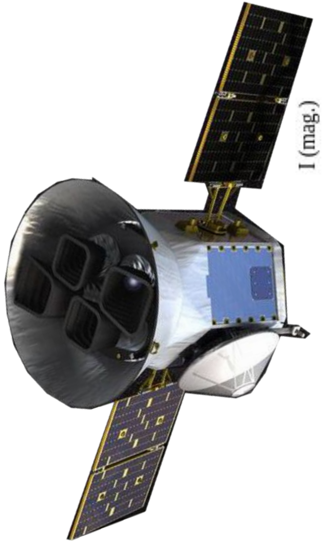
V1716 Sco (2023)

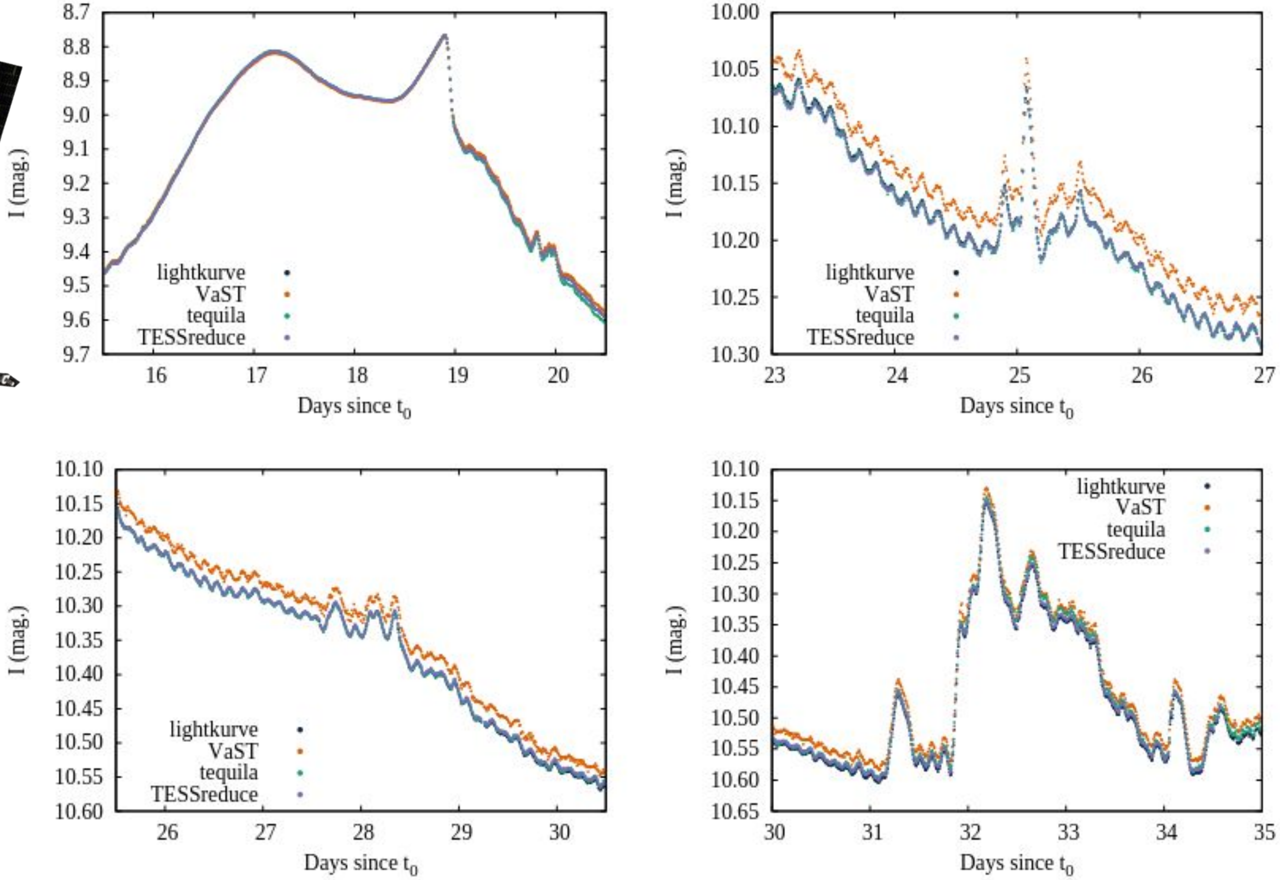
AAVSO

optical V filter

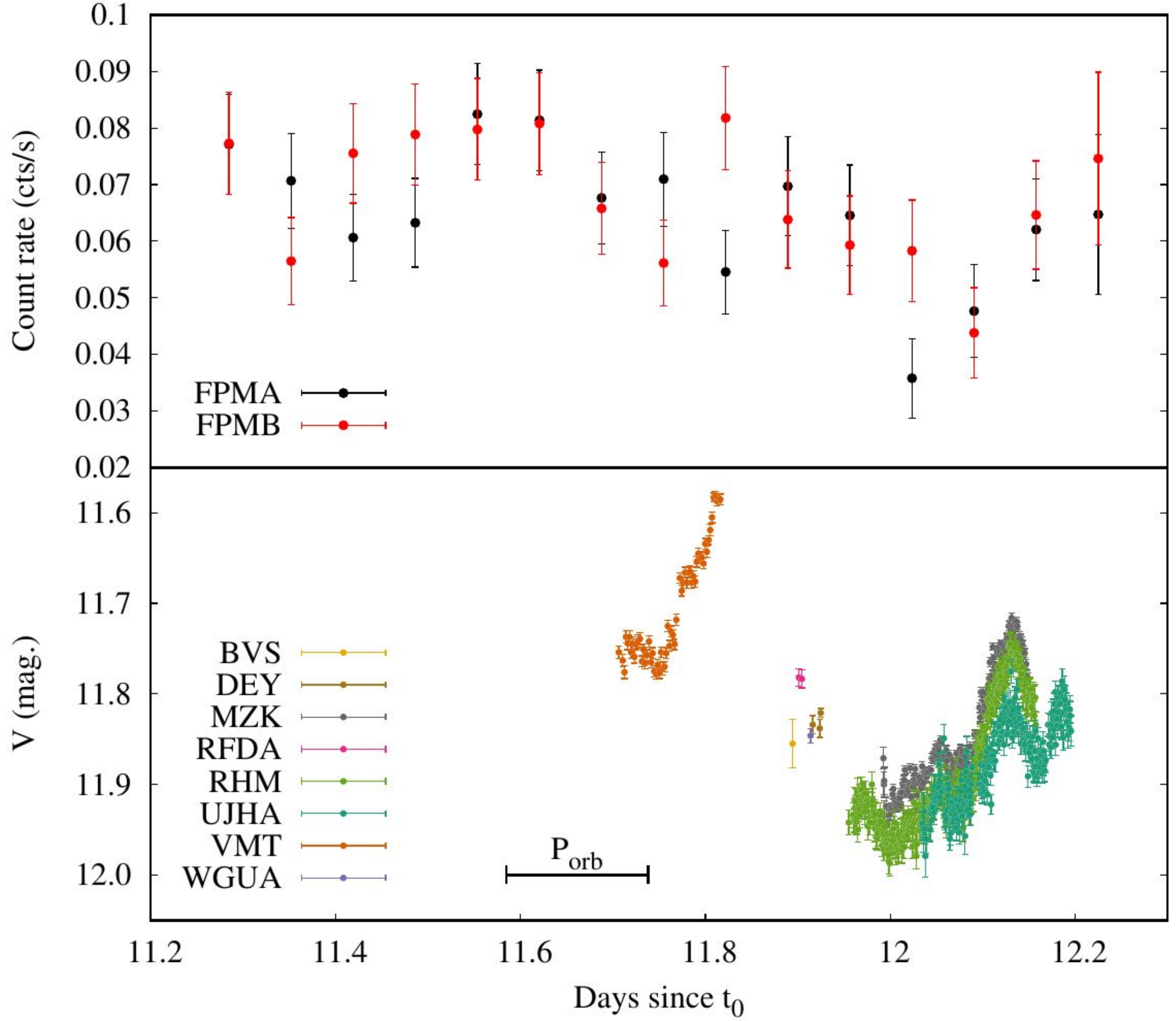
Searching for vast variability in novae is not crazy!

TESS mini-flares in V606 Vul





Sokolovsky et al. (2023, arXiv:2311.04903)



NuSTAR

X-ray 3-30 keV

V1674 Her

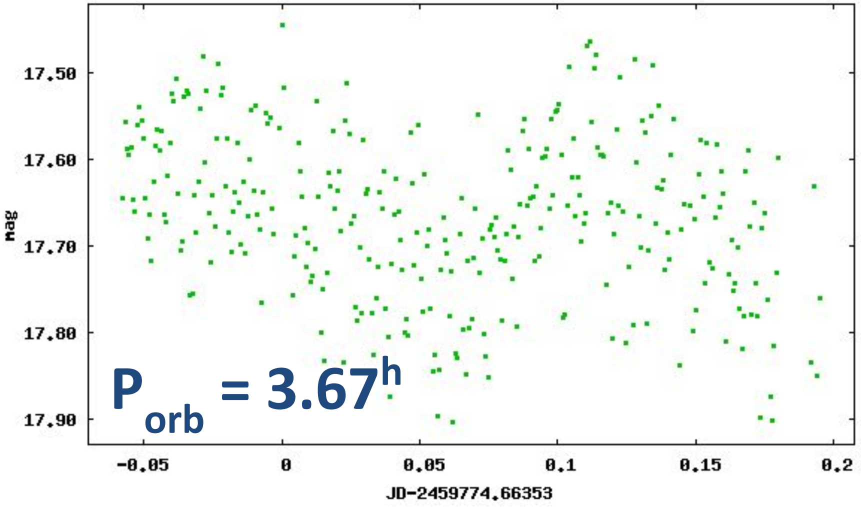
AAVSO

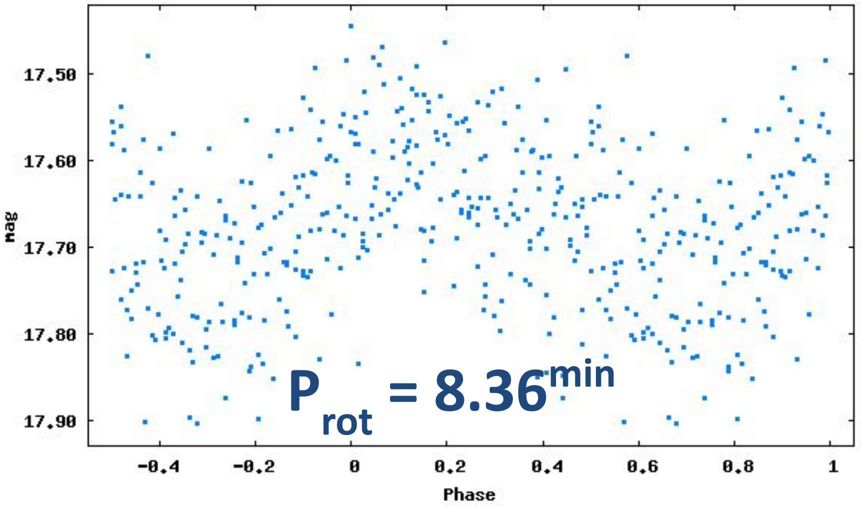
optical V filter

Sokolovsky et al. (2023, MNRAS, 521, 5453)

V1674 Her - optical photometry at MSU

V1674 Her host is an IP





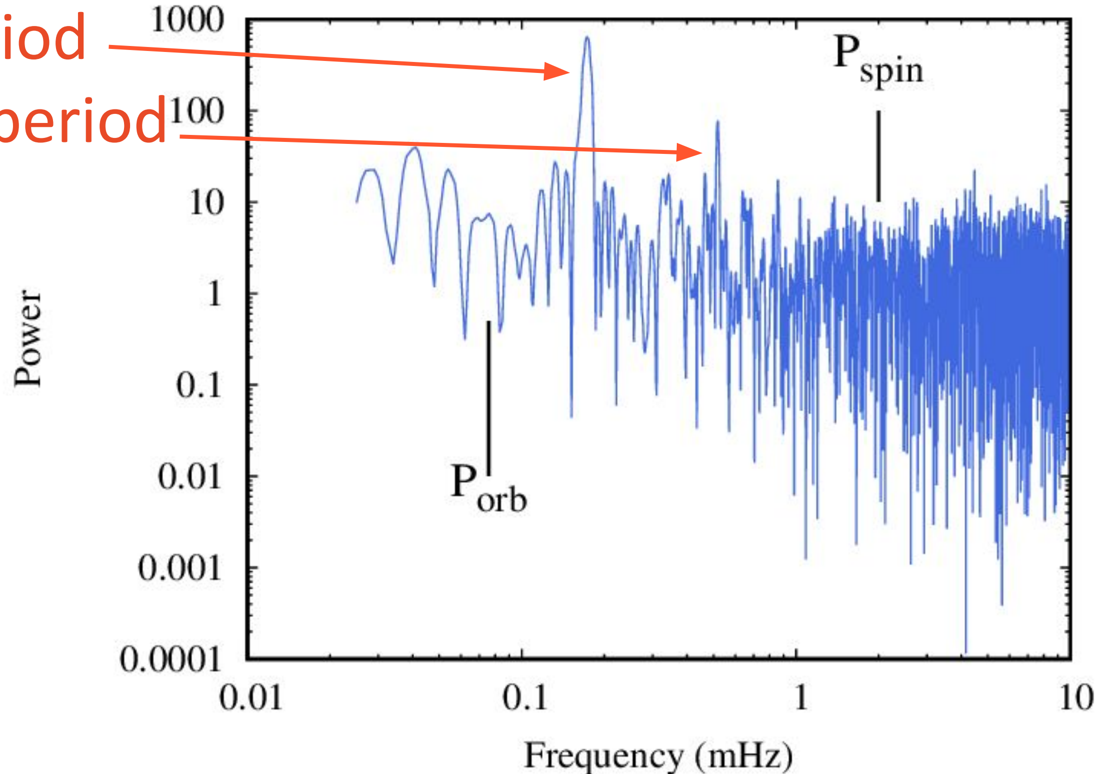
[Patterson et al. (2022, ApJ, 940, L56)]

NuSTAR 3-78 keV photon arrival times

Periodogram constructed with [patpc]() code has no peaks close to orbital and spin period (known from optical obs.)

