Nova explosions

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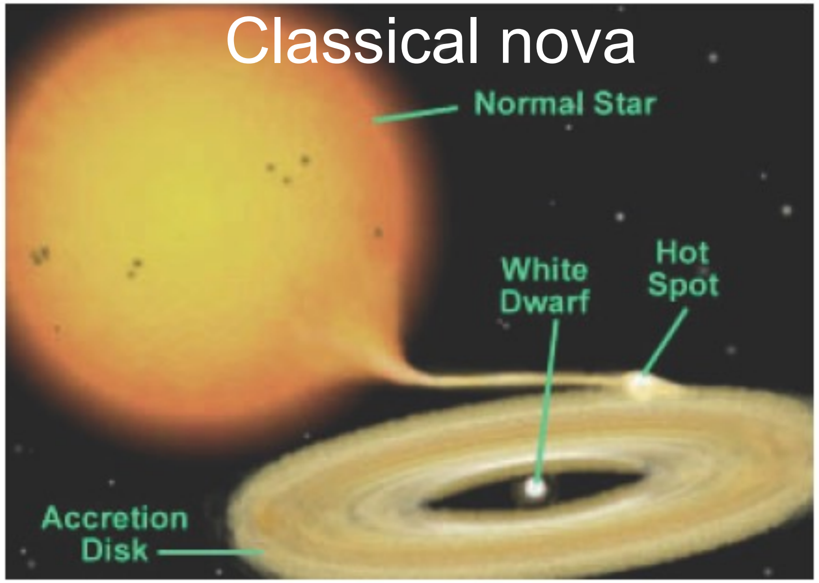
Stellar explosions: white dwarfs in close binary systems

Cataclysmic variable:

WD + Main Sequence (P_{orb} ~ hrs-day)

Roche lobe overflow - accretion disk



Hydrogen burning in degenerate conditions on top of the white dwarf

- **P_{rec} ~ 10^4-10^5 yr**
- rate ~ *35*/yr in our Galaxy (MW)

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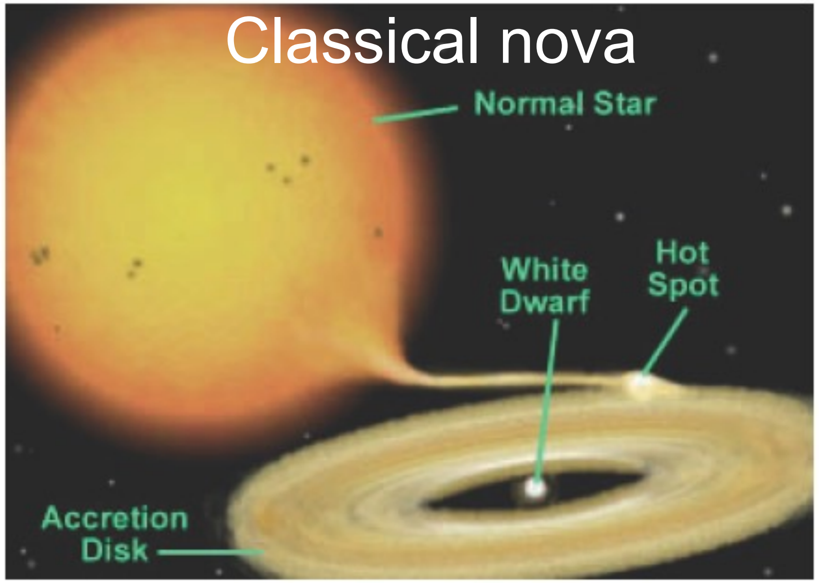

- **P_{rec} ~ 10^4-10^5 yr**
- rate ~ *35/yr* in our Galaxy (MW)

Hydrogen burning in degenerate conditions on top of the white dwarf

Symbiotic binary:

WD + Red Giant (P_{orb} ~100 days)

Accretion from a red giant wind (& disk)

- **P_{rec} < 100 yrs**
- **Occur on massive WDs & M_{wd} can increase → possible SNIa scenarios**

Two types of gamma-ray emission from novae

- Radioactivity in the ejecta:
  - traces nucleosynthesis directly
  - photons with ***E ~ MeV*** expected
  - not detected yet (*CGRO/Comptel, INTEGRAL/SPI*)

Two types of gamma-ray emission from novae

- Radioactivity in the ejecta:
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- Particle acceleration in strong external shocks between ejecta and circumstellar material (or internal shocks within the ejecta):
  - red giant wind in symbiotic recurrent nova
  - "dense circumstellar matter"
  - IC (leptonic) or π^0 decay (hadronic) ➔ photons with ***E>100 MeV***
  - detected with *Fermi/LAT* (now in several novae) - and also in VHE γ-rays in **RS Oph in 2021 (MAGIC, HESS, ...)**

High Energy (HE) Gamma-rays:
E > 100 MeV
"Fermi/LAT - GeV novae”

First evidence of particle acceleration - protons & electrons - to TeV energies in novae found before Fermi launch: RS Oph outburst in 2006

EVIDENCE FOR NONLINEAR DIFFUSIVE SHOCK ACCELERATION OF COSMIC RAYS IN THE 2006 OUTBURST OF THE RECURRENT NOVA RS OPHIUCHI

V. TATISCHEFF[1] AND M. HERNANZ

ApJL 2007

- RS Oph: symbiotic recurrent nova (WD + RG companion)
- Previous recorded (missed) eruptions: 1898, (1907), 1933, (1945), 1958, 1967
- Two latest nova eruptions (in February 2006): 1985 & 2006 (P_{rec} = 21 yrs, to be compared to 10^4-10^5 yrs in classical novae)
- P_{orb} = 456 days d $\approx$ 1.6 kpc (2.4 kpc)
- **Expanding shock wave sweeps red giant wind**

