FERMI-LAT GAMMA-RAY DETECTION OF THE RECURRENT NOVA RS OPHIUCHI DURING ITS 2021 OUTBURST

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ABSTRACT

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We report the *Fermi*-LAT γ-ray detection of the 2021 outburst of the symbiotic recurrent nova RS Ophiuchi. In this system, unlike classical novae from cataclysmic binaries, the ejecta from the white dwarf form shocks when interacting with the dense circumstellar wind environment of the red giant companion. We find the LAT spectra from 50 MeV to $\sim$20–23 GeV, the highest-energy photons detected in some sub-intervals, are consistent with π^0-decay emission from shocks in the ejecta as proposed by Tatischeff & Hernanz (2007) for its previous 2006 outburst. The LAT light-curve displayed a fast rise to its peak >0.1 GeV flux of $\simeq 6 \times 10^{-6}$ ph cm^{-2} s^{-1} beginning on day 0.745 after its optically-constrained eruption epoch of 2021 August 8.50. The peak lasted for $\sim$1 day, and exhibited a power-law decline up to the final LAT detection on day 45. We analyze the data on shorter timescales at early times and found evidence of an approximate doubling of emission over $\sim$200 minutes at day 2.2, possibly indicating a localized shock-acceleration event. Comparing the data collected by the AAVSO, we measured a constant ratio of $\sim 2.8 \times 10^{-3}$ between the γ-ray and optical luminosities except for a $\sim 5\times$ smaller ratio within the first day of the eruption likely indicating attenuation of γ rays by ejecta material and lower high-energy proton fluxes at the earliest stages of the shock development. The hard X-ray emission due to bremsstrahlung from shock-heated gas traced by the *Swift*-XRT 2–10 keV light-curve peaked at day $\sim$6, later than at GeV and optical energies. Using X-ray derived temperatures to constrain the velocity profile, we find the hadronic model reproduces the observed >0.1 GeV light-curve.

RS OPHIUCHI

- It's a symbiotic binary system with a 453.6 ± 0.4 day period consisting of a massive white dwarf ($1.2 - 1.4\ M_{\odot}$) and a red giant;
- It's the best studied recurrent nova because its numerous outburst (first detection in 1898);
- It has recurred at irregular intervals from 9 to 27 years;

Its 2006 outburst was well studied:

- X-ray $(2 - 25\ keV, 14 - 50\ keV)$ that indicated shocked emission in the nova eject;
- High-resolution radio imaging resolved the shocked regions;
- In gamma-rays, predicted high-energy particle acceleration in the nova ejecta from interactions with the dense RG wind that could have been observed in 2006 at GeV energies, but Fermi was launched in 2008.