NuSTAR orbital period

3x NuSTAR orbital period



[Sokolovsky et al. (2023, MNRAS, 521, 5453)]()

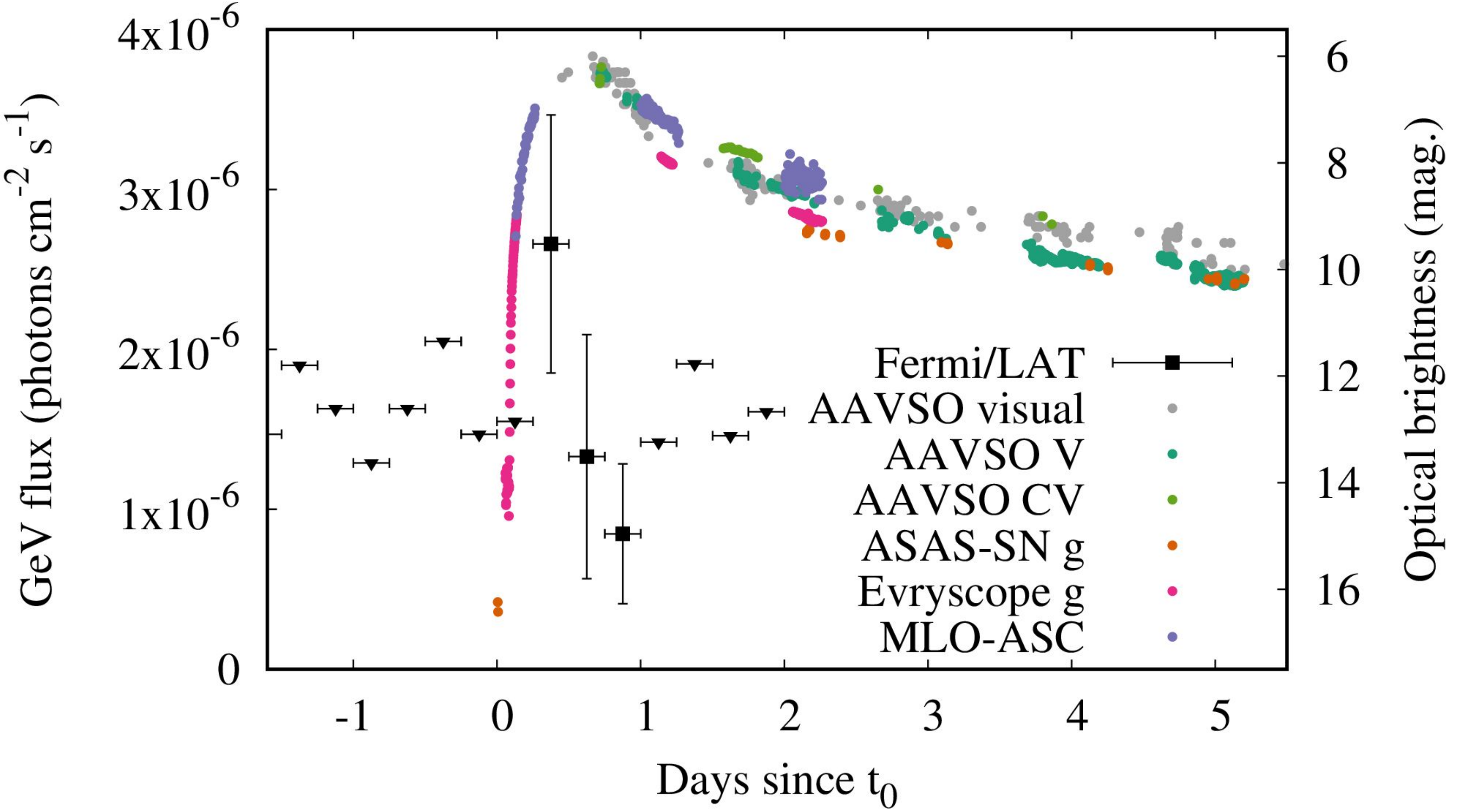
NuSTAR lightcurves and shock location

- Some **variability on ~10 hour timescale**
- **No periodic modulation** *(orbital/WD rotation)*
- **No obvious correlation with optical**

Shocked region is large compared to the binary?

Not directly related to optical - below the photosphere?

6h (~2 P_{orb}) GeV-optical lag in V1674 Her



L_X(NuSTAR) / L_γ(Fermi-LAT) ratio

Metzger et al. (2015, MNRAS, 450, 2739) suggested nova shocks should be radiative and shine in hard X-rays, spending fraction of their energy on particle acceleration, so **L_X(NuSTAR) / L_γ(Fermi-LAT) >> 1**

But this is not what we observe…

L_X(20 keV) / L_γ(100 MeV) << 1

4/6 novae detected simultaneously by NuSTAR and Fermi-LAT

Nova name	*T_0 +*	*L_X / L_γ*	*Detected*	*Reference*
V339 Del	9 d	**< 0.004**	**No**	Vurm & Metzger (2018, ApJ, 852, 62)
V5668 Sgr	13 d	**< 0.017**	**No**	Vurm & Metzger (2018, ApJ, 852, 62)
V5855 Sgr	13 d	**0.017**	**Yes**	Nelson et al. (2019, ApJ, 872, 86)
V906 Car	36 d + 57 d	**0.020**	**Yes + Yes**	Sokolovsky et al. (2020, MNRAS, 497, 2569)
YZ Ret	10 d	**0.007**	**Yes**	Sokolovsky et al. (2022, MNRAS, 514, 2239)
V1405 Cas	3 d		**Yes**	ATel #14530 (publication in prep.)
V1674 Her	12 d		**Yes**	Sokolovsky et al. (2023, MNRAS, 521, 5453)
V1716 Sco	2 d	**0.014**	**Yes**	ATel #16018 Sokolovsky et al. (in prep.)
V1723 Sco?	2 d + 47 d		**No + Yes**	ATel #16444 Fauverge et al. (in prep.)

L_X(NuSTAR) / L_γ(Fermi-LAT) ratio

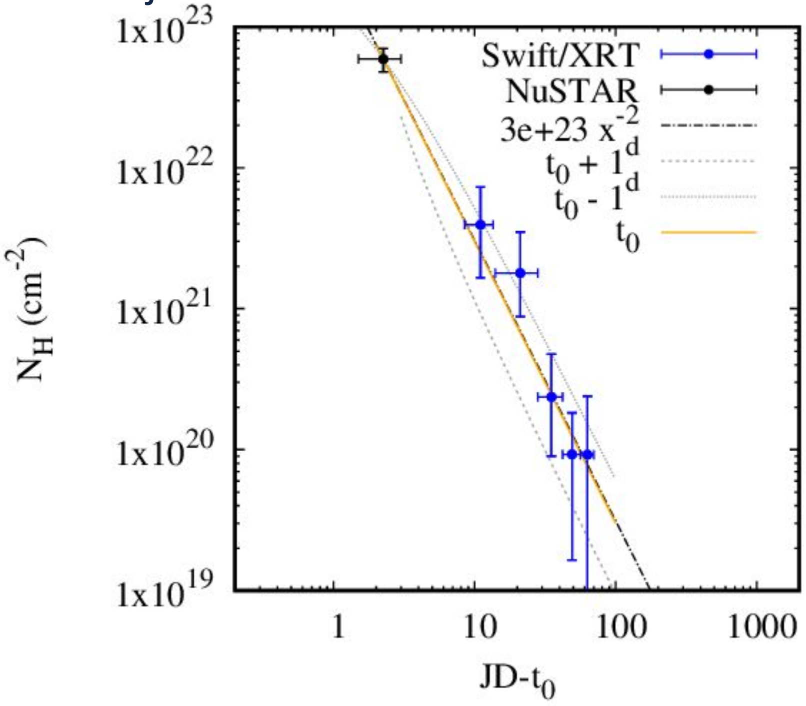
Possible explanations:

- The **shock is non–radiative** *(spends in energy mostly on adiabatic expansion, particle acceleration)*
- **Multiple shocks**: *the shock responsible for GeV emission is distinct from the one heating X-ray plasma* (forward-reverse? del Valle et al., 2022, A&A, 660, A104). *The GeV shock's X-rays are so soft/absorbed that remain hidden for NuSTAR?*
- **Corrugated shock** front suppressing X-ray emission (Steinberg & Metzger, 2018, MNRAS, 479, 687)

Ejecta mass and ejection time from N_H

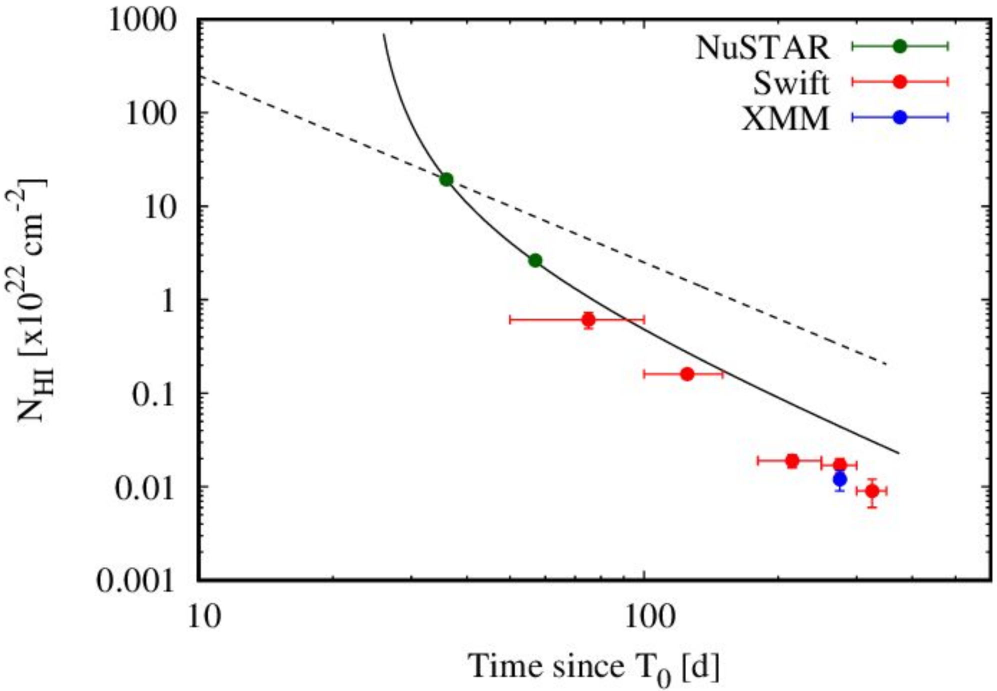
V1716 Sco, ejection at t_0

M_{ej} = **$8x10^{-8}$ $M_\odot$**



V906 Car, ejection at t_0+ 24^d

M_{ej} = **$3x10^{-5}$ $M_\odot$**



Sokolovsky et al. (2020, MNRAS, 497, 2569)