➢ *Newer eruption: August 2021 → P_{rec} = 15 yrs*

First evidence of particle acceleration - p & e - to TeV energies in novae

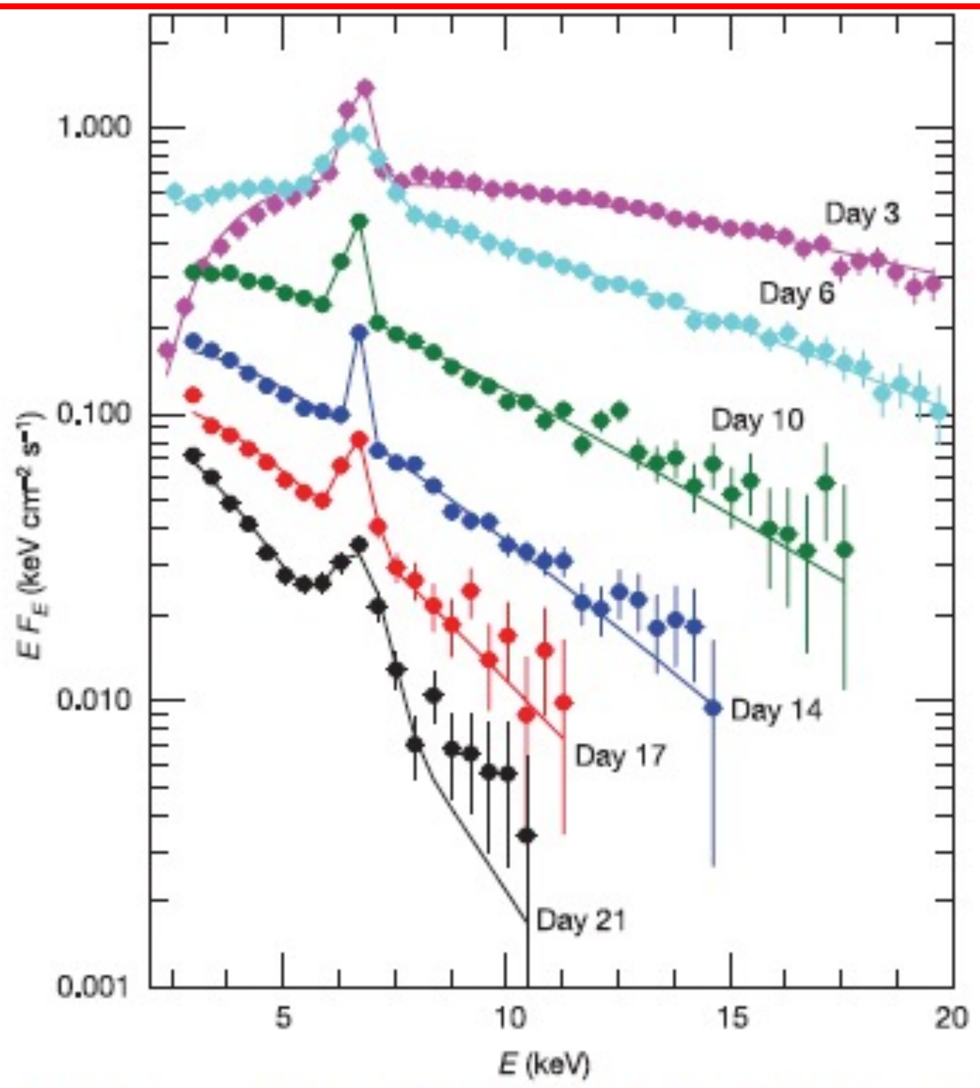
RS Oph outburst in 2006: blast wave evolution

RS Oph observations with RXTE/PCA:

X-ray spectra at various times (first 3 weeks)

→ T_{shock} (t)

Sokoloski et al. Nature (2006)



First evidence of particle acceleration - p & e - to TeV energies in novae
RS Oph outburst in 2006: blast wave evolution

Velocities (t)

- IR (Das et al 2006, Evans et al. 2007)
- X-rays, RXTE & Swift (Sokoloski et al. 2006, Bode et al. 2006)

Two caveats:

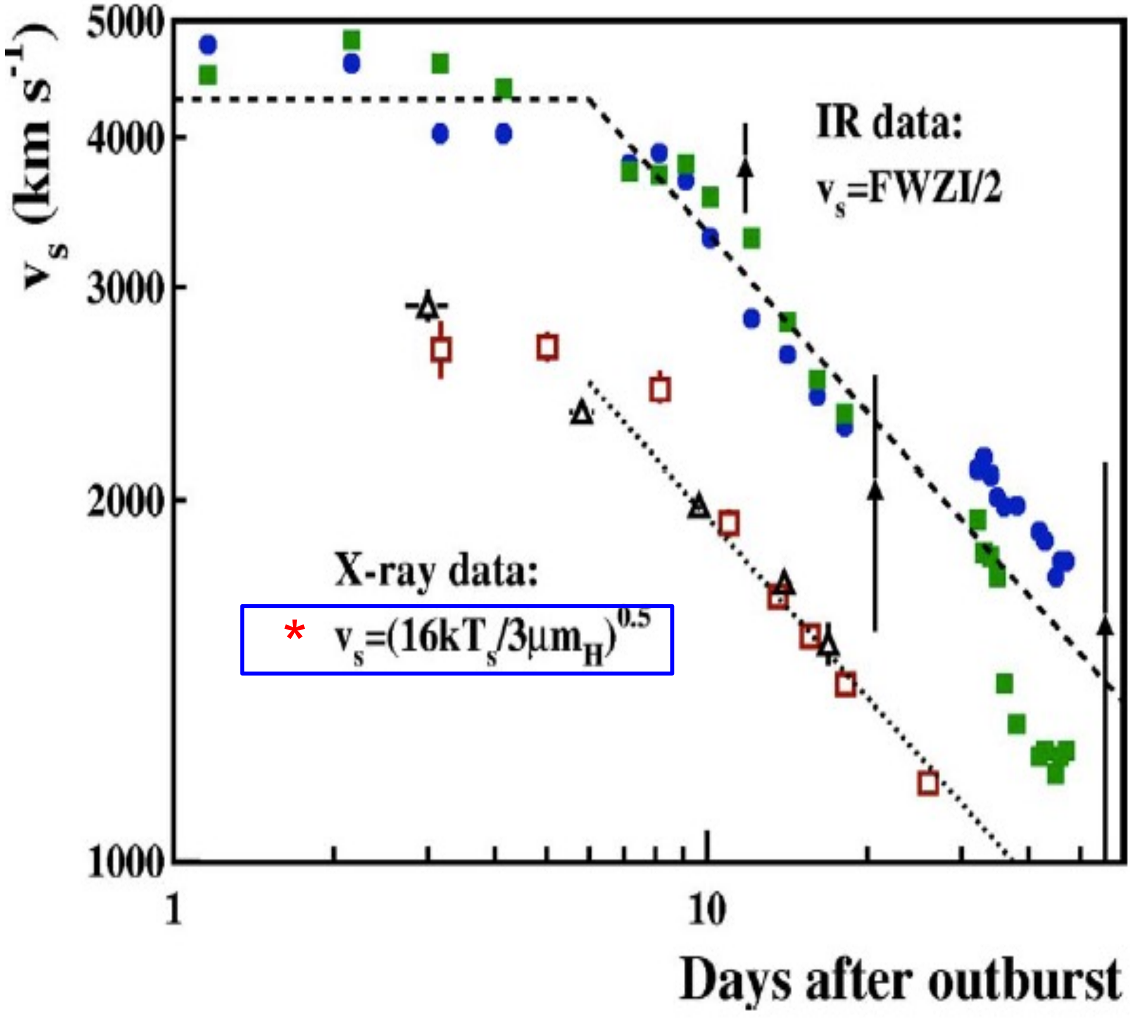
❑ v (X-rays) < v (IR)

*v_{shock} (X-rays) valid for test-particle adiabatic shock, but underestimates v_{shock} when particle acceleration is efficient

❑ After day 6, forward shock cooled very ("too") fast:

$t^{-1/2}$ (radiative phase) instead of $t^{-1/3}$ (adiabatic phase)