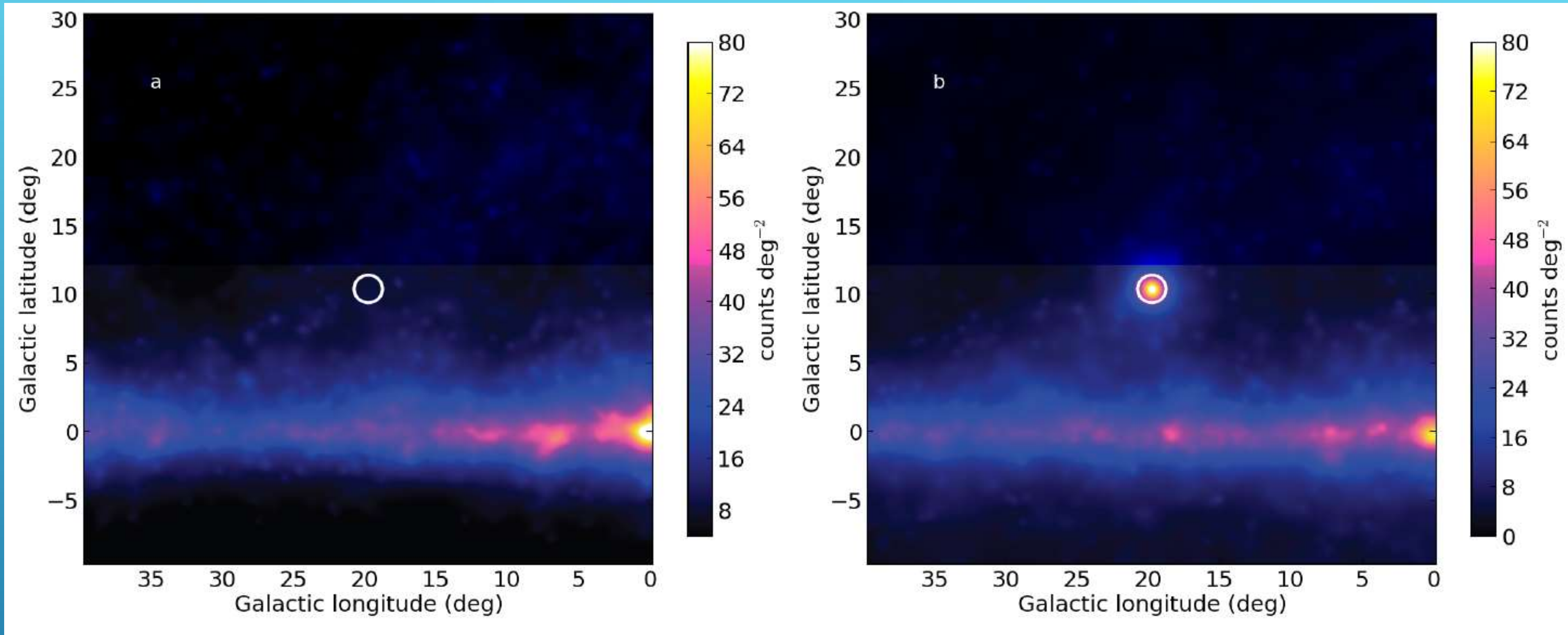
PREVIOUS 2006 OUTBURST

2021 OUTBURST

- The optical outburst was highly anticipated by multi-wavelenght observers, particularly its >0.1 GeV observations by Fermi-LAT
- Discovered in 2021
- Time since 2006 detection is 15.5 years

DATA ANALYSIS PREPARATION

- Photons with $0.05 - 300\ GeV$ energies, within 25° of R.A, Decl (J2000) = $267.7^{\circ} - 6.7^{\circ}$, and with a maximum zenith angle of 90° were selected;
- The ROI was choosen to put RS Oph near the center;
- Filtered the events to include only good time intervals, when LAT data were flagged as good and the instrument was in nominal science observations mode;
- Constructed a spatial and spectral model of the ROI starting from the 4FGL catalog based on the twelve years of LAT data. We included all DR3 sources within 35° of the ROI center as well as a model for the Galactic diffuse emission and a diffuse isotropic emission component.



July 29.0 to August 6.5

August 9.0 to 11.8

LAT counts map of $0.2 - 5\ GeV$ energy photons centered on the optical positions of RS Oph (1° radius in white).

It's relatively isolated from other 4FGL-DR3 sources and the Galactic diffuse emission. But close enough for contaminion by the latter at lowest energy.

- Added a point source at the optical position of the nova;
- Initially assuming a single PL spectral shape formula;
- Perform a binned maximum likelihood analysis (on a $35.3° \, x \, 35.3°$ square region, binning data into $0.1° \, x \, 0.1°$ pixels);

MODELING THE NOVA

- To refine our starting model, we fit a one-year dataset from 2020 July 19 to 2021 July 19, 20 days before t0;
- Fit over 0.05-300 GeV;
- Result: no significant detection at the position of the nova;
- Using this results, we created a new model of the region for the following 10-day spectral analyisis of the nova outburst.