Summary

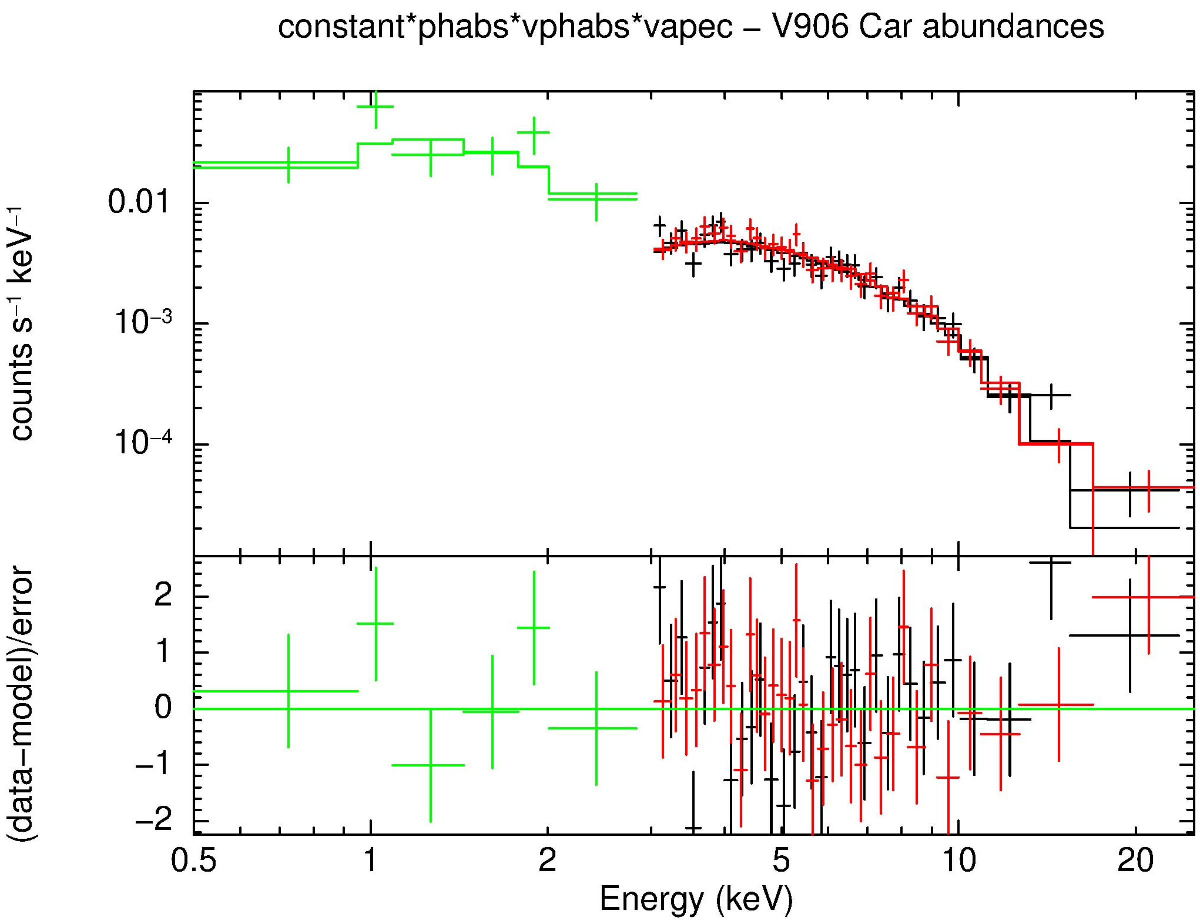
- **NuSTAR spectra** of all detected novae **look alike**
- Consistent with **single-temperature CNO-enriched** plasma
- Heavily **absorbed** - shocks are deep within ejecta
- But **no fast variability**, so not too close to the WD
- $\boldsymbol{L_X / L_\gamma \ll 1}$, defying explanation

Thanks!

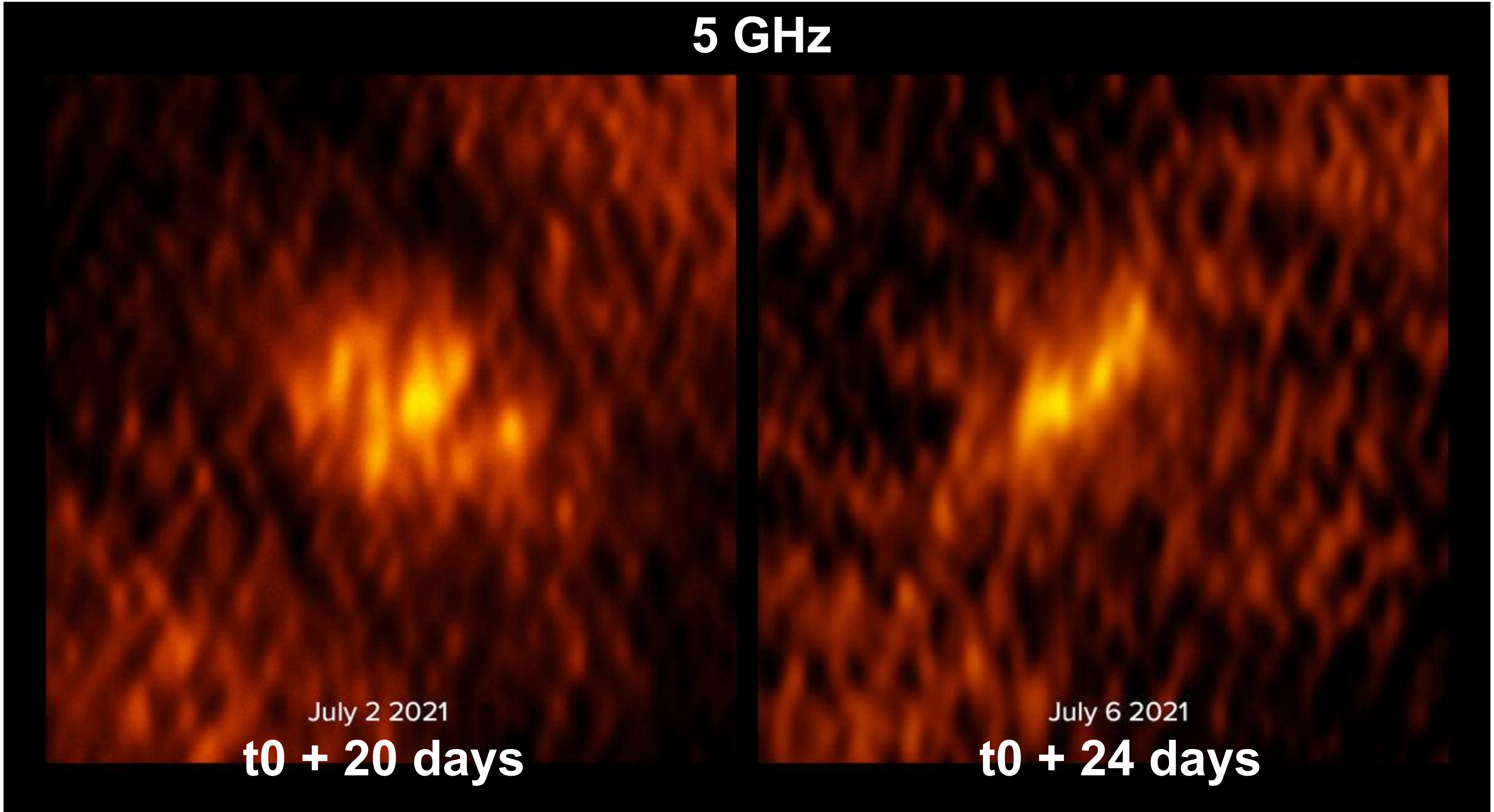
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

X-ray spectrum of V1674 Her (NuSTAR+Swift)

- **t_0 + 12 days**
- Thermal
  kT = 4 keV
- No intrinsic absorption
- Non-solar abundances

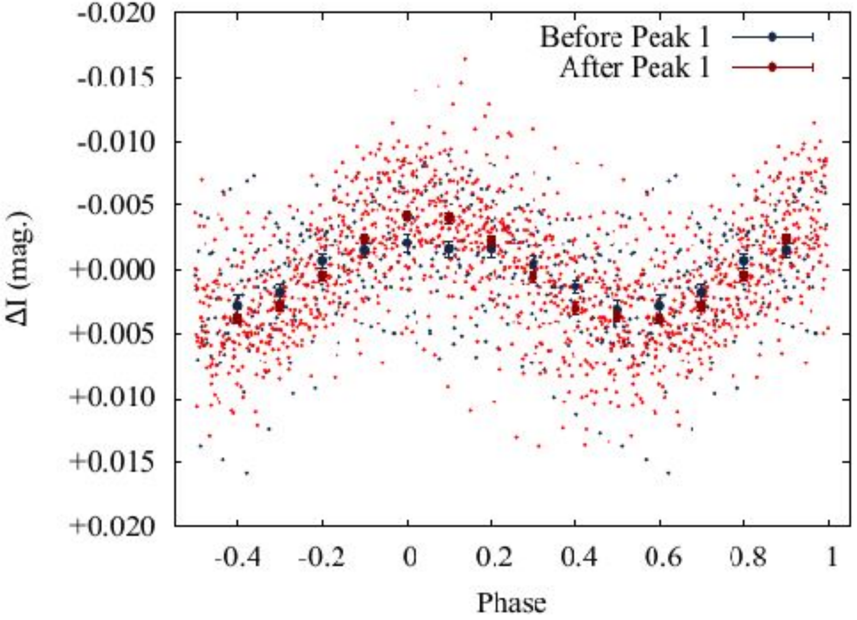


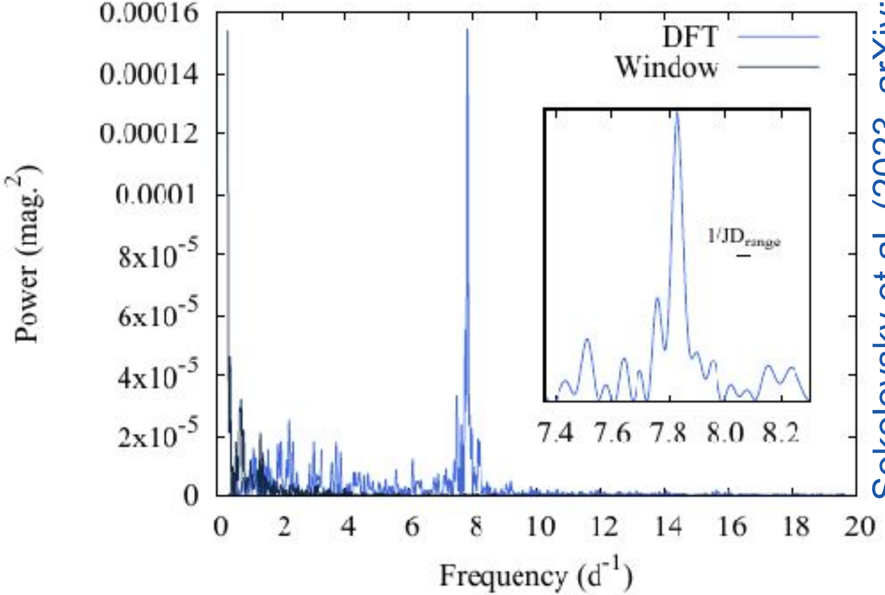
V1674 Her - VLBA synchrotron emission images



Williams et al. (2023, AAS 242, 109.6)

Periodic signal in V606 Vul





Sokolovsky et al. (2023, arXiv:2311.04903)

Periodic signal in V606 Vul

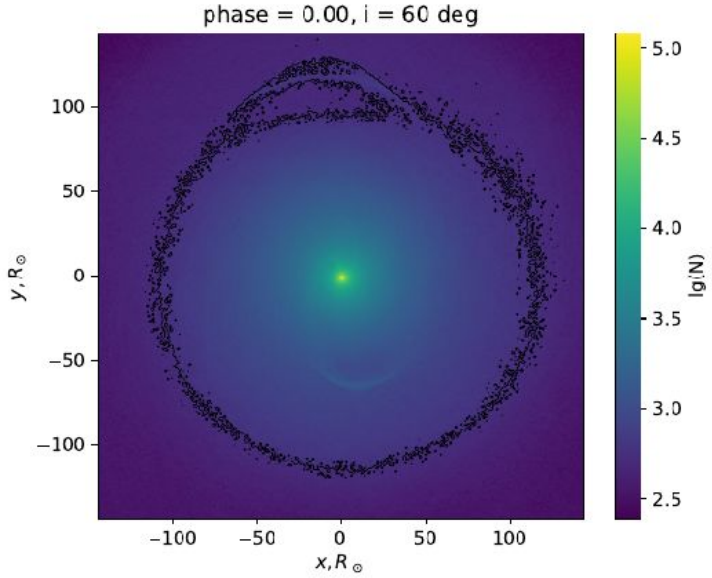
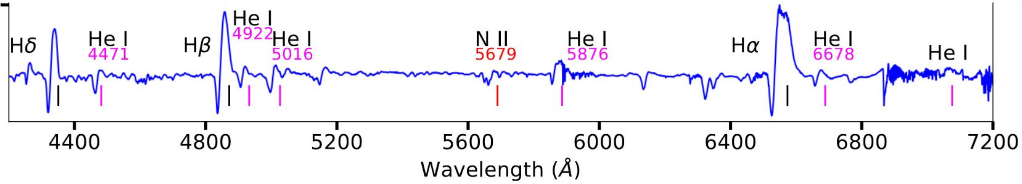


Figure 9. Simulated column density N in the image plane: the color represents number of test particles per pixel. The black curve shows a fiducial border of the photosphere at $N \simeq 560$ particles/pix.

Sokolovsky et al. (2023, arXiv:2311.04903)

Novae - first recognized type of transients

First spectra of novae from late 19th century revealed P Cyg profiles hinting that we are witnessing some kind of explosion



Nova V339 Del spectrum ([Aydi et al. arXiv:2309.07097](arXiv:2309.07097))

The New Star in Carina.

Gentlemen,—

As announced in Circular No. 1 of the Harvard College Observatory, a new star has appeared in Carina. Its spectrum is practically identical with that of Nova Aurigæ and Nova Normæ. In 'Astronomy and Astro-Physics,' 1894, p. 201, I called attention to the improbability of two successive collisions between stars, occurring nearly in the line of sight, in both cases a bright- and a dark-line star being involved, and in each case the bright-line star being the one to recede from us. The same remarks apply to the theory of the collision of a star and a nebula. As a substitute I offered an explosion hypothesis, in which a dark sun suddenly gave out in all directions large quantities of hydrogen in an incandescent state. This would of course merely produce a spectrum with bright lines. But if the expulsion of hydrogen continued, the outer layers of gas would cool, producing absorption lines in the spectrum of the approaching hydrogen, but still leaving the spectrum lines of the receding hydrogen bright. Finally, when the expulsion ceased, we should find a heated spherical mass of gas, similar to a planetary nebula. It was shown that the velocities which were observed in the cases of these two *novæ* were less than 50 per cent. greater than what had occasionally been observed in our own Sun. The discovery of this third *nova*, with a spectrum identical with that of the two others, increases many times the improbability of the collision theories, and thereby strengthens the explosion hypothesis. If the latter is correct, we must look upon the phenomena presented by a *nova* not as indicating the birth of a new star, but rather as a cataclysm testifying to the death and final disrupture of an old one.