➢ acceleration of particles in the blast wave - escape of the highest E ions from the shock region



Tatischeff & Hernanz, ApJL (2007)

ICE CSIC EXCELENCIA MARÍA DE MAEZTU IEEC

First evidence of particle acceleration - p & e - to TeV energies in nova found before Fermi launch: RS Oph outburst in 2006

- Acceleration of particles (p and e) to TeV energies in a nova - RS Oph (2006) - demonstrated for the first time
- Explains why the observed cooling of the shock started so early (6 days after outburst)
- Reconciles shock velocities deduced from X-ray data with those measured from broad IR lines
- **Emission of HE & VHE gamma-rays**
- "Miniature SN remnant"- much dimmer & evolving much faster ➔ study of time dependence *of cosmic ray acceleration in a blast wave is possible*
  - *Nova remnant vs SN remnant – like μQSO vs QSO*

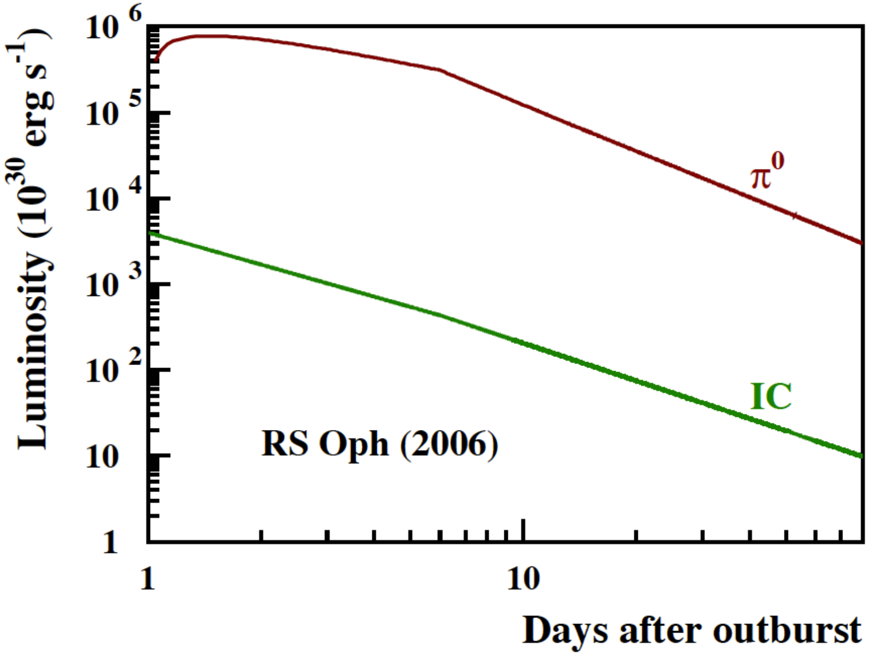
Tatischeff & Hernanz, ApJL (2007)

RS Oph (2006): predicted HE gamma-ray emission

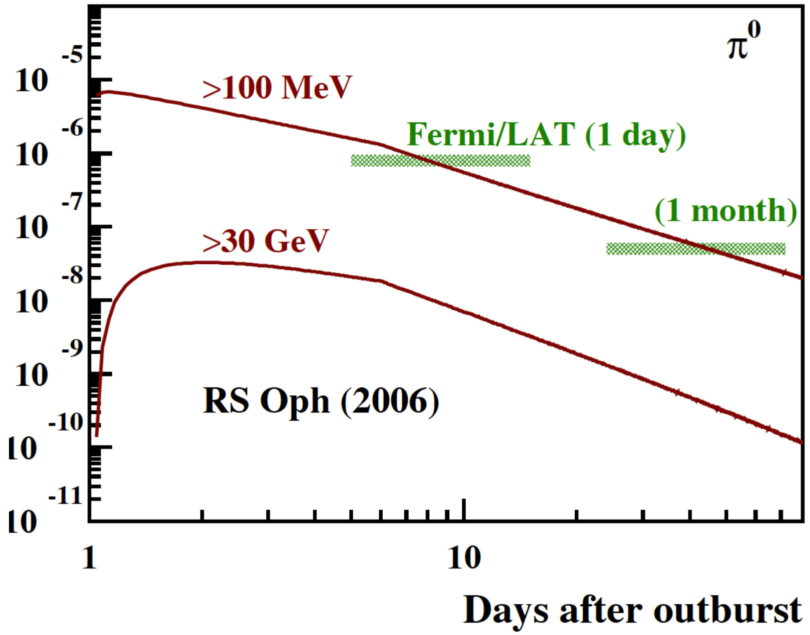
- π^0 production: (p-p collisions; hadronic)
- IC contribution: (e^- -photons; leptonic) derived from non thermal synchrotron (radio) and ejecta L_{ej}~L_{Edd}

➔ π^0 production dominates

RS Oph would have been detected by Fermi in 2006 - but it was not yet launched



- *V.Tatischeff, MH, ApJL 2007*
- *VT&MH, Cospar Symposium 2008*
- *MH,V.Tatischeff, Balt. Astr. 2011 (arXiv:1111.4129)*



First Nova detected in (HE) gamma-rays, by Fermi/LAT - E>100 MeV

Gamma-Ray Emission Concurrent with the Nova in the Symbiotic Binary V407 Cygni

SCIENCE VOL 329 13 AUGUST 2010

The Fermi-LAT Collaboration*†

Novae are thermonuclear explosions on a white dwarf surface fueled by mass accreted from a companion star. Current physical models posit that shocked expanding gas from the nova shell can produce x-ray emission, but emission at higher energies has not been widely expected. Here, we report the Fermi Large Area Telescope detection of variable γ-ray emission (0.1 to 10 billion electron volts) from the recently detected optical nova of the symbiotic star V407 Cygni. We propose that the material of the nova shell interacts with the dense ambient medium of the red giant primary and that particles can be accelerated effectively to produce π^0 decay γ-rays from proton-proton interactions. Emission involving inverse Compton scattering of the red giant radiation is also considered and is not ruled out.

Fermi establishes classical novae as a distinct class of gamma-ray sources

The Fermi-LAT Collaboration*†

Science **345**, 554 (2014)

A classical nova results from runaway thermonuclear explosions on the surface of a white dwarf that accretes matter from a low-mass main-sequence stellar companion. In 2012 and 2013, three novae were detected in γ rays and stood in contrast to the first γ-ray–detected nova V407 Cygni 2010, which belongs to a rare class of symbiotic binary systems. Despite likely differences in the compositions and masses of their white dwarf progenitors, the three classical novae are similarly characterized as soft-spectrum transient γ-ray sources detected over 2- to 3-week durations. The γ-ray detections point to unexpected high-energy particle acceleration processes linked to the mass ejection from thermonuclear explosions in an unanticipated class of Galactic γ-ray sources.