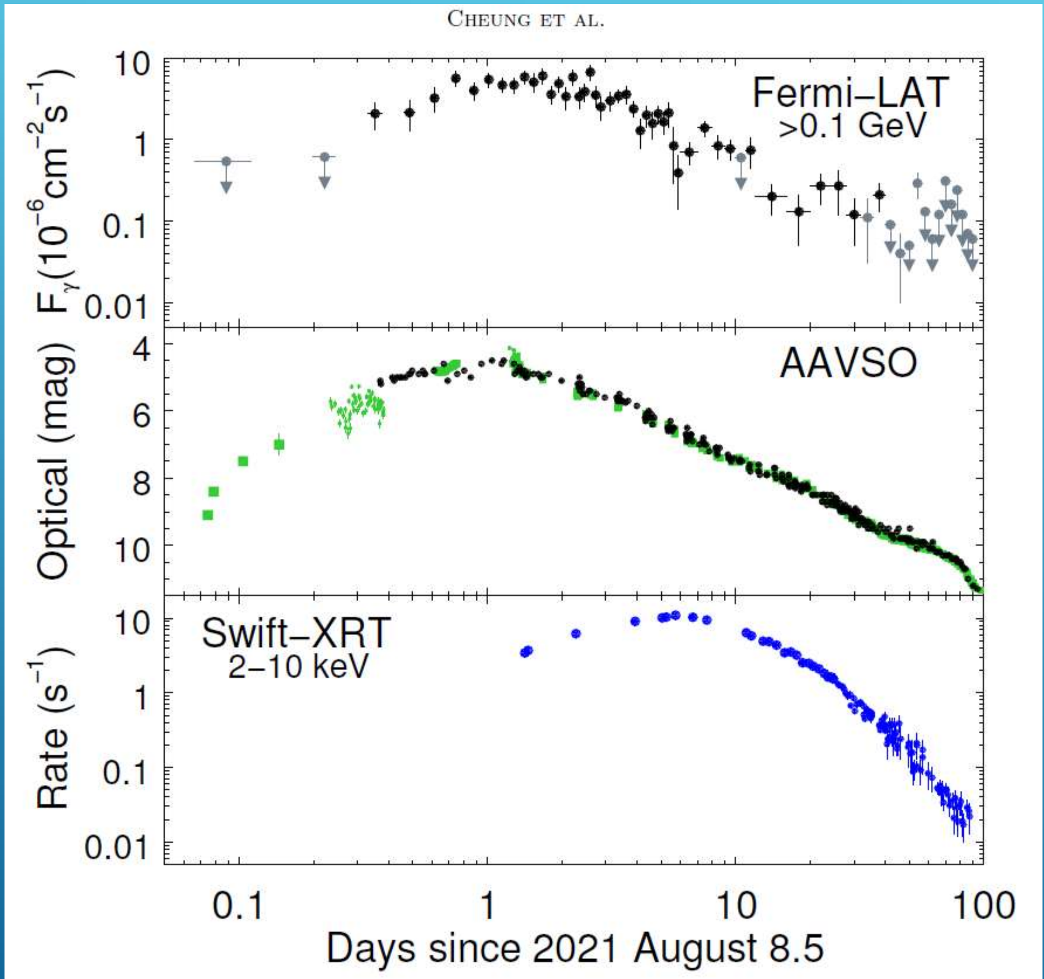
REFINE THE MODEL

- Previous analysis of gmma-ray novae found significative curvature in the spectrum → best fit model ECPL formula;
- To test the curvature → binned maximum likelihood analysis from 2021 August 8.5 to 18.5 (main activity) at $0.05 - 300\ GeV$ energies;
- To compare PL and ECPL spectrum, we analyzed the spectra with both the model and derived $TS_{curve} = -2(L_{ECPL} - L_{PL})$, as a measure of significance of curvature;
- $TS = 66$ → evidence of curvature in the spectrum → hadronic origin of the emission.

ECPL ANALYSIS

- We generated gamma-ray flux light-curves starting 20 days before the optical eruption epoch, t0 = 2021 August 8.5 and ending a t0+92 days, in 6-hr, 1-day and 4-day bins.
- Energies $> 0.1\ GeV$;
- In each time bin, we performed a binned maximum likelihood analysis (on 21.2° x 21.2° region, binned into pixels 0.1° on a side);
- For the nova used an ECPL model.

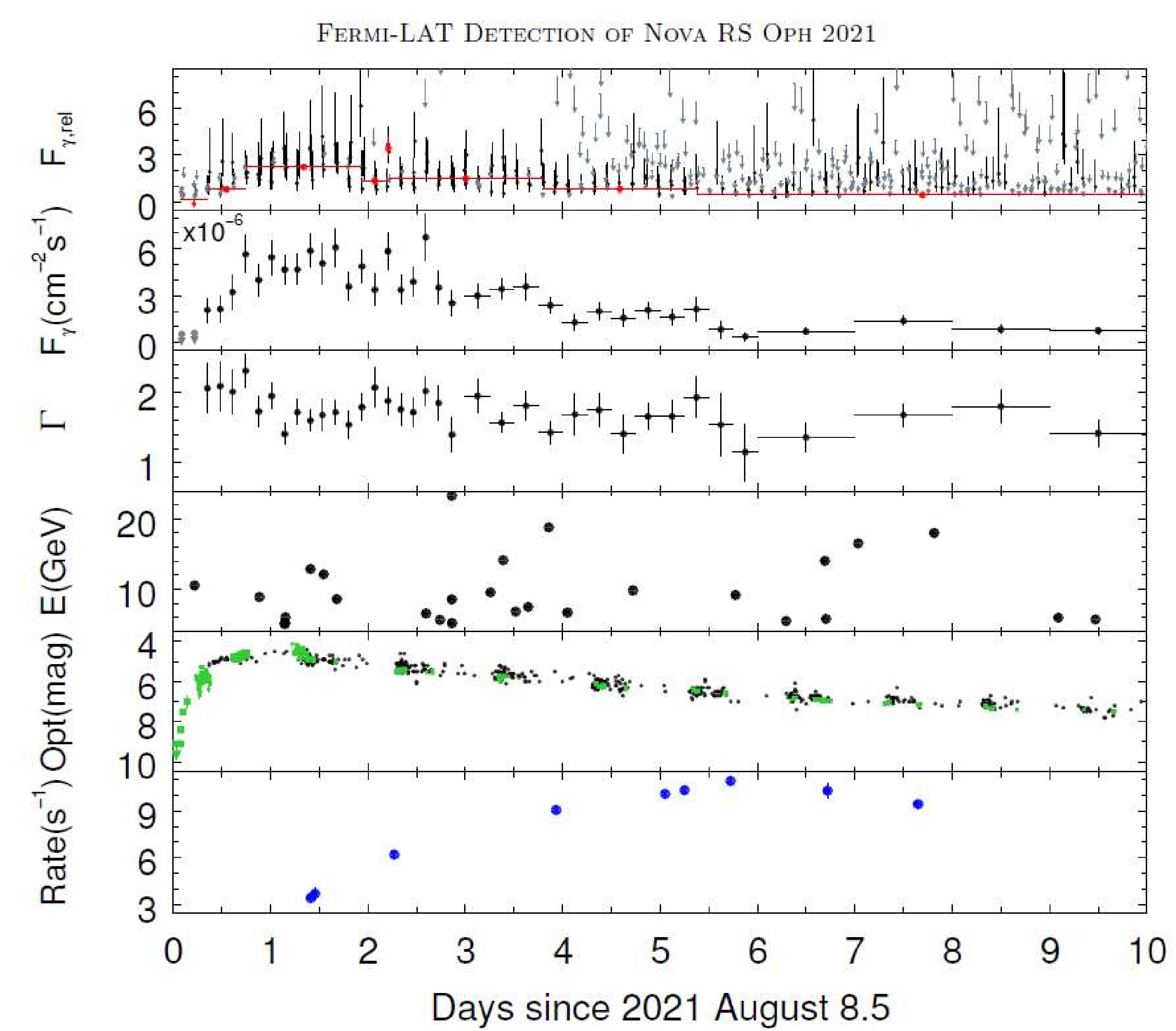
LAT LIGHT CURVES



Black points → significant detection at $TS \geq 12$.
Grey points → lower significance, in the 4-days analysis $TS = 6 - 12$.
Upper limits in wich the nova was found with $TS < 6$.