Yours truly,
William H. Pickering.

Harvard College Observatory,
1895, Nov. 5.

[Pickering (1895, The Observatory, Vol. 18, p. 436)]

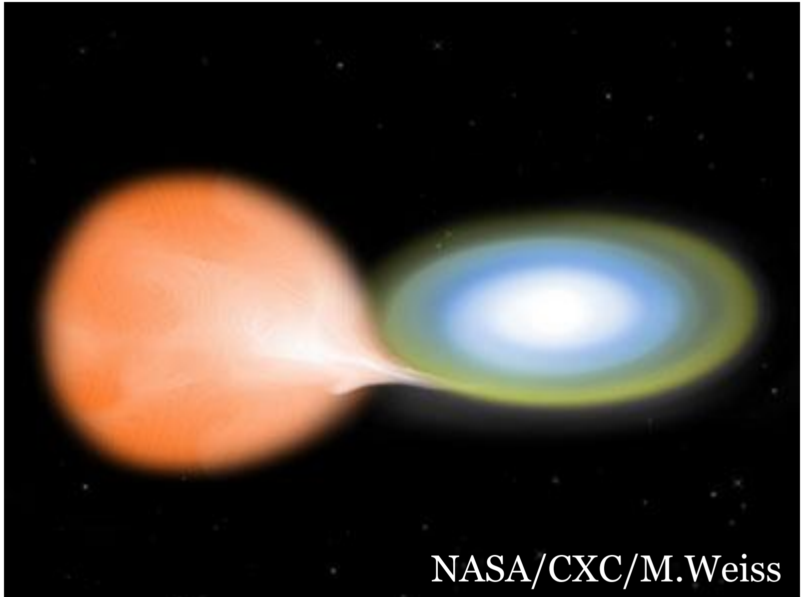
What is a nova eruption?

Sudden re-ignition of thermonuclear reactions in a H-rich layer on the accreting white dwarf.

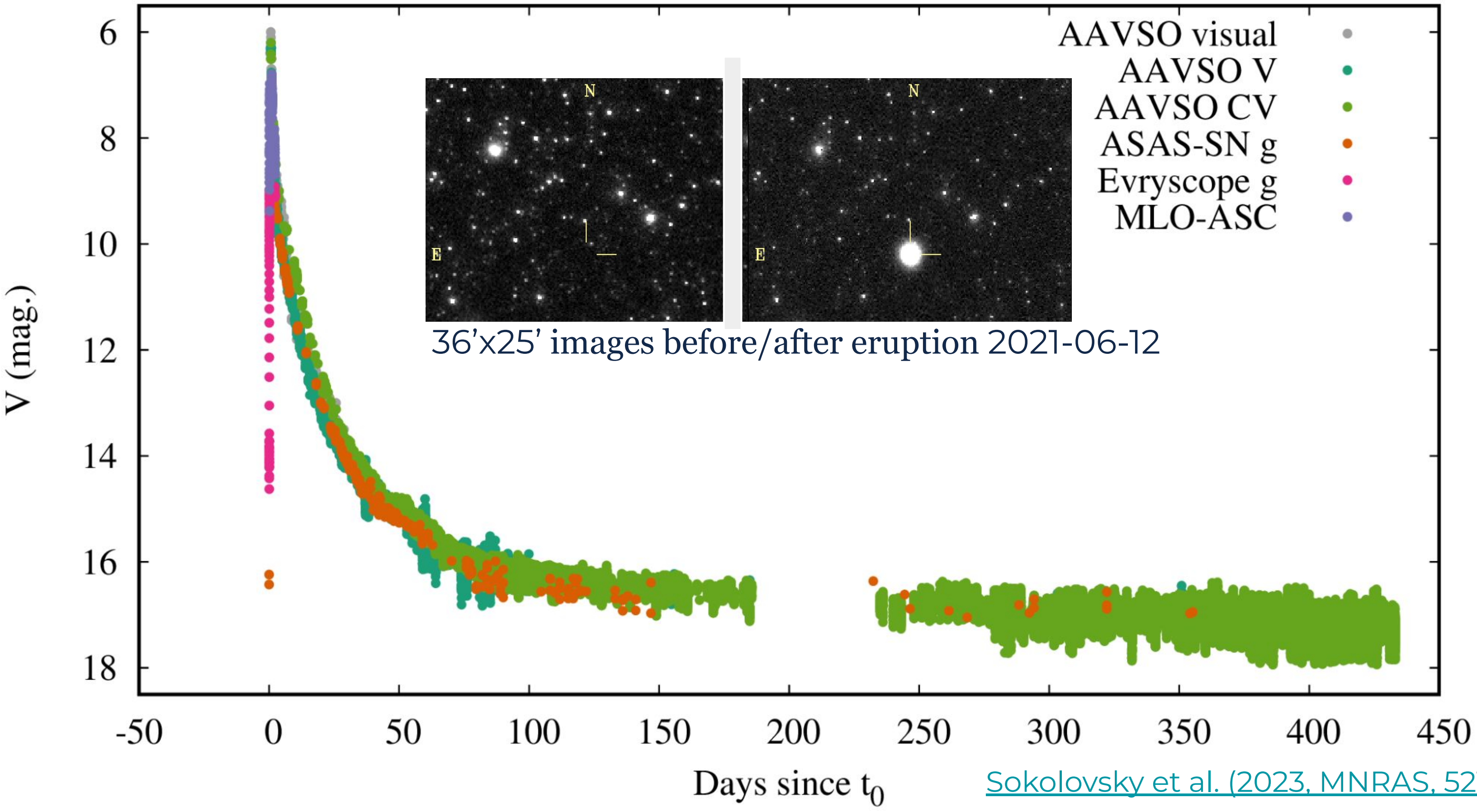
The binary brightens by **$8\text{-}15^m$** reaching

$M_V \sim -4^m$ до -10^m

for **days-months**

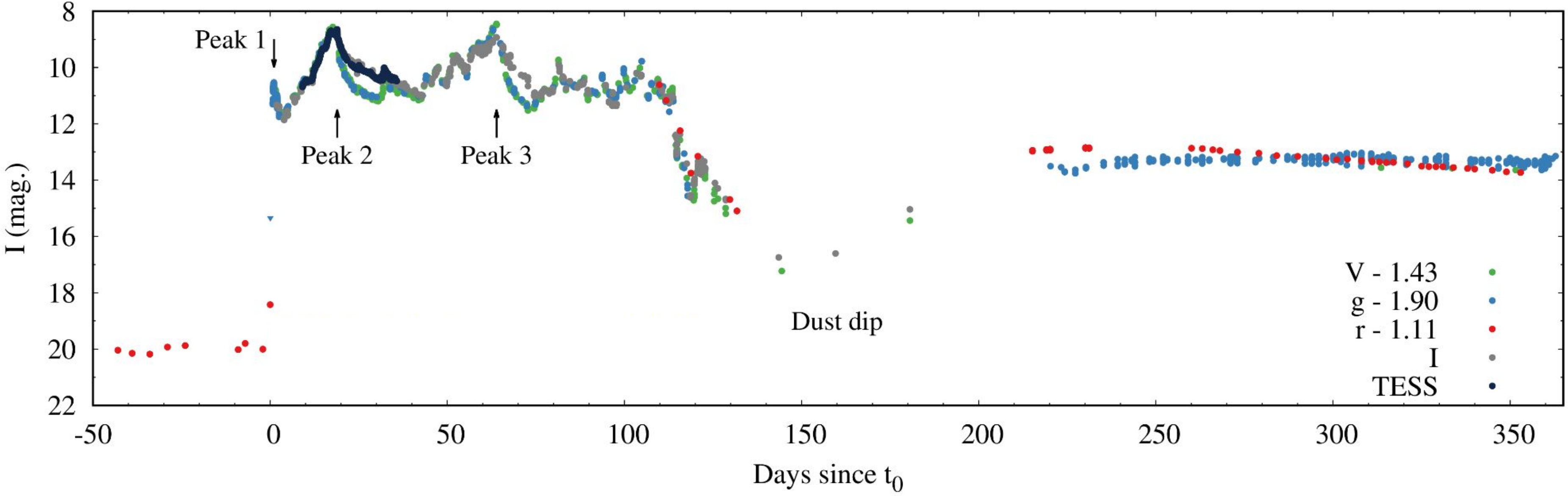


Lightcurve of a (very fast) nova V1674 Her



Sokolovsky et al. (2023, MNRAS, 521, 5453)

Lightcurve of a slow nova V606 Vul



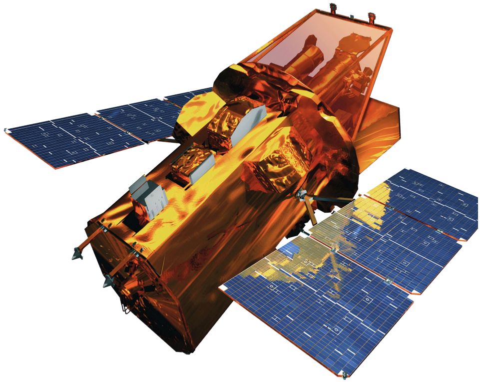
t_0 = 2021-07-15.384

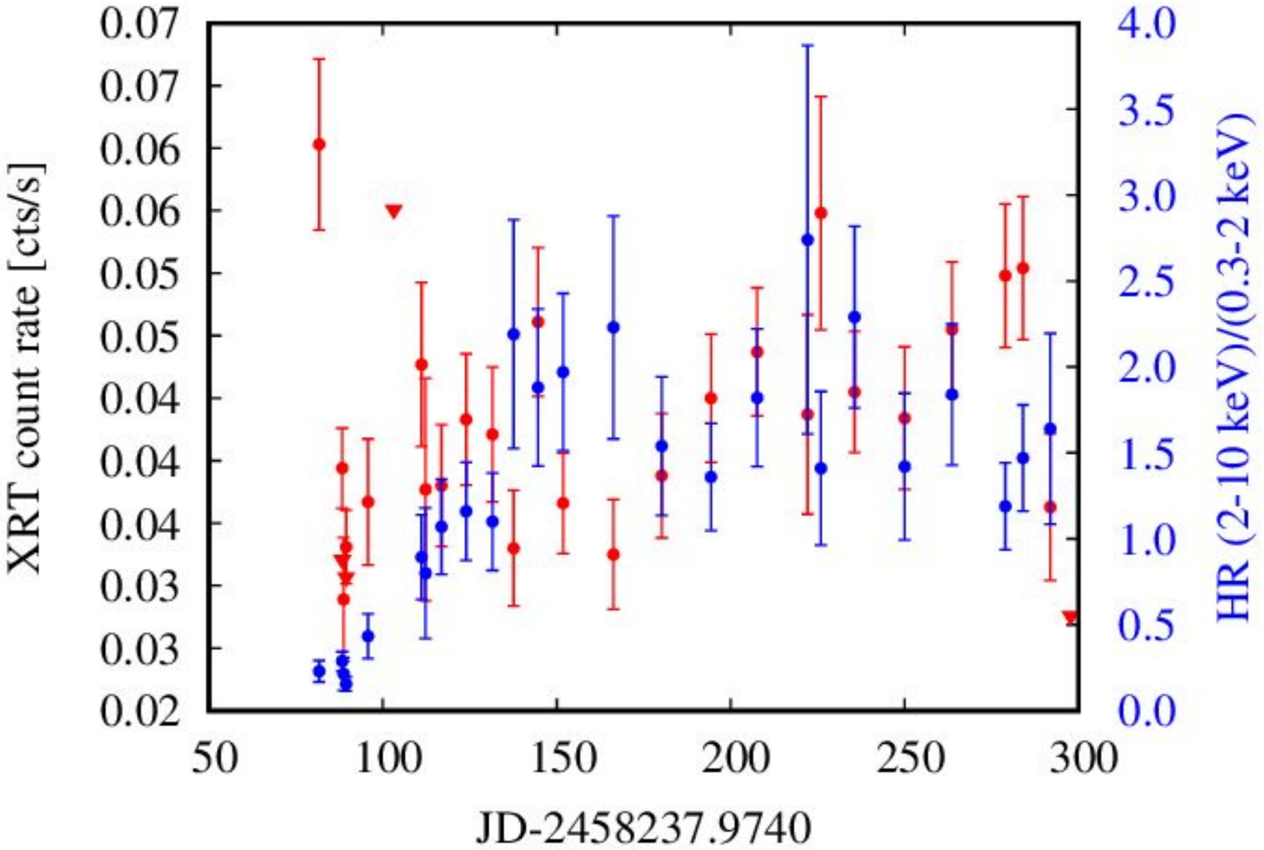
Combined ZTF, ASAS-SN, Evryscope, AAVSO & TESS lightcurve