- *V407 Cyg: WD + red giant system (symbiotic binary, RG wind)*
- *CNe: WD + MS (cataclysmic variable, no wind) also detected by Fermi at E>100 MeV*

Science **345**, 554 (2014)

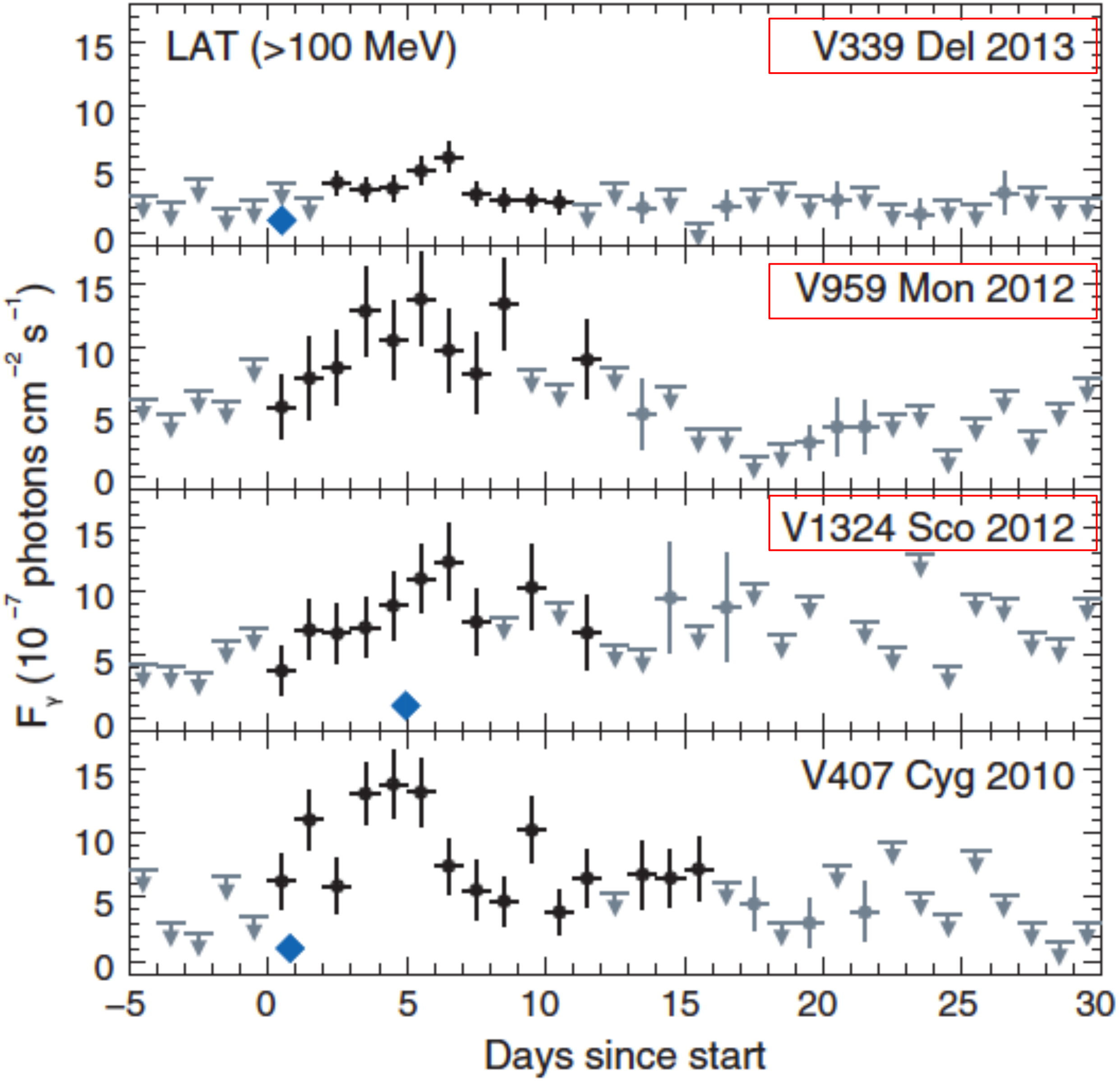


Fig. 2. Fermi-LAT 1-day binned light curves of the four γ-ray detected novae. Vertical bars indicate 1 σ uncertainties for data points with >3 σ (black) and 2 to 3 σ (gray) significances; otherwise, 2 σ upper limits are indicated with gray arrows. Start times t_s (from top to bottom panels) of 16 August 2013, 19 June 2012, 15 June 2012, and 10 March 2010 were defined as the day of the first γ-ray detection. In V339 Del, there was a 2.4 σ detection in 0.5-day binned data beginning 16.5 August (*13*), the epoch of the optical peak (blue diamond in each panel).