- We searched for variability on the shortest timescales in the first 10 days of LAT data, we estimated the likelihood as a function of only the nova flux in 10-minutes time-bins;
- We subsequently grouped these intervals into longer partitions with the Bayesian block algorithm;
- This analysis indicated a potential additional ~ 20 minutes duration feature at day 2.21 with $F_{\gamma,rel} = 3.45 \pm 0.54. > 2 \times$ brighter than the preceding day and subsequent day.

SHORTEST-TIMESCALE LAT ANALYSIS



LAT $> 0.1\ GeV$ light curve in 10-minutes bin.
Upper limits in gray arrows.
Bayesian Block partition indicated in red.

- We searched for the highest-energy LAT events from t0-20 to t0+92 days, selecting $> 5\ GeV$ photons within $0.5°$ from the optical positions of RS Oph;
- There are eight $> 10\ GeV$ LAT photons detected with gtsrcprob (probability of association calculated using best-fit ECPL model) of > 0.90;
- Highest energy photon is $23\ GeV$ on day 2.861, just after the flux peak.

HIGHEST-ENERGY LAT PHOTONS

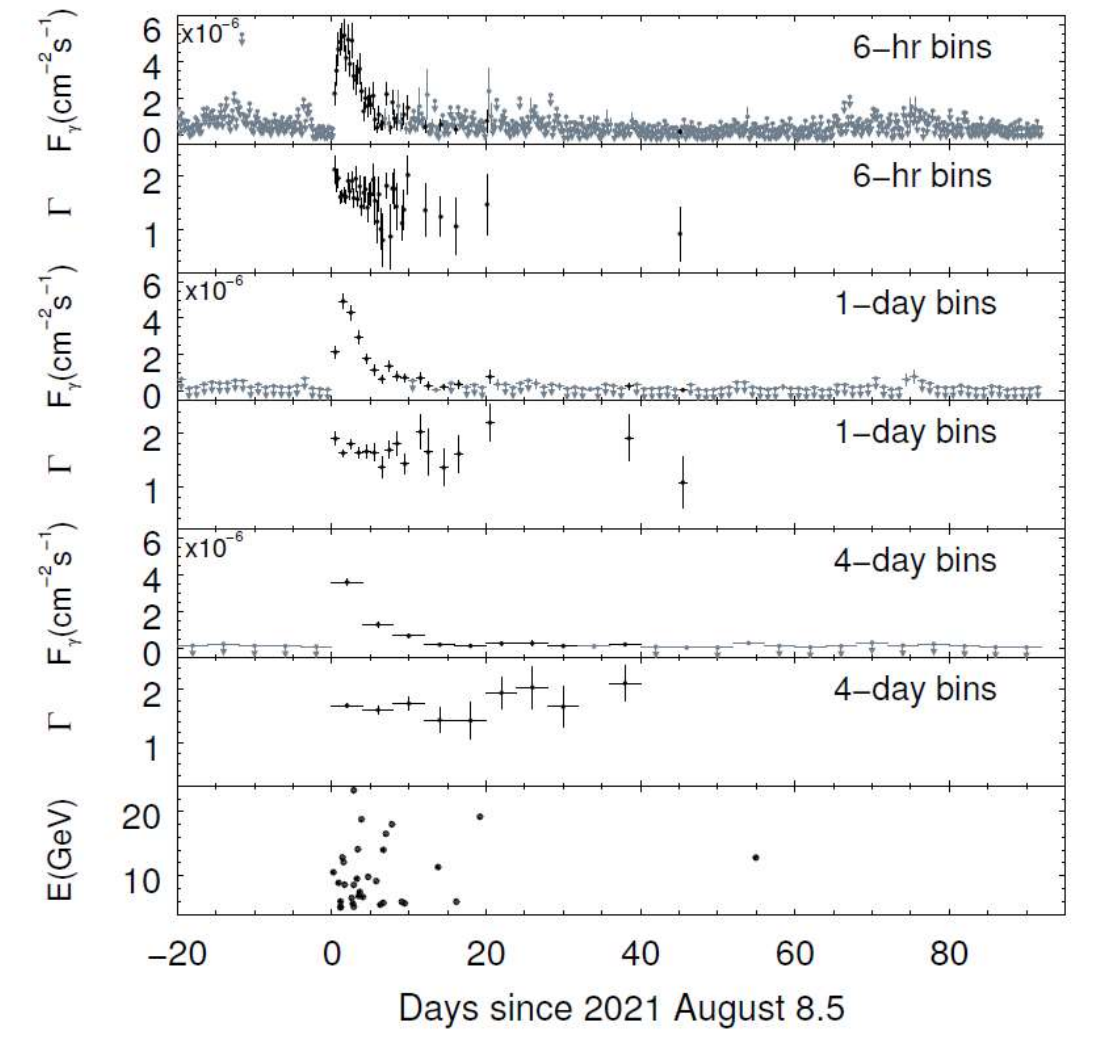
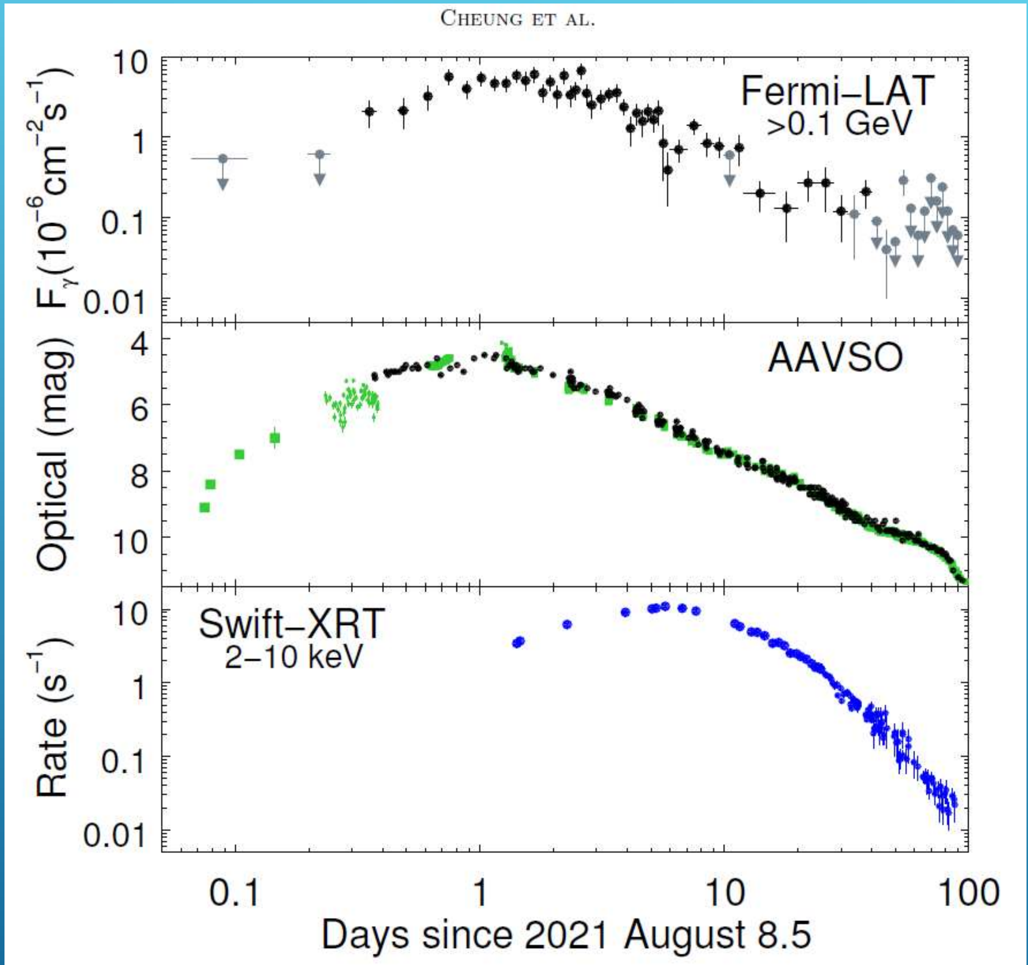


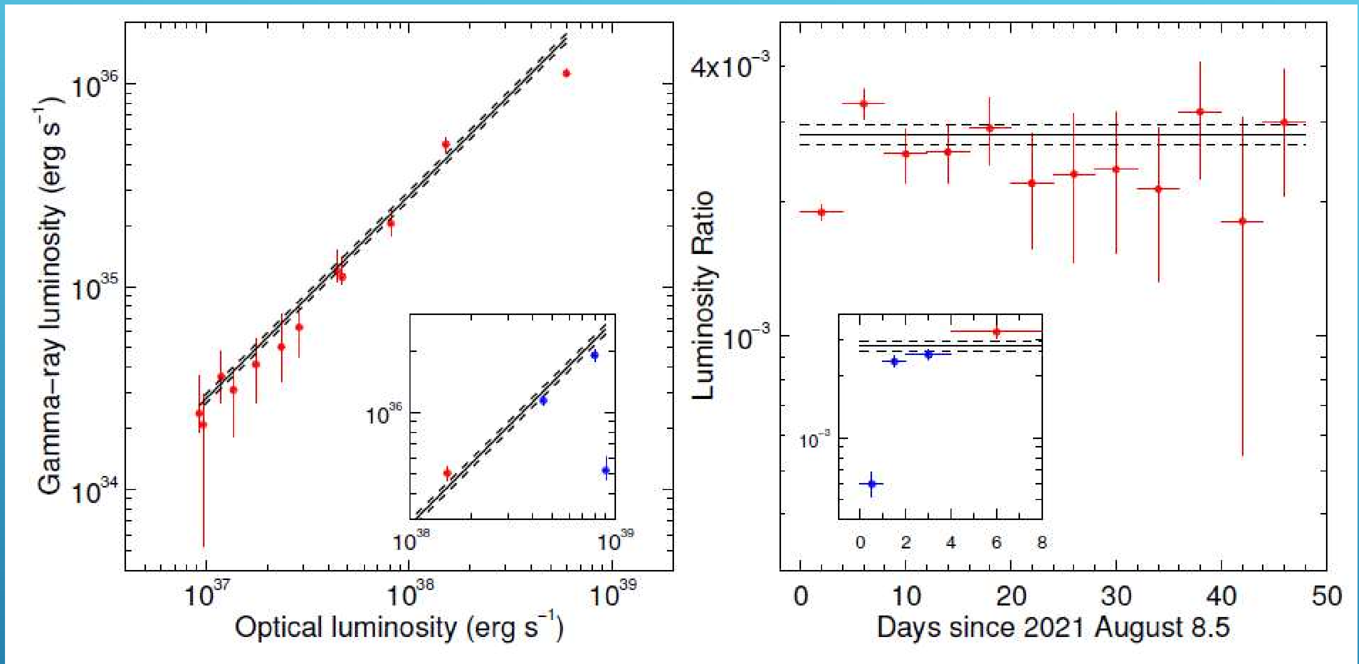
Table 2. Highest-energy LAT photons selected at $E > 5\,\text{GeV}$.