As SSS fades, accretion-powered X-rays take over

V392 Per -

Swift/XRT

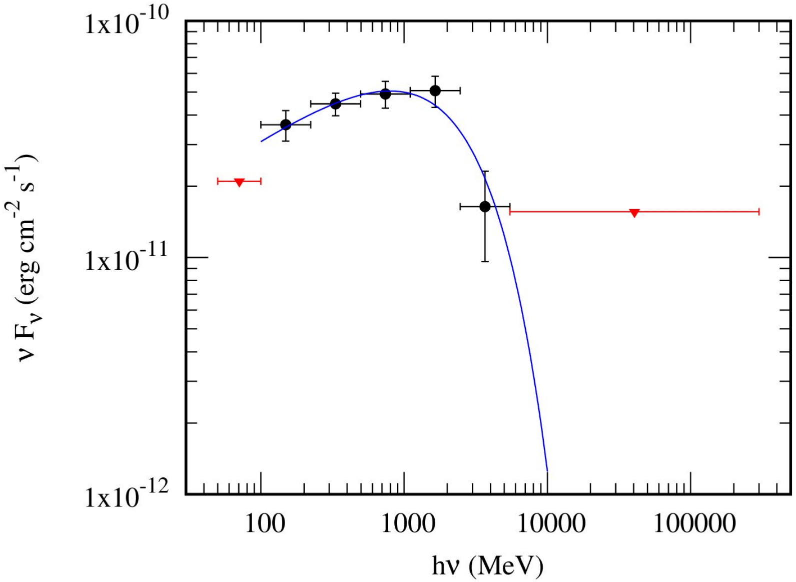




Back to the Shock phase - GeV emission

YZ Ret - Fermi/LAT

Band	Luminosity
γ-ray/optical peak at $t_0 + 3.6$ d:	
0.1–300 GeV	3.3×10^{35} erg s^{-1}
bolometric optical	8.1×10^{38} erg s^{-1}
NuSTAR epoch at $t_0 + 10$ d:	
0.1–300 GeV	1.4×10^{35} erg s^{-1}
3.5–78 keV	1×10^{33} erg s^{-1}
extrapolated 0.3–78 keV	2×10^{33} erg s^{-1}
bolometric optical	2.7×10^{38} erg s^{-1}

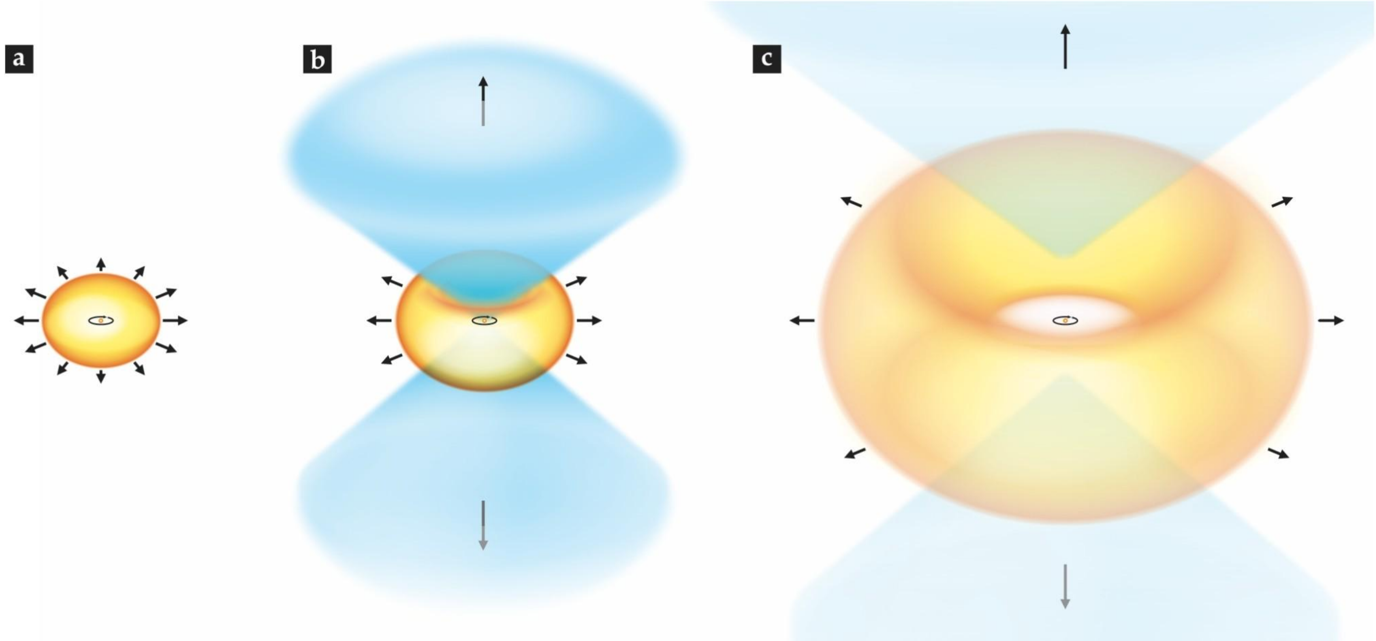


Modelling L_gamma/L_x - Metzger et al. (2015, MNRAS, 450, 2739)

Neutrino search with IceCube - Abbasi et al. (2023, ApJ, 953, 160)

Slow torus and fast WD wind?

- Optical spectra show 2 (or more) sets of lines with different velocities (Aydi et al. 2020, ApJ, 905, 62)
- Line profile modelling and high-resolution IR/radio imaging



Fermi/LAT GeV view of V1674 Her

just 6 h after nova eruption start, but Porb = 3.67 ч

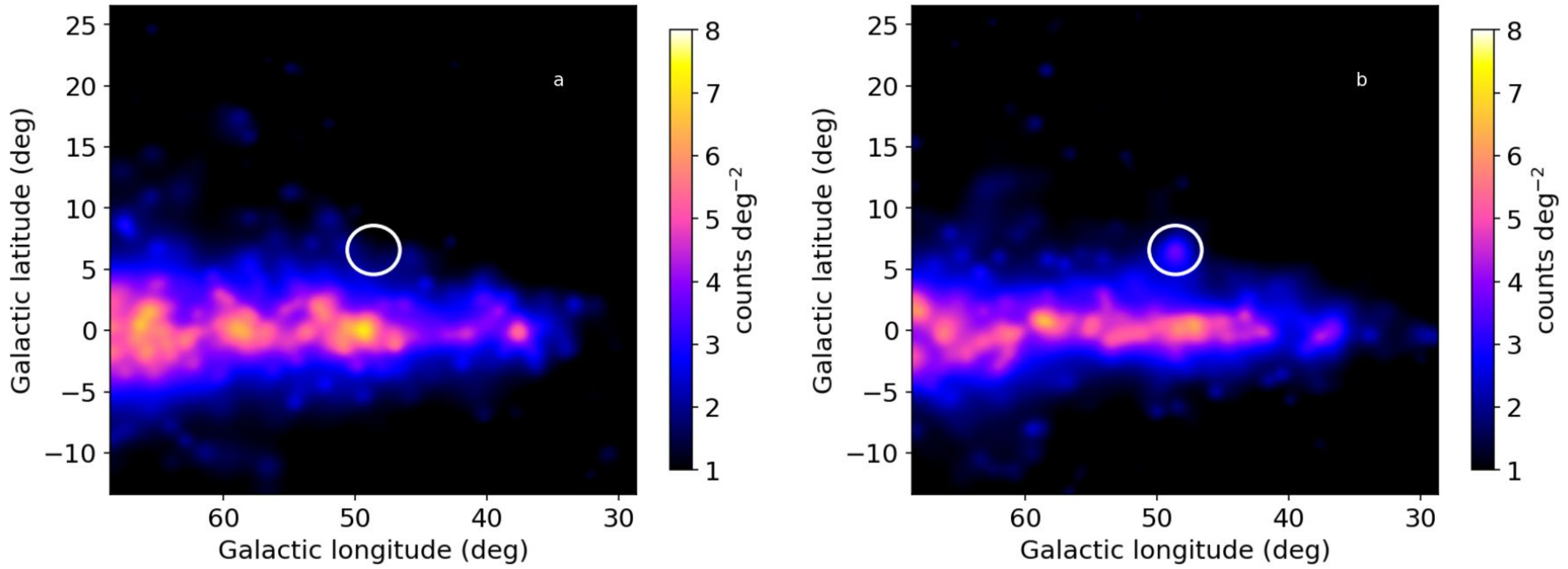
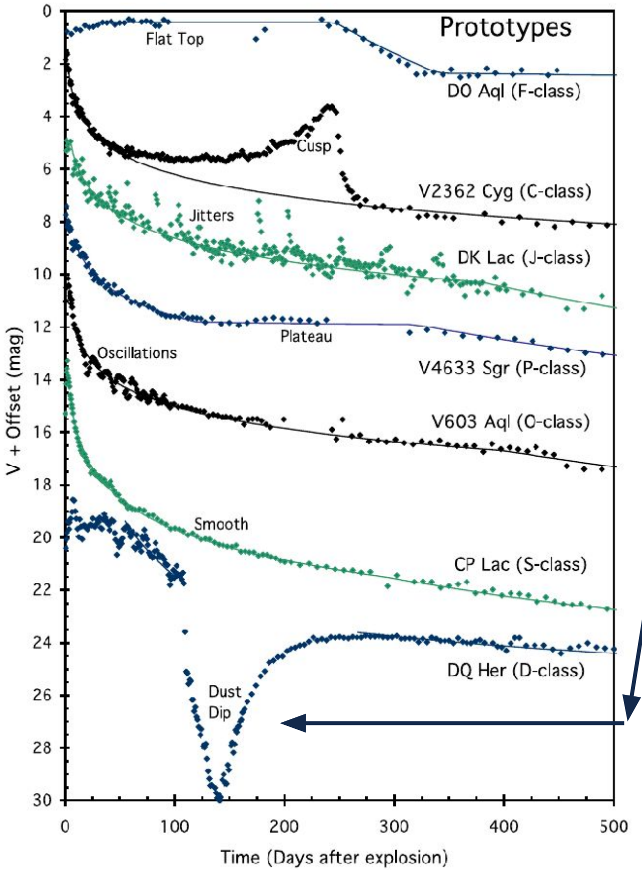


Figure 5. The *Fermi*/LAT smoothed 0.1–2 GeV count images centered on V1674 Her. The left image (a) covers the time interval 2021-06-10 10:34 to 2021-06-11 08:34 UT before the eruption. The right image (b) covers the 18 h interval when the γ-ray emission was detected. The white circle marks the optical position of the nova.

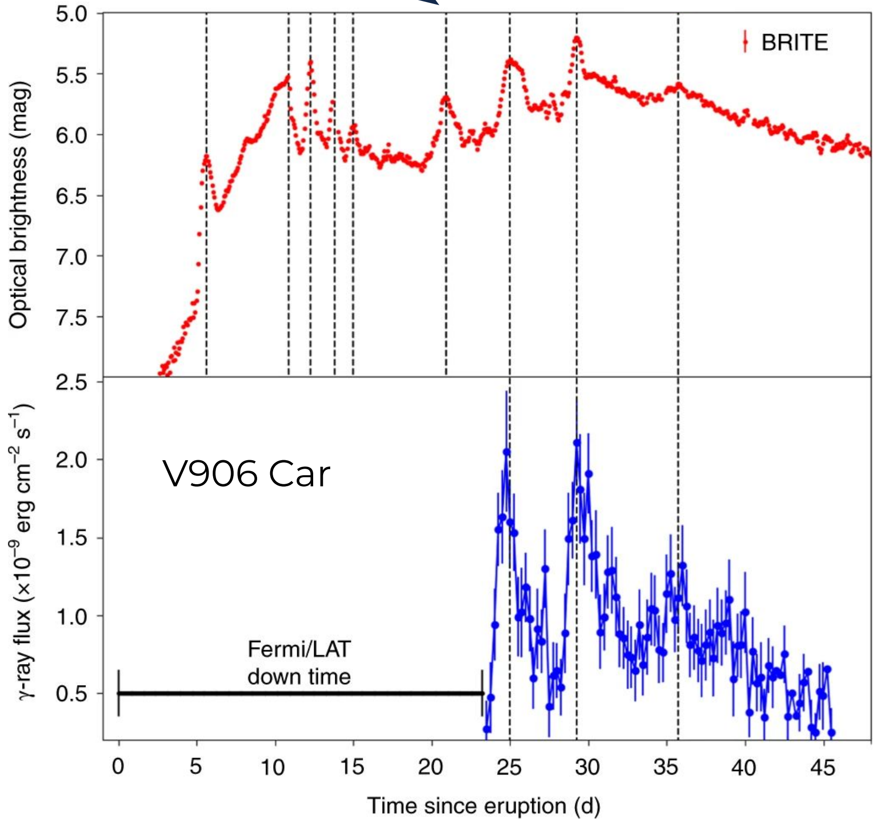
Shocks produce optical mini-flares

Strope, Schaefer, Bradley & Henden (2010, AJ, 140, 34)