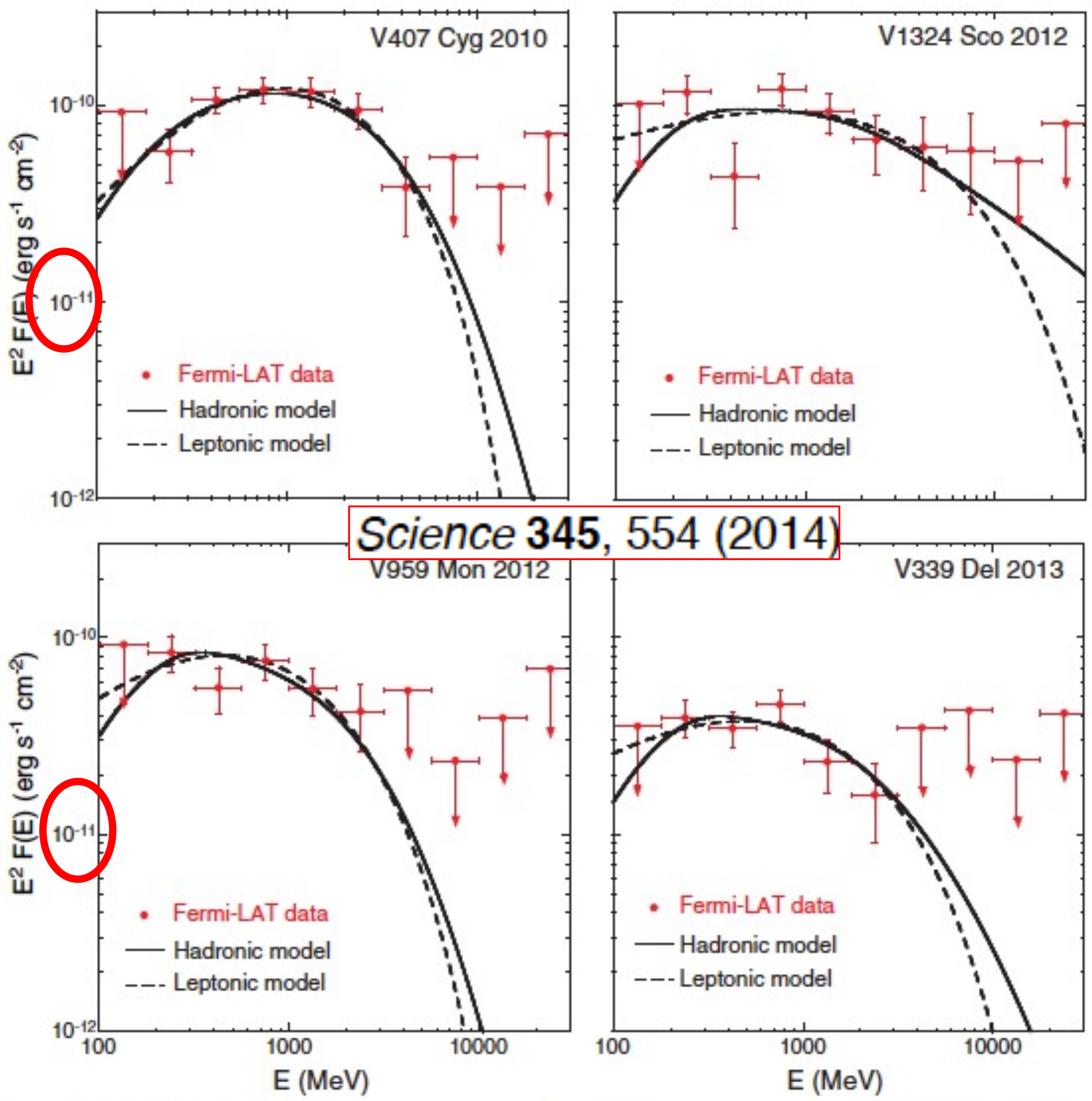


Fig. 3. Fermi-LAT >100-MeV average γ-ray spectra of the four novae over the full 17- to 27-day durations. Vertical bars indicate 1 σ uncertainties for data points with significances >2 σ otherwise, arrows indicate 2 σ limits. The best-fit hadronic and leptonic model curves are overlaid.

Discrimination between hadronic and leptonic emission models requires a sensitivity of **~10^{-11} erg cm^{-2} s^{-1} at 30 MeV in ~10 days** (P. Jean priv. comm.)

Should be possible with e-ASTROGAM not approved by ESA – now re-proposed as AS-ASTROGAM

AMEGO?

FERMI-LAT GAMMA-RAY DETECTIONS OF CLASSICAL NOVAE V1369 CENTAURI 2013 AND V5668 SAGITTARII 2015

Cheung et al. ApJ (2016)

- Dimmer and with longer duration
- Multiple peaks in optical and gamma-ray light curves

see more details later about comparison of optical and γ-ray light curves

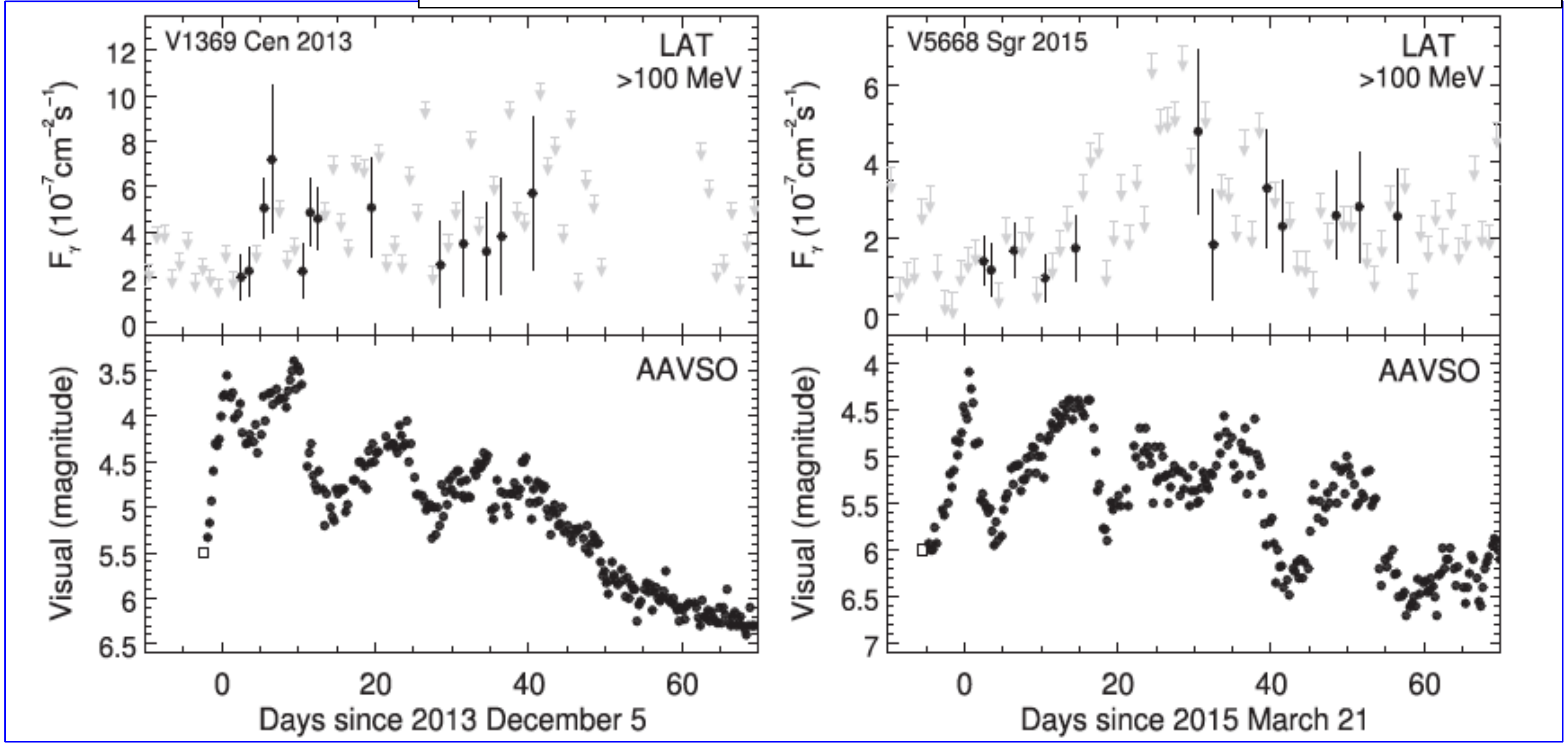


Figure 1. *Fermi*-LAT 1-day bin >100 MeV γ-ray (top panels) and optical (bottom panels) light curves for V1369 Cen (left) and V5668 Sgr (right). For the LAT data, vertical lines indicate 1σ uncertainties when TS $\geqslant$ 4.0 and gray arrows indicate 2σ upper limits when TS < 4.0 (see Appendix A for tabulated fluxes, TS values, and corresponding exposures). The optical discovery measurements (open squares) are shown separately from the subsequent 0.25-day bin averaged data extracted from the AAVSO database (filled circles).