Day	MET (sec)	E (GeV)	gtsrcprob
0.222	650136003.9	10.54	0.957
0.887	650193475.7	8.90	0.998
1.146	650215820.9	5.07	0.999
1.151	650216236.4	5.19	0.999
1.155	650216600.8	6.01	0.999
1.411	650238679.9	12.86	0.998
1.546	650250356.7	12.12	0.999
1.681	650262005.6	8.61	0.999
2.597	650341199.0	6.55	0.968
2.740	650353560.9	5.65	1.000
2.861	650363956.4	23.32	0.999
2.861	650363998.8	8.57	0.997
2.863	650364171.6	5.18	0.969
3.260	650398494.0	9.53	0.999
3.391	650409765.4	14.12	0.999
3.518	650420734.2	6.84	0.999
3.645	650431699.5	7.48	0.996
3.859	650450260.5	18.80	0.971
4.049	650466613.6	6.69	0.992
4.721	650524733.6	9.83	1.000
5.774	650615677.8	9.17	0.996
6.295	650660671.4	5.48	0.999
6.692	650694990.2	14.03	1.000
6.703	650695986.1	5.78	0.998
7.034	650724541.4	16.54	0.881
7.815	650791983.0	18.02	0.916
9.090	650902208.1	5.95	0.999
9.471	650935065.6	5.70	0.999
13.776	651307020.6	11.35	0.978
16.147	651511940.3	5.96	1.000
19.205	651776094.4	19.20	0.996
54.945	654864060.0	12.83	0.847



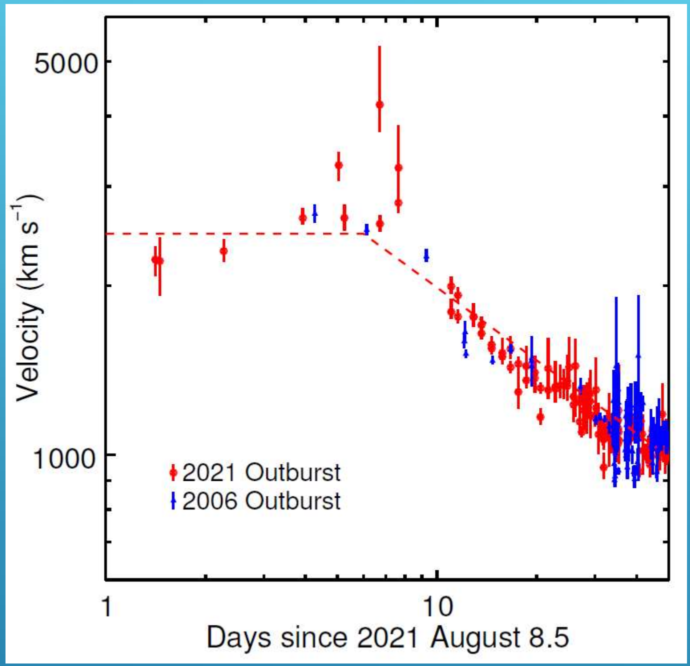
- The observed gamma-ray onset is constrained to the orbit centered on day 0.35, with a flux, $F_\gamma = (2.1 \pm 0.7) \times 10^{-6}\, ph\, cm^{-2}\, s^{-1}$;
- The sources rises to a peak $F_\gamma = (5.7 \pm 1.2) \times 10^{-6}\, ph\, cm^{-2}\, s^{-1}$ at day 0.745;
- The peak is flat, with an approximately constant and average $F \simeq 5 \times 10^{-6}\, ph\, cm^{-2}\, s^{-1}$ through to day 2.5;
- The flux declined by a factor of two from the day 0.745 flux value at approximately day 3;
- The total gamma ray duration was approximately 45 days;
- Gamma ray and optical light-curves are similar, both peaking early, while the X-rays peak later.