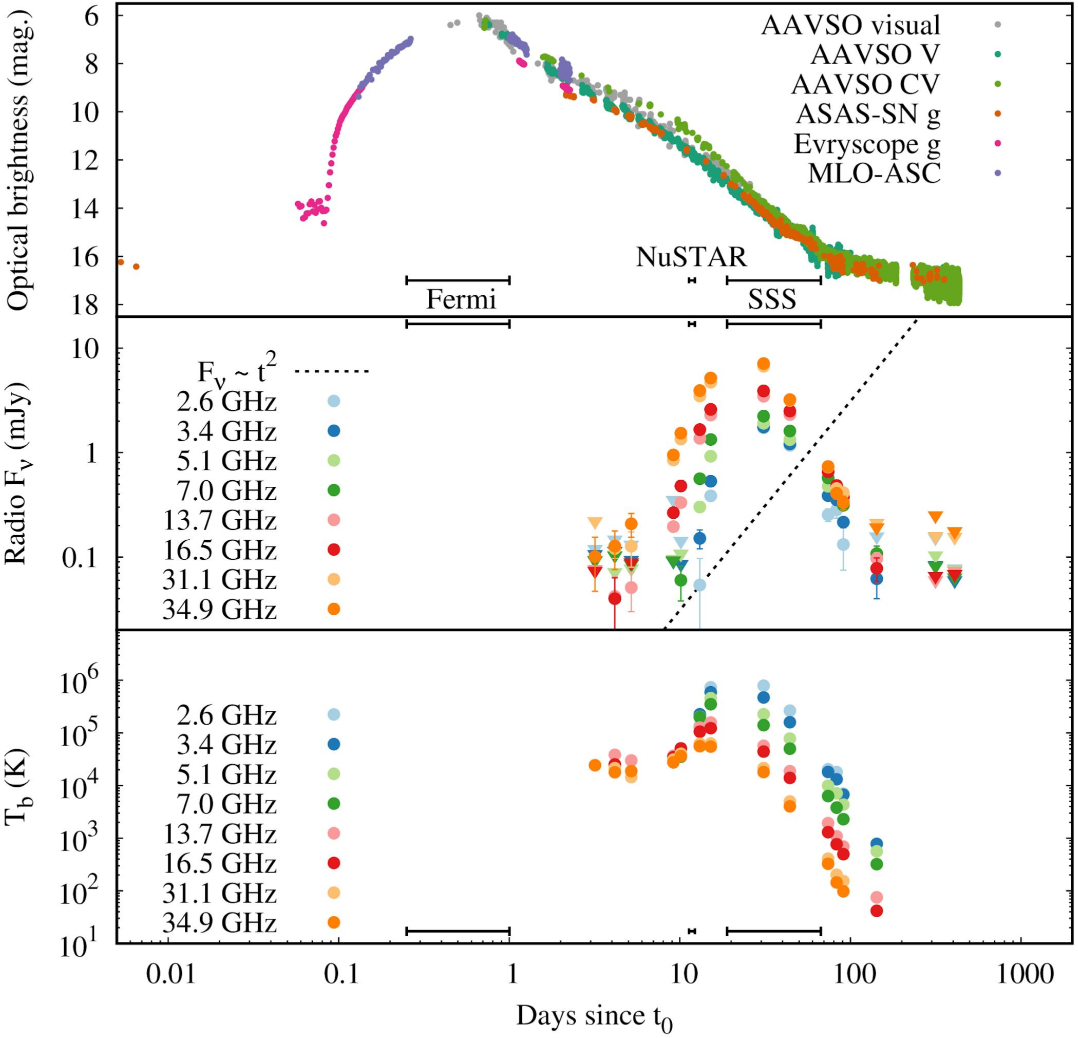
Prototypes of light curves classes. The seven binned light curves show the distinct features of each class

dust dips + shock-powered flares + unexplained features



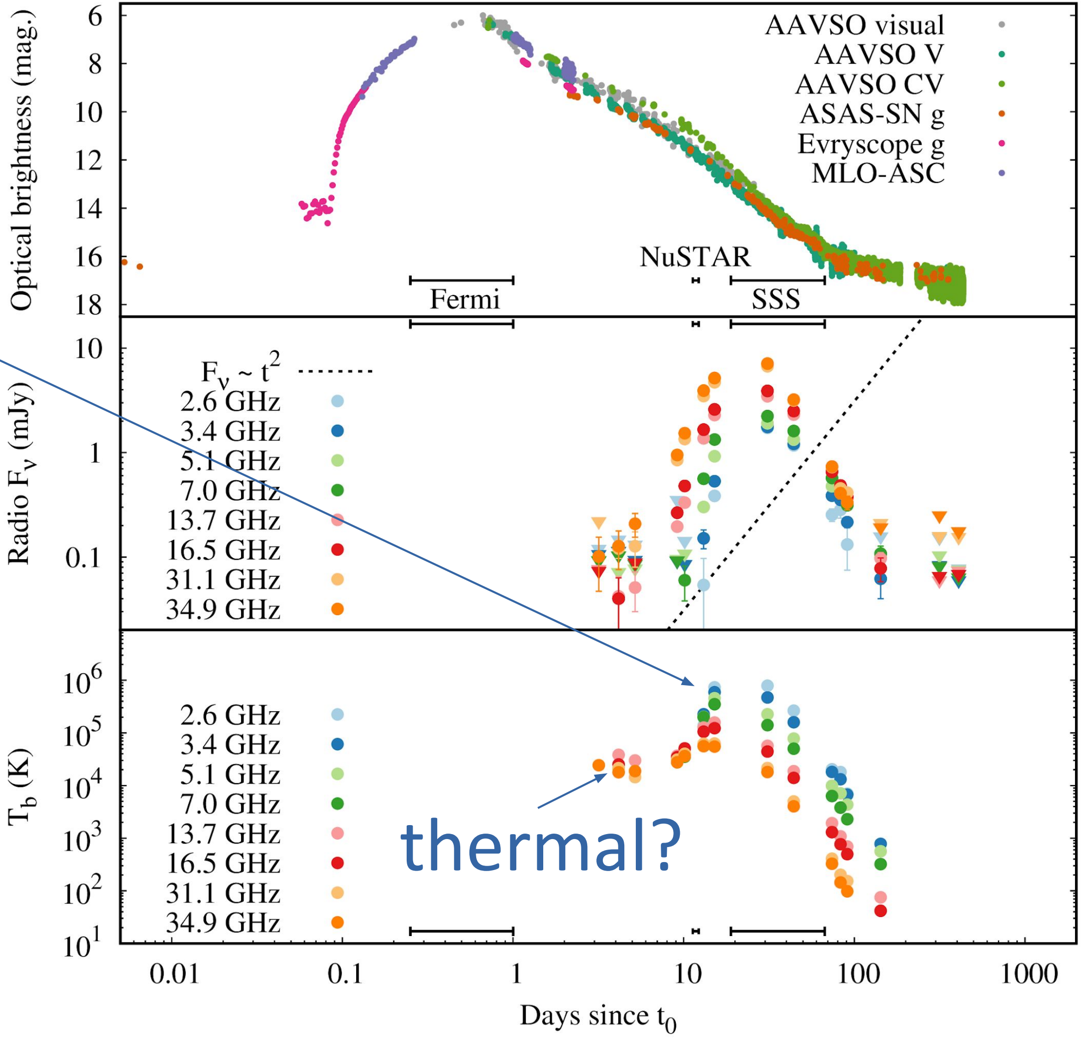
Aydi et al. (2020, Nature Astronomy, 4, 776)

V1674 Her - VLA



Sokolovsky et al. (2023, MNRAS, 521, 5453)

High T_b points to synchrotron origin



Sokolovsky et al. (2023, MNRAS, 521, 5453)

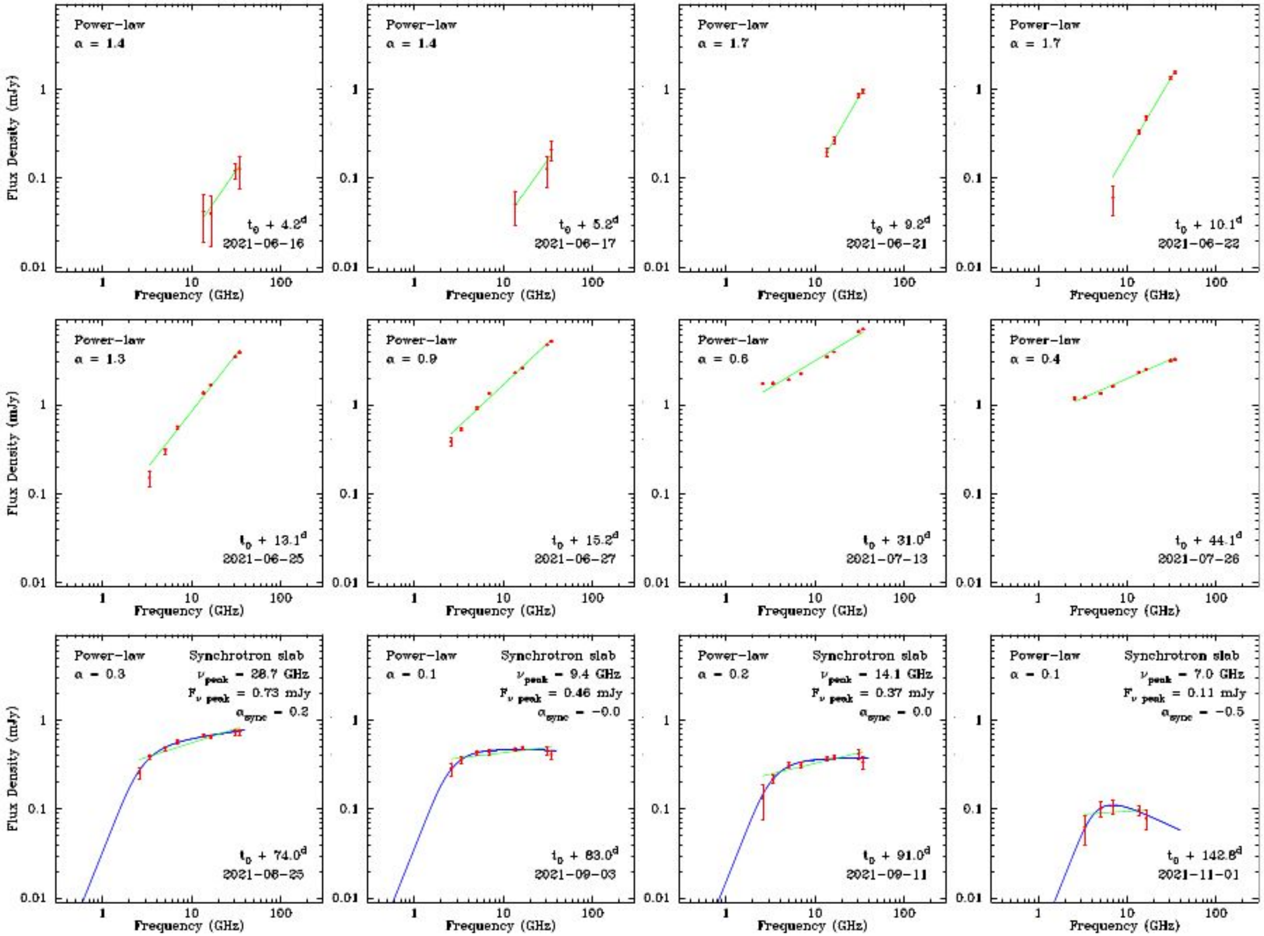
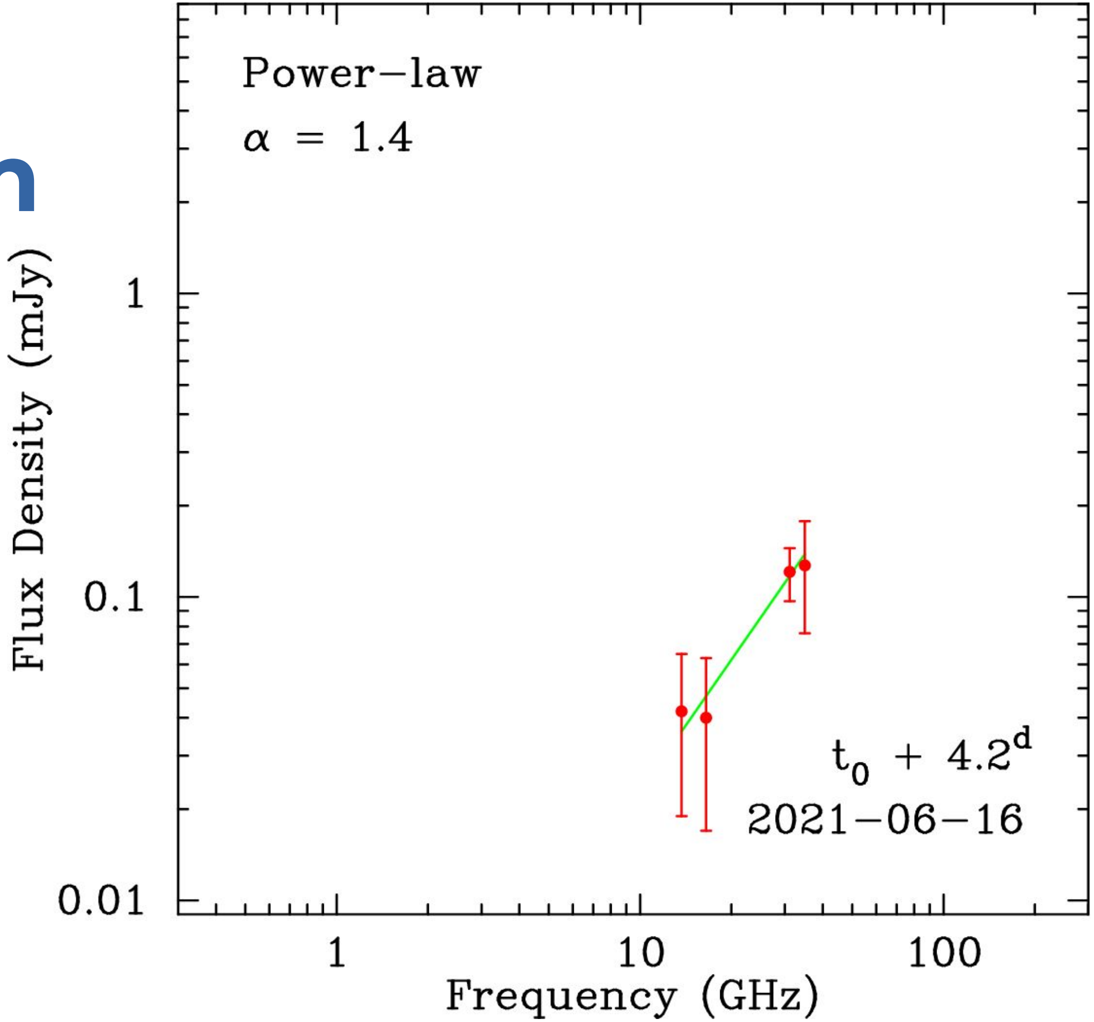


Figure 8. The evolution of the radio spectrum of V1674 Her. The VLA flux density measurements (red) are compared to the simple power-law fit (green line) and a spectrum of a uniform synchrotron-emitting slab. The uncertainty on the reported spectral index values is ~ 0.3 for the power law fits on 2021-06-16, 2021-06-17, 2021-11-01 and $\lesssim 0.1$ in all other cases. The synchrotron slab spectrum can approximate the observations only at late epochs. The spectrum shape is most likely determined by the non-uniform optical depth effects across the source.