Mechanism of particle acceleration in classical novae: not fully understood yet

Metzger et al., 2015, MNRAS

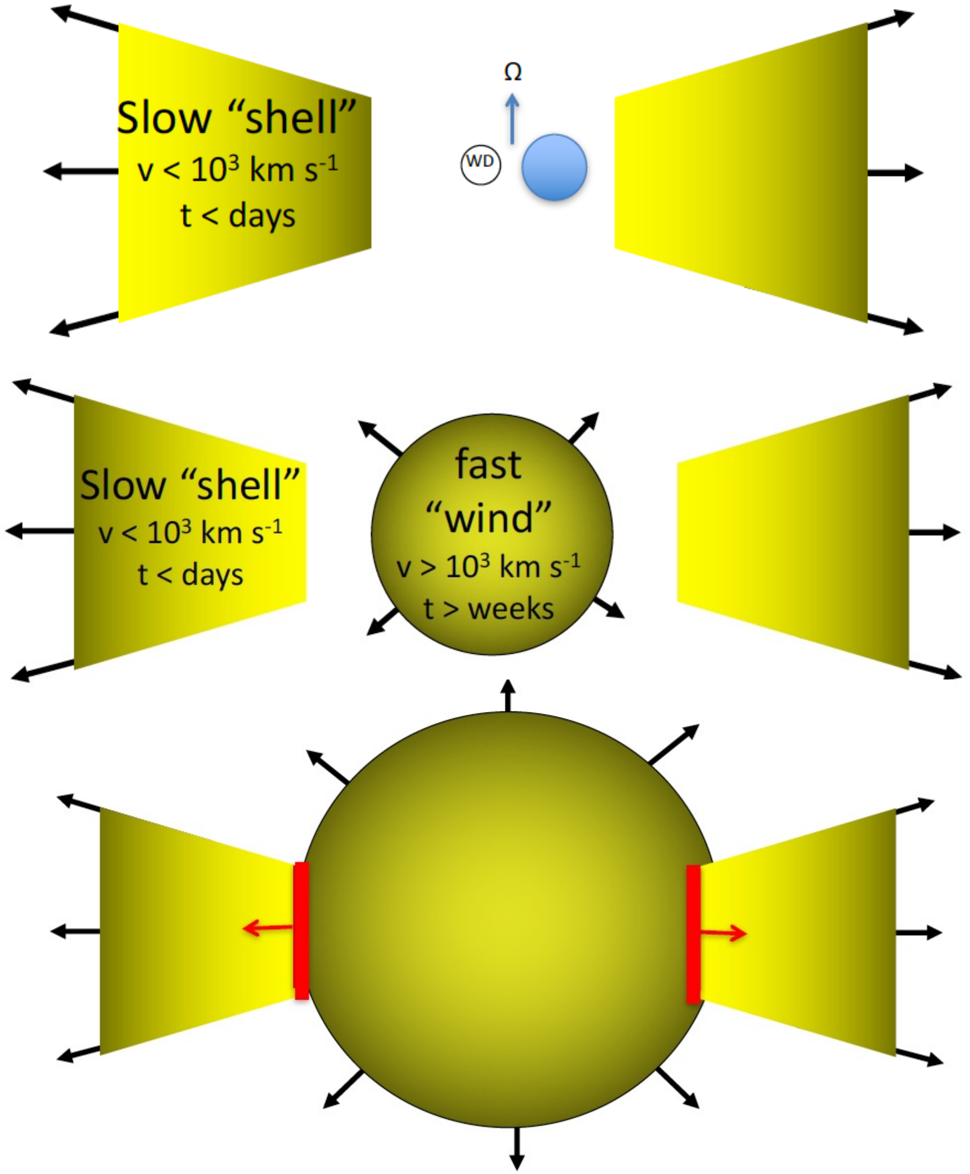
- Slow shell ejected first (equatorial "belt" shaped by binary orbit)
- Fast wind sweeps that shell: shocks, revealed by radio *(see next slide)*

Figures from B. Metzger: "Shocks in novae and supernovae" - Meeting at Columbia University, June 2017

➢ see also later

see also Martin, Dubus, Tatischeff, Dosne, 2018, A&A

Geometry of Classical Nova Shocks



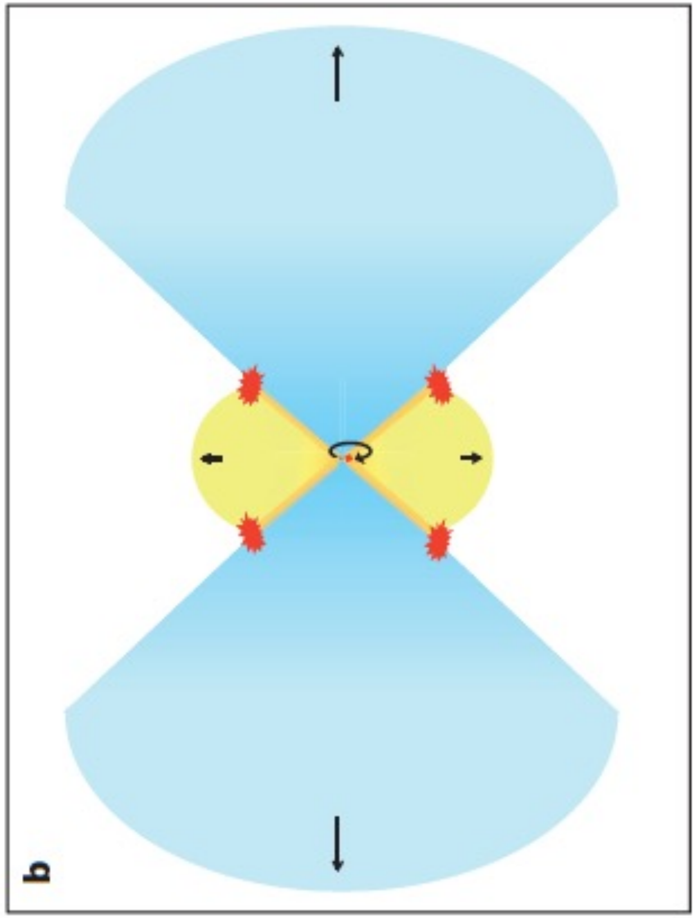
Mechanism of particle acceleration in classical novae not fully understood

Binary orbits as the driver of γ-ray emission and mass ejection in classical novae

Laura Chomiuk[1], Justin D. Linford[1], Jun Yang[2,3,4], T. J. O'Brien[5], Zsolt Paragi[3], Amy J. Mioduszewski[6], R. J. Beswick[5], C. C. Cheung[7], Koji Mukai[8,9], Thomas Nelson[10], Valério A. R. M. Ribeiro[11], Michael P. Rupen[6,12], J. L. Sokoloski[13], Jennifer Weston[13], Yong Zheng[13], Michael F. Bode[14], Stewart Eyres[15], Nirupam Roy[16] & Gregory B. Taylor[17]