FERMI-LAT AND MULTIWAVELENGTH RESULTS



- We examined the best-fit gamma-ray luminosity in 4-day bins obtained from the LAT data analysis as a function of the observed optical luminosity estimated in 4-days bins using the AAVSO data;
- Luminosity are proportional to each other, except for the largest luminosity value;
- The ratio of the gamma-ray to optical luminosities in RS Oph are similar to those derived for classica novae;
- Blue points are reanalysis of the first 4-day bin in smaller time intervals (day 0-1,1-2,2-4)

FERMI-LAT AND MULTIWAVELENGTH RESULTS

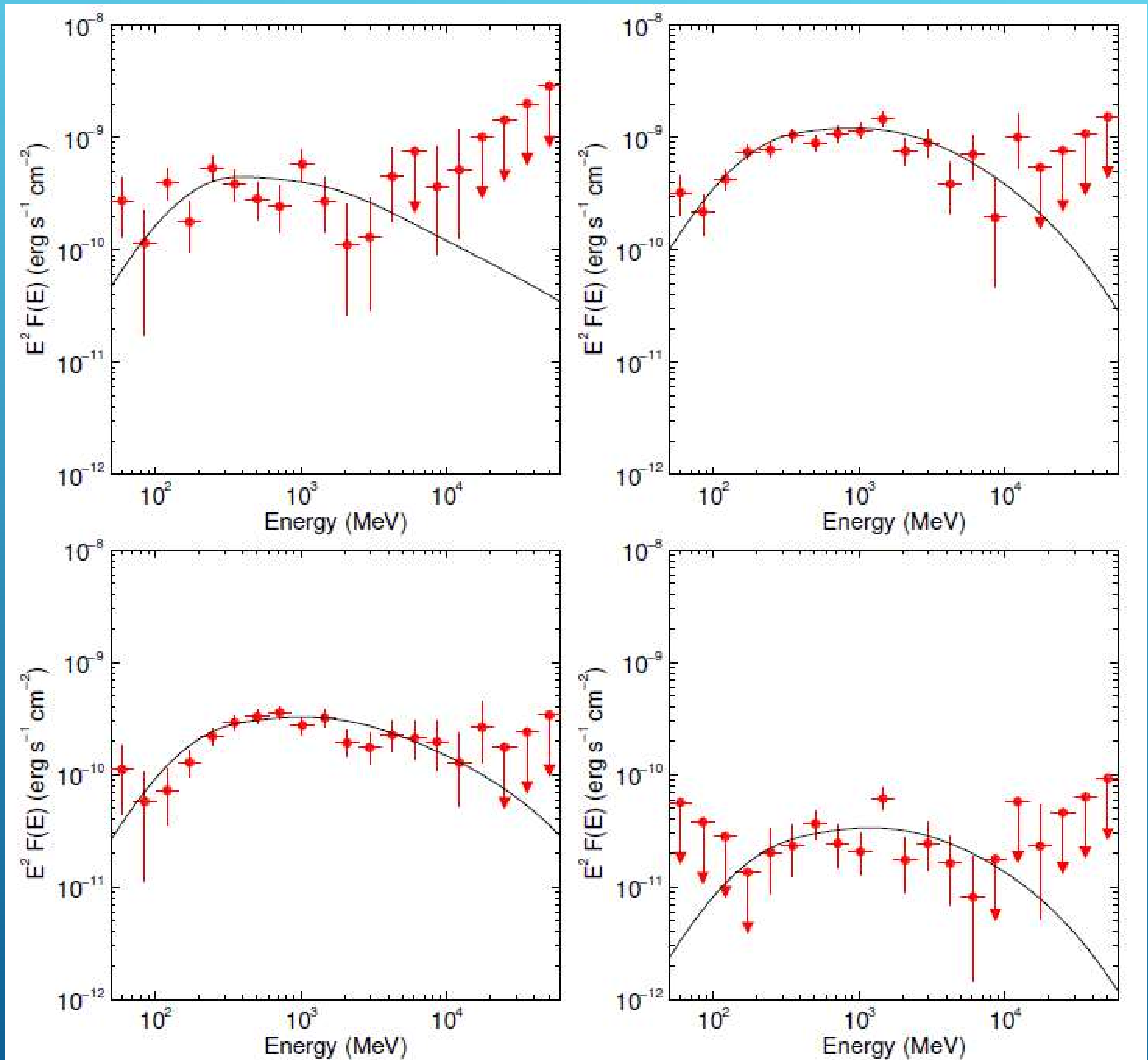


- XRT $2 - 10\ keV$ light-curves are used to compare to the LAT and optical light-curves;
- Early X-ray emission at $> 2\ keV$ energies is dominated by bremsstrahlung from shocked gas in the nova ejecta;
- The results of the X-ray temperature spectral fits are used to constrain the temporal evolution of the ejecta velocity

FERMI-LAT AND MULTIWAVELENGTH RESULTS

- In the context of the hadronic model, we define 4 emission phase for spectral study with the >50 MeV LAT data: Rise (0-1.0 days), Peak (1.0-2.75 days), Decline-a (3.0-9.0), Decline-b (9.0 – 46.0);
- Gamma ray spectrum is calculated assuming that the energy distribution of the high energy protons is a power law in proton momentum multiplied by an expontential cutoff;