Sokolovsky et al. (2023, MNRAS, 521, 5453)

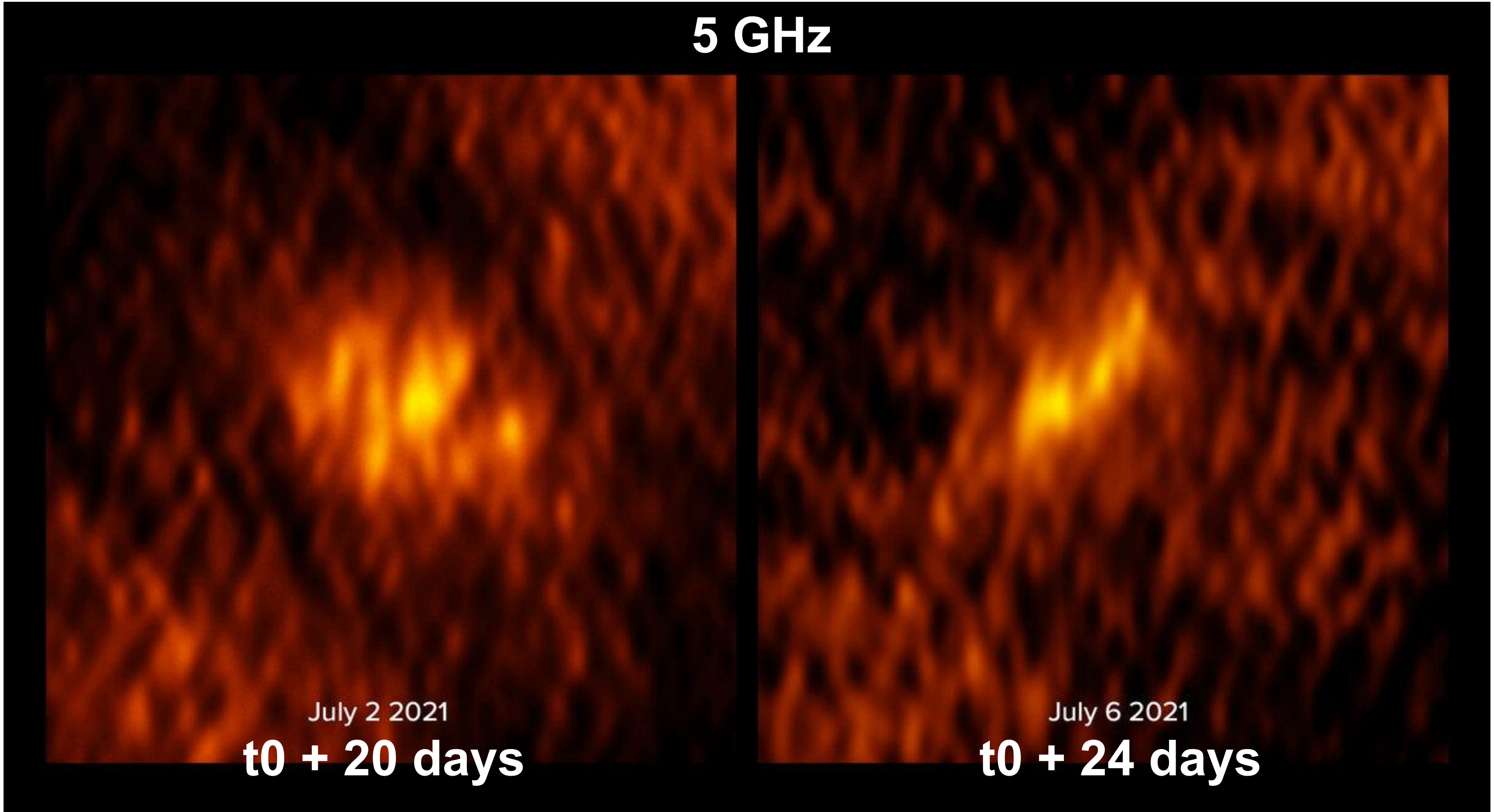
V1674 Her VLA spectrum evolution



Sokolovsky et al. (2023, MNRAS, 521, 5453)

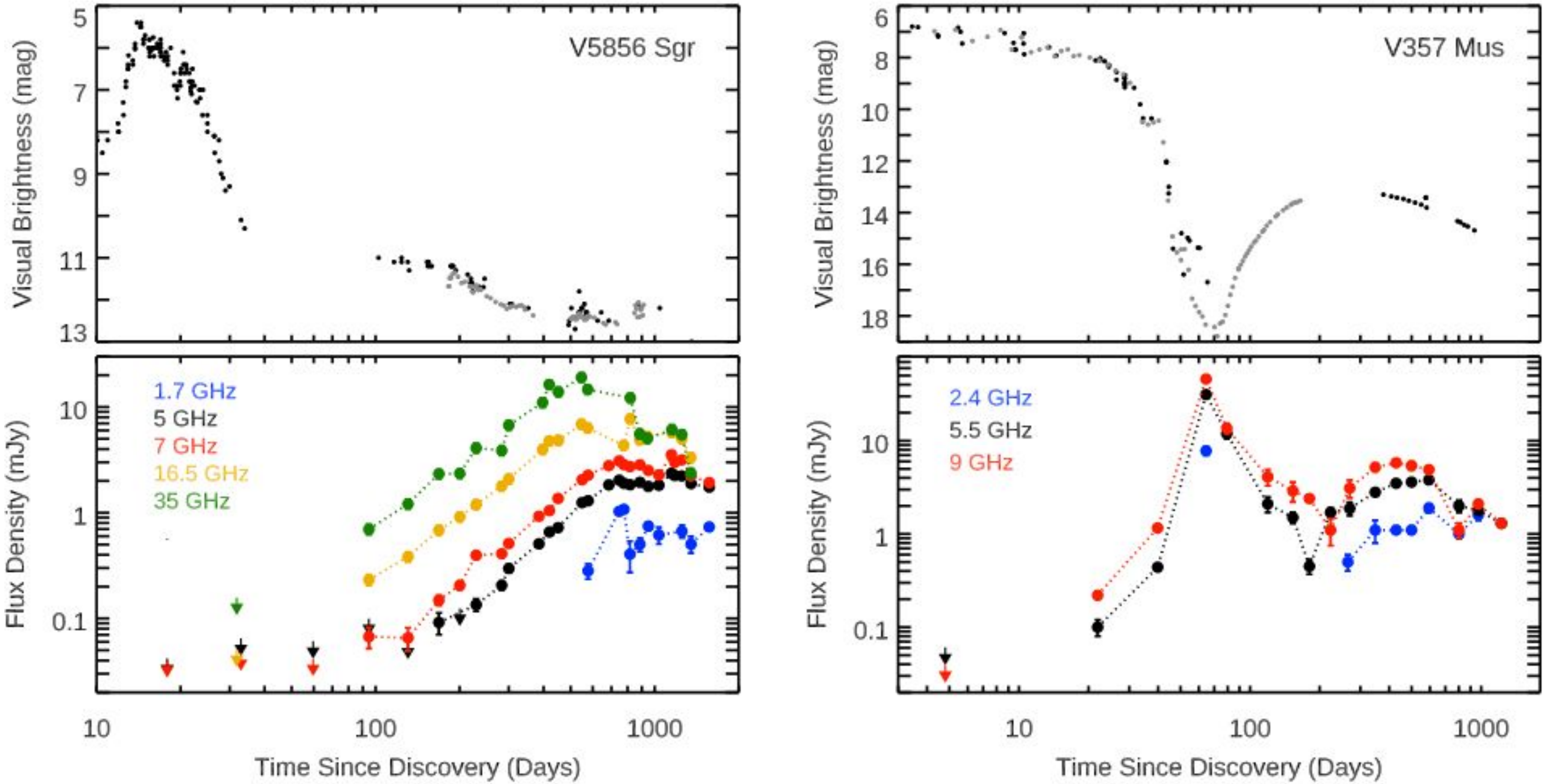
V1674 Her - VLBA synchrotron emission images

5 GHz



Williams et al. (2023, AAS 242, 109.6)

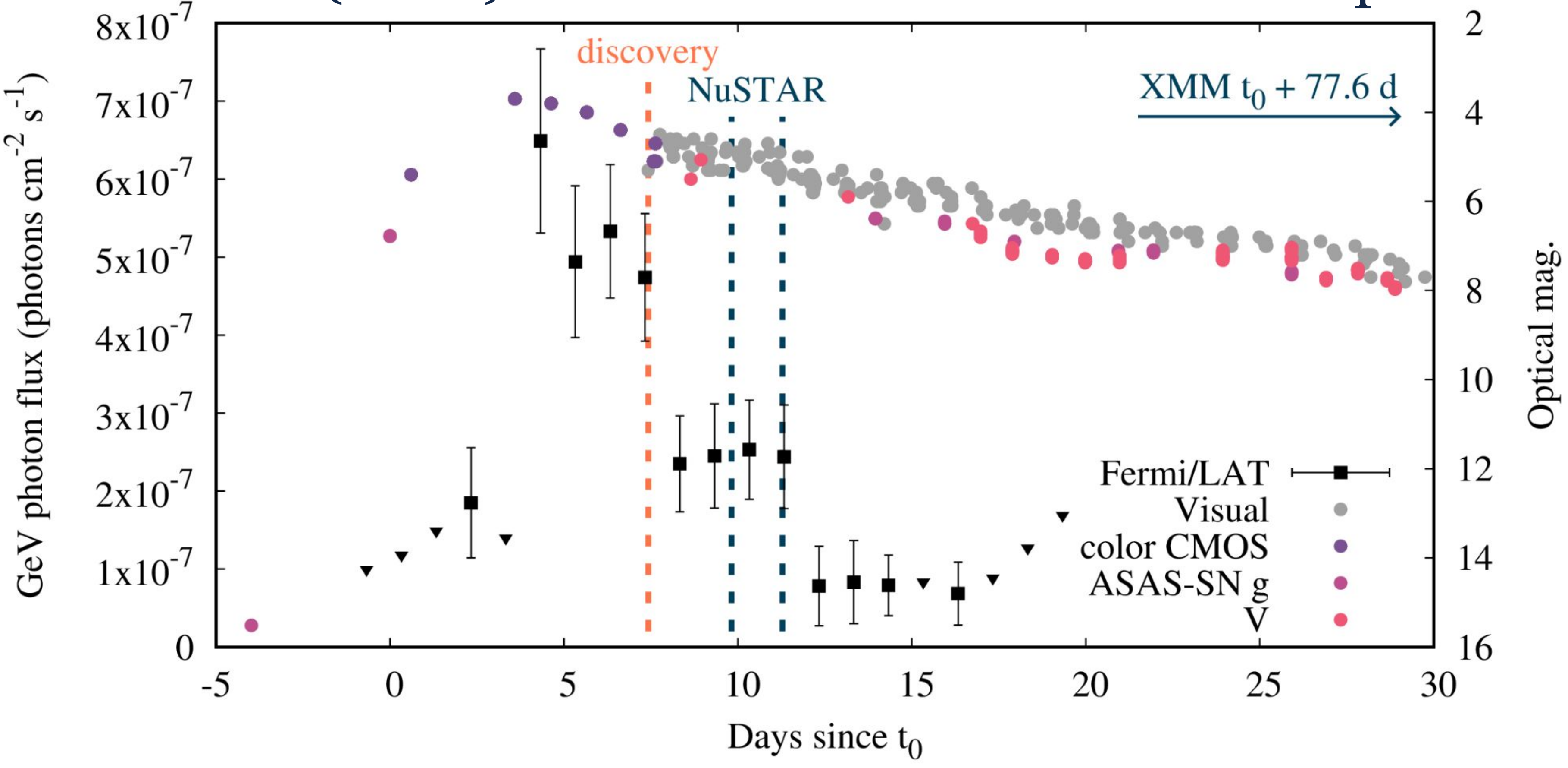
Thermal and synchrotron humps?