Nature, 2014

ejecta. Here we report high-resolution radio imaging of the γ-ray-emitting nova V959 Mon. We find that its ejecta were shaped by the motion of the binary system: some gas was expelled rapidly along the poles as a wind from the white dwarf, while denser material drifted out along the equatorial plane, propelled by orbital motion[6,7]. At the interface between the equatorial and polar regions, we observe synchrotron emission indicative of shocks and relativistic particle acceleration, thereby pinpointing the location of γ-ray production. Binary shaping of the nova ejecta and associated internal shocks are expected to be widespread among novae[8], explaining why many novae are



Annual Review of Astronomy and Astrophysics

New Insights into Classical Novae

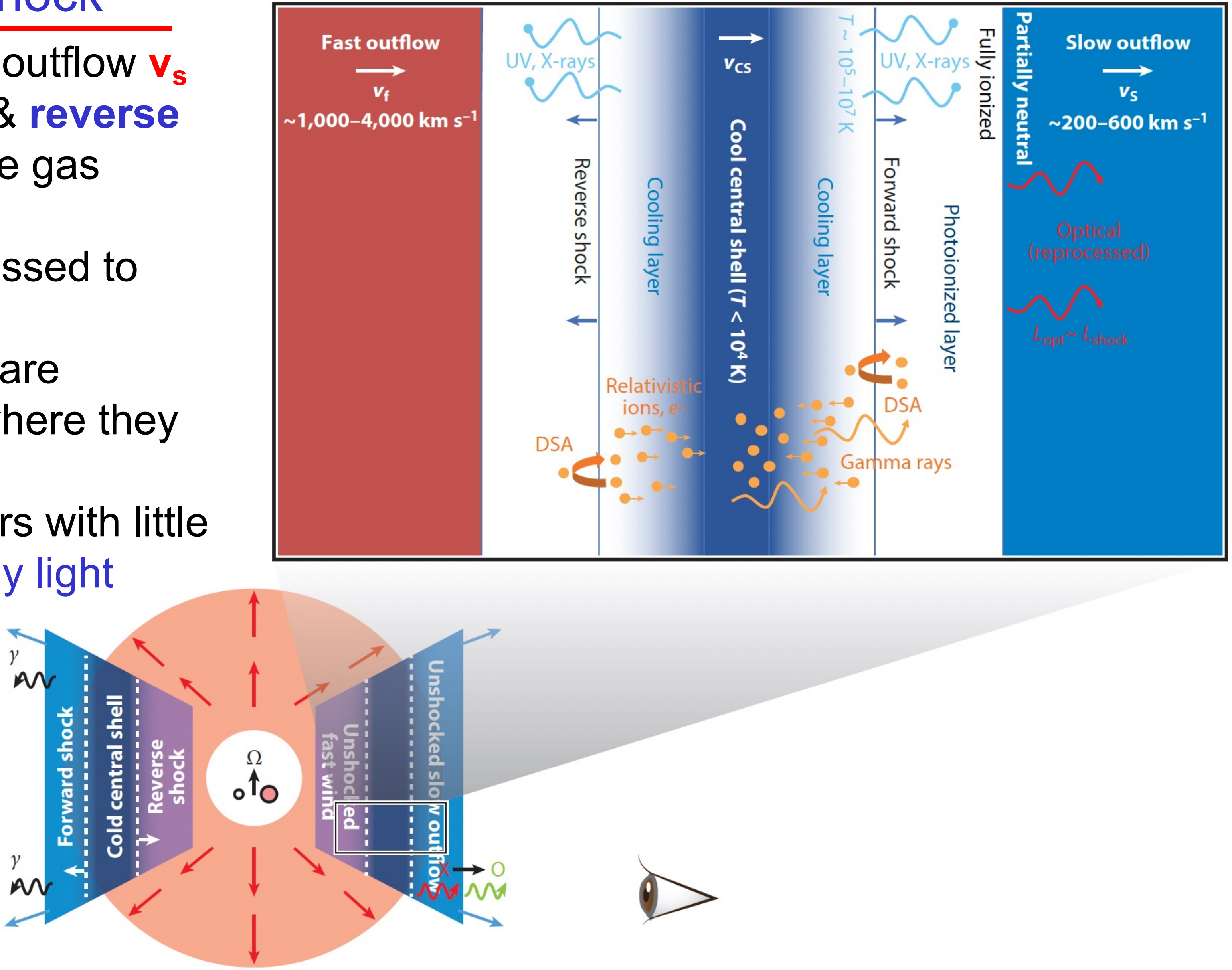
Laura Chomiuk,[1] Brian D. Metzger,[2] and Ken J. Shen[3]

Annu. Rev. Astron. Astrophys. 2021, 59: 391-444

Contents

"Anatomy of a nova internal shock"

- ❖ Fast outflow $\mathbf{v_f}$ collides with slower outflow $\mathbf{v_s}$ → **forward shock** (into slow flow) & **reverse shock** (into fast flow): heating of the gas
- Gas cools via UV & X-rays
- UV & X-rays absorbed and reprocessed to UVOIR
- ❖ e & ions accelerated at the shocks are advected to the cold central shell where they **emit γ-rays**
- Optical and γ-rays production occurs with little delay → correlated optical and γ-ray light curves



Chomiuk, Metzger & Chen (2021)

Figure 13 in ARAA, adapted from Metzger et al. 2015

Novae detected by Fermi: comparison of optical and γ-ray light curves

Chomiuk, Metzger & Chen (2021)