PION-DECAY GAMMA-RAY EMISSION

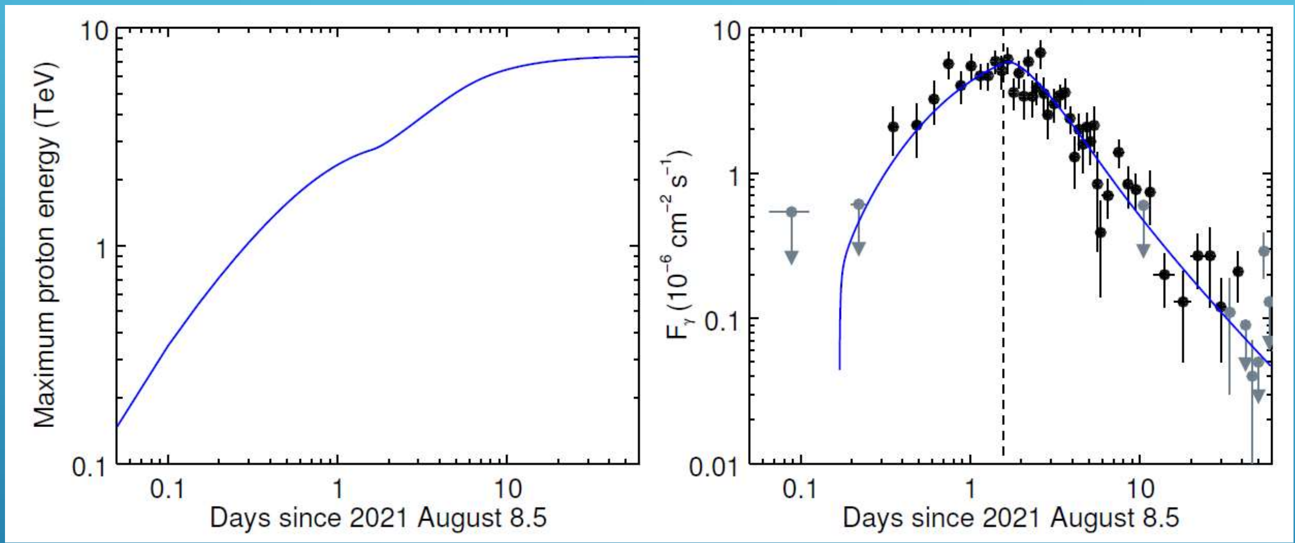


- According to the ΔTS values, the hadronic model provides a fit as good as the one obtained with the ECPL model, except for Decline-a period where is preferred the hadronic model;

PION-DECAY GAMMA-RAY EMISSION

- The protons are accelerated via the Fermi process in the shock between the nova eject as it propagates thorugh the RG wind;
- We estimated the speed of the ejecta with time using an analytical model fitted to the velocities derived from the X-ray temperatures measured with the Swift-XRT data;
- This velocity model is used to compute the time evolution of the nova shell radius. ($2470\ km/s$ for $t < 6$ days, $t^{0.43}\ per\ \ t > 6$);
- The RG wind density is assumed to be uniform;
- With this information we calculated the maximum energy of accelerated protons as a function of time by integrating the sum of energy loss and gain rates;
- Energy gain calculated with a compression ratio of the shock of 4 and magnetic fields estimated assuming equipartition in the compressed gas with a wind temperature of $10^4\ K$;
- Energy loss takes in account coulomb collisions and inelastic pp collision in the compressed gas.

PION-DECAY GAMMA-RAY EMISSION



- Maximum energy is $7.4\ TeV$;
- Maximum proton energies are $> 1\ TeV$ starting at 0.3 days after the outburst;
- The maximum proton energy changes from $2\ to\ 5\ TeV$ between days 1.3 to 5.4;
- To calculate the gamma-ray light curves, we assumed that an injection fraction of the RG wind protons crossed by the shock is accelerated toward the expanding ejecta;
- The resulting gamma-ray model fluxes compare well with the observed LAT light curve data

PION-DECAY GAMMA-RAY EMISSION

- With a peak flux of $F_{\gamma} \simeq 6 \times 10^{-6}\ ph\ cm^{-2}\ s^{-1}$, the RS Oph 2021 outburst is the brightest nova detected thus far in gamma rays by the LAT;
- RS Oph's brightness in the LAT band extend to higher energies, resulting in the first VHE detection of a nova. The VHE observation constrain the maximum energy of the accelerated protons to be $10\ TeV$;
- The LAT-observed $> 0.1\ GeV$ gamma rays peaked at 1 day after the optical outburst and could reflect the time needed for the shock to accelerate enough protons to significant energy;
- The LAT light curve showed evidence of factors of two fluctuations in the flux on timescales of 30 to 200 minutes during the first few days → may be expected because of the density variations of the swept-up material by the shock in the inner part of the binary sistem and changes in the outflow;
- The decline of gamma-ray emission starting at days 2-3 could correspond to the timescale at wich the shock enters a region where the density of the RG wind decreases with the shock radius;
- The hadronic process from the external shock is the dominant component.

DISCUSSION AND SUMMARY