Chomiuk et al. (2021, ApJS, 257, 49)

Finding novae is not really solved

YZ Ret (2020) was discovered a *week* after eruption!

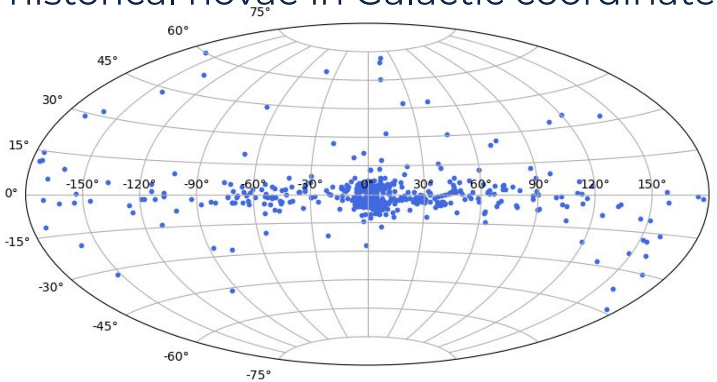


Should be 25/year (observed 10/year)

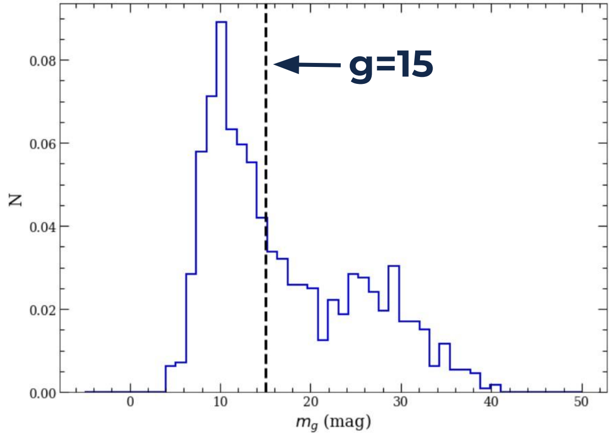
Why do we need more novae?

- Test our understanding of **nova population** and their contribution to the Galaxy chemical evolution (most ^{7}Li is from novae?? Kemp et al. 2022, ApJ, 933, L30)
- Minimize **eruption to discovery time** for organizing MW follow-up with pointed instruments: NuSTAR, VLA, etc.

493 historical novae in Galactic coordinates



Simulated peak magnitudes of novae



Kawash et al. (2021, ApJ, 922, 25)

Novae are being discovered by professional and amateur surveys mostly in optical, but also NIR

ASAS-SN

Gaia Alerts

amateurs in Japan, Australia, Brazil are especially active

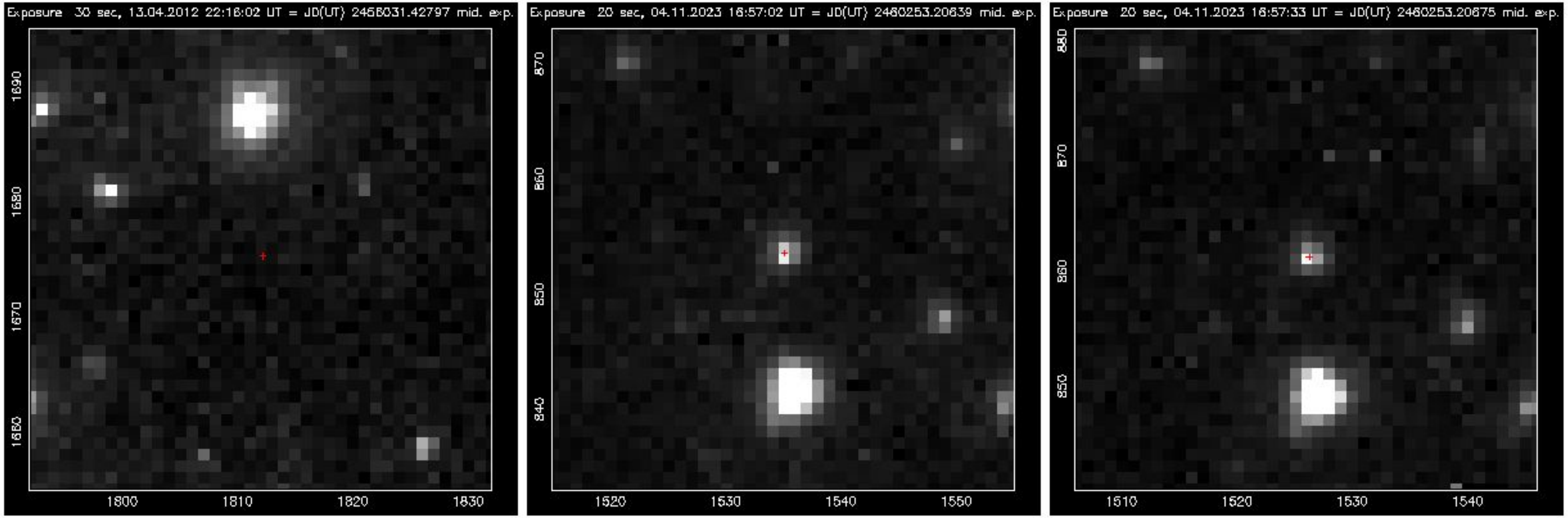
Koichi Itagaki

Amateur-led survey I participate in: [New Milky Way]

- Stanislav Korotkiy - is the main force behind the survey
- 135mm telephoto lens + CCD camera (2 sets)
- All Milky Way visible from the observing site down to ~13mag every clear night
- Automated imaging control and transient detection pipeline

TCP J20315286+2740166 dwarf nova found by NMW

32400_Vul7_2023-11-4_16-58-2_003



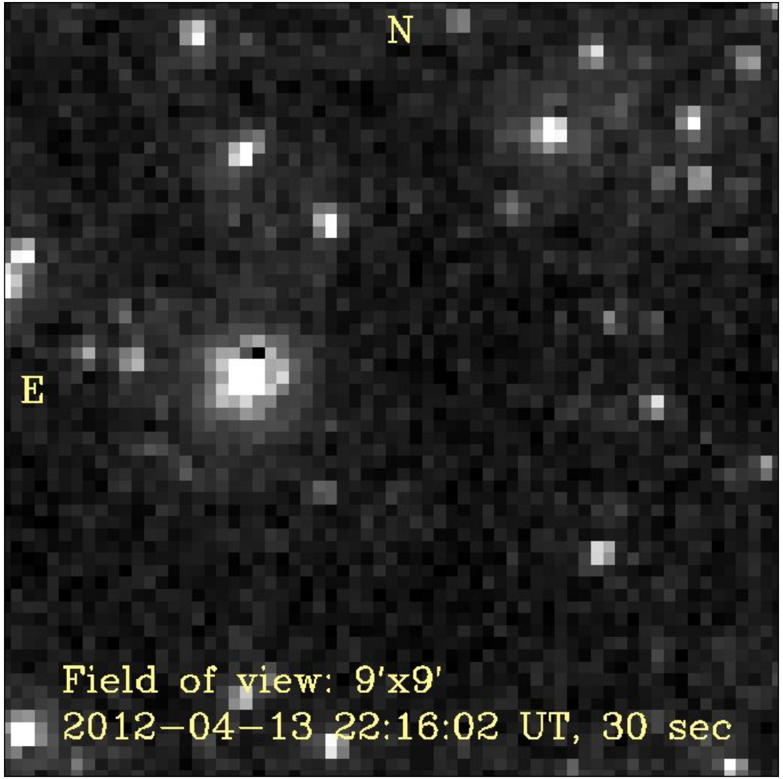
	Date (UTC)	JD(UTC)	mag.	R.A. & Dec.(J2000)	X & Y (pix)	Image
Discovery image 1	2023 11 04.7064	2460253.2064	12.43	20:31:52.85 +27:40:16.5	1535 0854	/dataX/kirx/NMW_NG_rt3_autumn2019/web_upload/img_2023-11-04_Vul7_19
Discovery image 2	2023 11 04.7068	2460253.2067	12.44	20:31:52.88 +27:40:16.8	1526 0861	/dataX/kirx/NMW_NG_rt3_autumn2019/web_upload/img_2023-11-04_Vul7_19

Mean magnitude and position on the discovery images:
2023 11 04.7066 2460253.2066 12.44 20:31:52.86 +27:40:16.6
69.02766 -7.04962 galactic Vul Second-epoch detections are separated by 0.4" and 11.7 pix
The object was not found in VSX
The object was not found in ASASSN-V
The object was not found in astcheck.
online_id | target | 20:31:52.86 +27:40:16.6 (user input) | T | P | (position from user input) may be a
Check this position in TNS. Manually check the ASAS-SN list of transients!
Search this object in SIMBAD.
Search this object in VizieR catalogs. WISE atlas Aladin Lite SNAD ZTF viewer
Online MPChecker may fail to identify bright comets! Please manually check the Seiichi Yoshida's and Gideon van Buitenen's pages.

Online MPChecker | Search VSX online | Catalina photometry | NMW images | ASAS-3 lightcurve

Preview of the reference image(s) and two 2nd epoch images (are there clouds/trees in the view?) 2nd epoch FITS
Example VaST+ds9 commands for visual image inspection (blink images in ds9). VaST command line (re-run VaST)
The analysis script (re-run the full search) Stub MPC report (for online MPChecker) Stub TOCP report Stub variable star reports Make finder charts with VaST

TCP J20315286+2740166 dwarf nova found by NMW



Non optical-IR nova searches? (V959 Mon)

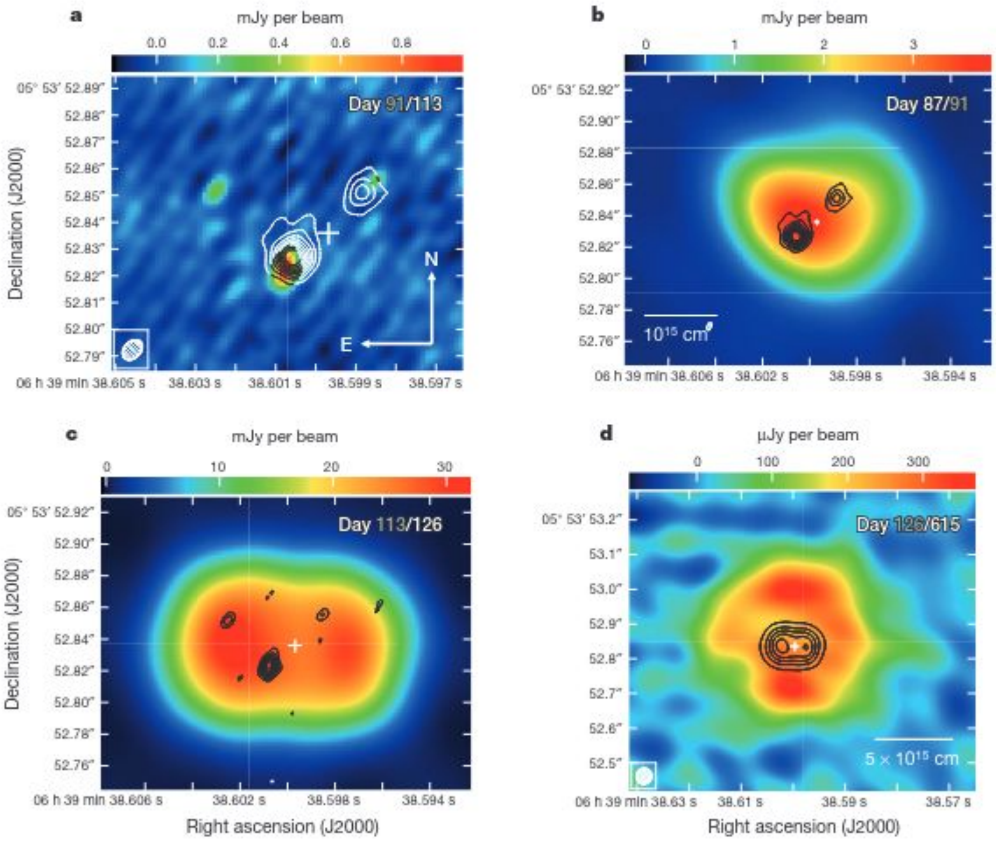


Figure 2 | Radio imaging of V959 Mon. **a**, Illustration of the expansion of the compact radio knots, with a high-resolution 5 GHz EVN image from 113 d after γ-ray discovery shown in colour, and contours representing the EVN image from day 91. Contour levels span 0.125–2 mJy per beam in steps of 0.125 mJy per beam. **b**, 5.8 GHz e-MERLIN colour image of thermal nova ejecta on day 87. The compact VLBI knots from day 91 are superimposed as contours, with levels as in **a**. **c**, Components similar to those in **b**, but one month later, with a 36.5 GHz VLA colour image of the thermal ejecta on day 126. The VLBI knots from day 113 are contours. **d**, Expansion and flip of the thermal nova ejecta, comparing VLA images from four months and, respectively, two years after outburst. The 17.5 GHz image from day 615 is shown in colour, overplotted with the 36.5 GHz day-126 image now in black contours (3.2, 9.6, 16, 22.4 and 28.8 mJy per beam). In all panels, the presumed location of the binary is marked as a white cross. Scale bars in **b** and **d** assume a distance of 1.5 kpc (ref. 11). Synthesized beams for contours are shown in the bottom left corners of **a** and **d**. White date labels are for colour images; grey labels are for contours.

Chomiuk et al. (2014, Nature, 514, 339)