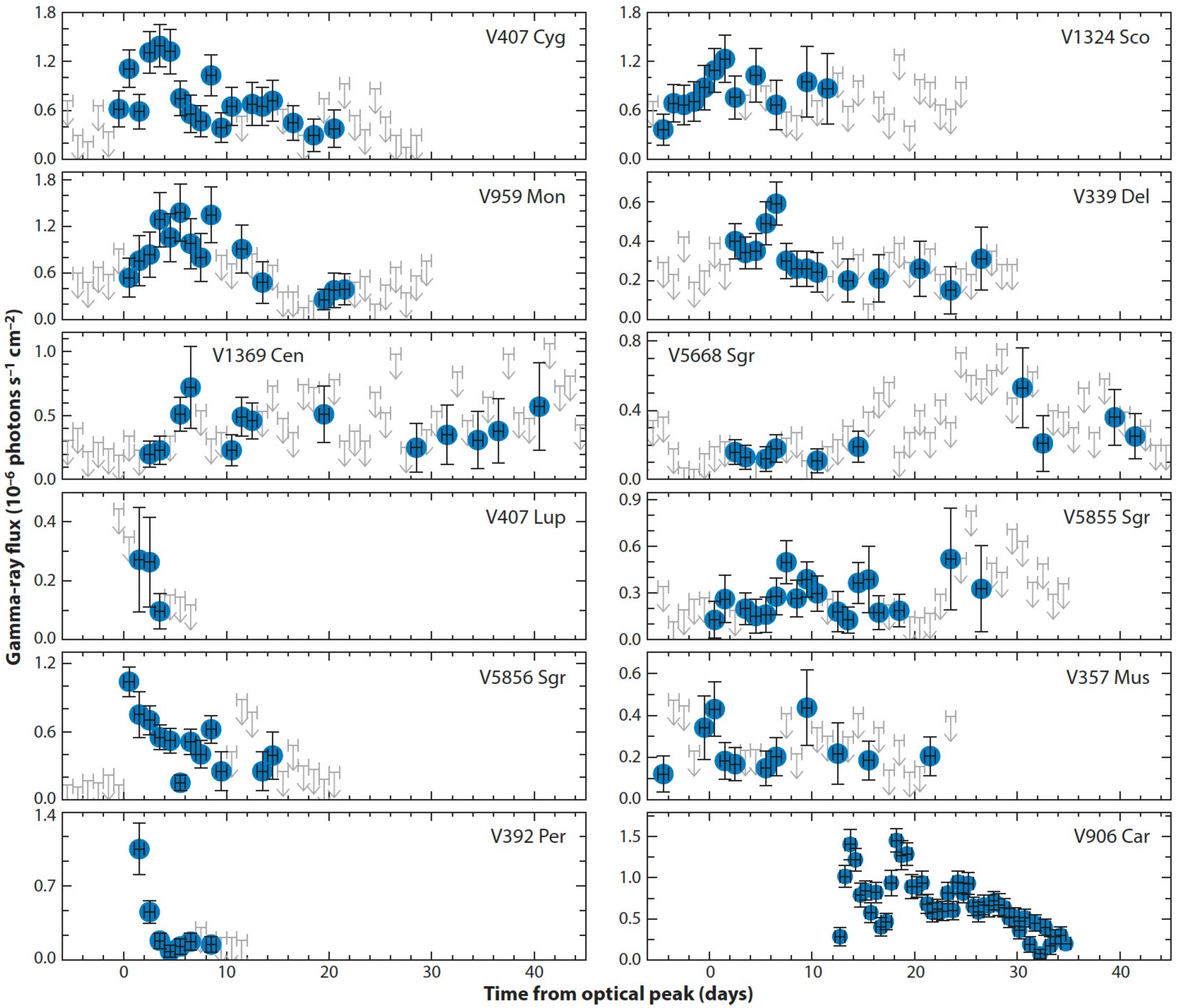


Figure 8

GeV gamma-ray light curves for 12 novae, as measured by *Fermi*-LAT (*Fermi* Large Area Telescope) for photon energies >100 MeV. Dates with >2σ significance detections are marked as black dots, whereas 95% upper limits are plotted as gray arrows for nondetections. Plotted times are relative to optical light curve maximum, except in the case of V959 Mon, which was discovered with *Fermi* during solar conjunction; in this case $t = 0$ marks the first gamma-ray detection. Due to a solar panel issue, there are no *Fermi*-LAT data available before the gamma-ray detections of V392 Per and before or after the gamma-ray detections of V906 Car.

Novae detected by Fermi: spectral properties

Novae detected up to 4.5 kpc

Chomiuk, Metzger & Chen (2021)

Supplemental Table 1: Gamma-Ray Detected Novae (>3σ Significance)

Nova	D (kpc)	t_γ^a (days)	Γ^b	E_c^c (GeV)	F_γ (10^{-7} cm^{-2} s^{-1})	
V407 Cyg 2010	3.5 ± 0.3	22	1.3 ± 0.2	2.0 ± 0.5	3.5 ± 0.4	1,14,20
V1324 Sco 2012	> 6.5	17	1.9 ± 0.2	7.7 ± 4.7	4.4 ± 0.9	2,14,21
V959 Mon 2012	1.4 ± 0.4	22	1.5 ± 0.3	1.3 ± 0.5	2.6 ± 0.5	2,14,22
V339 Del 2013	4.5 ± 0.6	27	1.7 ± 0.2	3.0 ± 1.8	1.5 ± 0.2	2,14,23
V1369 Cen 2013	$\sim$2	39	2.0 ± 0.3	2.0 ± 1.0	2.5 ± 0.5	3,14,24
V5668 Sgr 2015	2.8 ± 0.5	55	2.1 ± 0.1	-	0.6 ± 0.1	3,14,5
V407 Lup 2016[e]	4.2 ± 0.5	3	2.2 ± 0.3	-	1.6 ± 0.7	4,5
V5855 Sgr 2016	$\sim$4.5	26	2.3 ± 0.1	-	3.0 ± 0.8	6
V5856 Sgr 2016[f]	2.5 ± 0.5	15	1.9 ± 0.1	5.9 ± 2.6	5.4 ± 0.5	7,5
V549 Vel 2017[g]	>4	33	1.8 ± 0.2	-	0.4 ± 0.2	8,5
V357 Mus 2018	3.2 ± 0.5	27	2.2 ± 0.1	-	1.3 ± 0.2	5
V906 Car 2018[h]	4.0 ± 1.5	> 20[i]	1.8 ± 0.1	5.9 ± 1.1	12.2 ± 0.4	9
V392 Per 2018	$4.1^{+2.3}_{-0.4}$	$\gtrsim$8[j]	2.0 ± 0.1	-	2.2 ± 0.4	10,25
V1707 Sco 2019	>6	5	2.1 ± 0.2	-	2.9 ± 1.0	11,12
YZ Ret	2.7 ± 0.4	18	2.2 ± 0.1	-	2.6 ± 0.2	12,13,26

[a]Duration over which gamma-rays were detected at $> 2\sigma$ confidence, when light curves are binned at 1 day cadence. [b]Gamma-ray photon index. [c]Cut-off energy to a power-law gamma-ray spectrum (if an exponential cut-off yields a better fit than a simple power law). [d]Average photon flux over the time period t_γ, for photon energies >100 MeV. [e]ASASSN-16kt; [f]ASASSN-16ma; [g]ASASSN-17mt; [h]ASASSN-18fv; [i]This is a lower limit; LAT observations were not available for roughly 3 weeks before, and roughly 2 weeks after the gamma-ray detection interval. [j]This is a lower limit; LAT observations were not available for roughly 2 weeks before the gamma-ray detection interval.

Summary

Before RS Oph 2021 outburst:

- High-E gamma-ray observations probe the mechanism of mass ejection in novae
- Comparison with SNRs: same phases but with shorter evolutionary timescales
- Contemporaneous multiwavelength coverage is crucial (radio, IR, X)
- HE gamma-rays: ASTROGAM - AMEGO? would represent an important step forward for the understanding of the process of particle acceleration in novae, e.g., leptonic versus hadronic, and nova mass outflows in general (*especially for those non detectable in VHE gamma-rays*)

RS Oph 2021 outburst:

- Detection with Fermi/LAT (not new in novae): it's the brightest nova in GeV gamma-rays ever
- Detection at VHE gamma-rays (1st time for novae) with MAGIC, HESS, ...
- Shown that p acceleration occurs, as predicted in the 2006 previous RS Oph eruption in 2006

➢ *See presentations this afternoon*