Gamma-ray emission from the nova RS Oph by the MAGIC Telescopes

David Green (MPP)
Vandad Fallah Ramazani, Francesco Leone, Rubén López-Coto, Alicia López-Oramas, and Julian Sitarek
on behalf of the MAGIC Collaboration

Credit: Dan Lopez IAC

Novae: Known Sources for Gamma-ray Emission

- V407 Cyg was the first nova (symbiotic) detected by the high energy (HE) gamma-ray energy range (Fermi-LAT, Science 2010)
- Classical nova soon followed with in 2014 (Fermi-LAT, Science 2014)
- Unable to distinguish between Hadronic or Leptonic (IC + Brem) origins

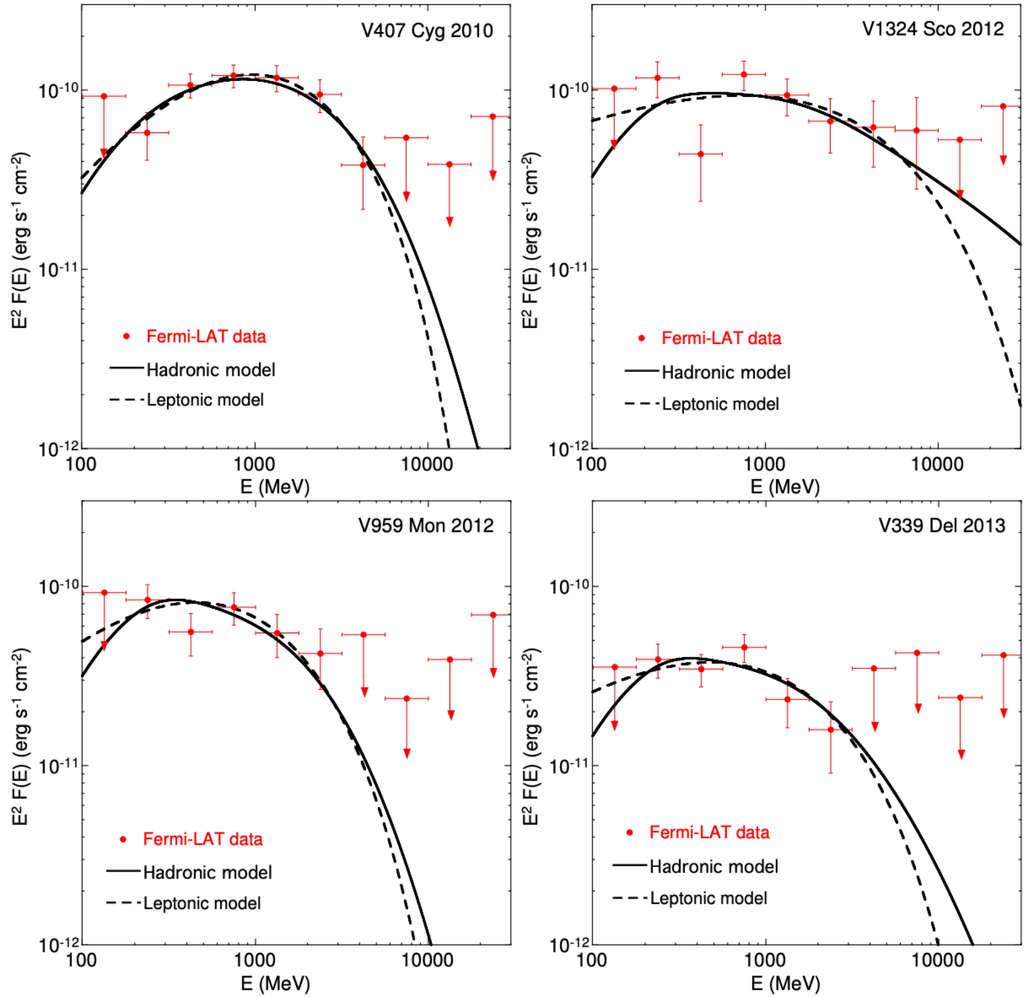
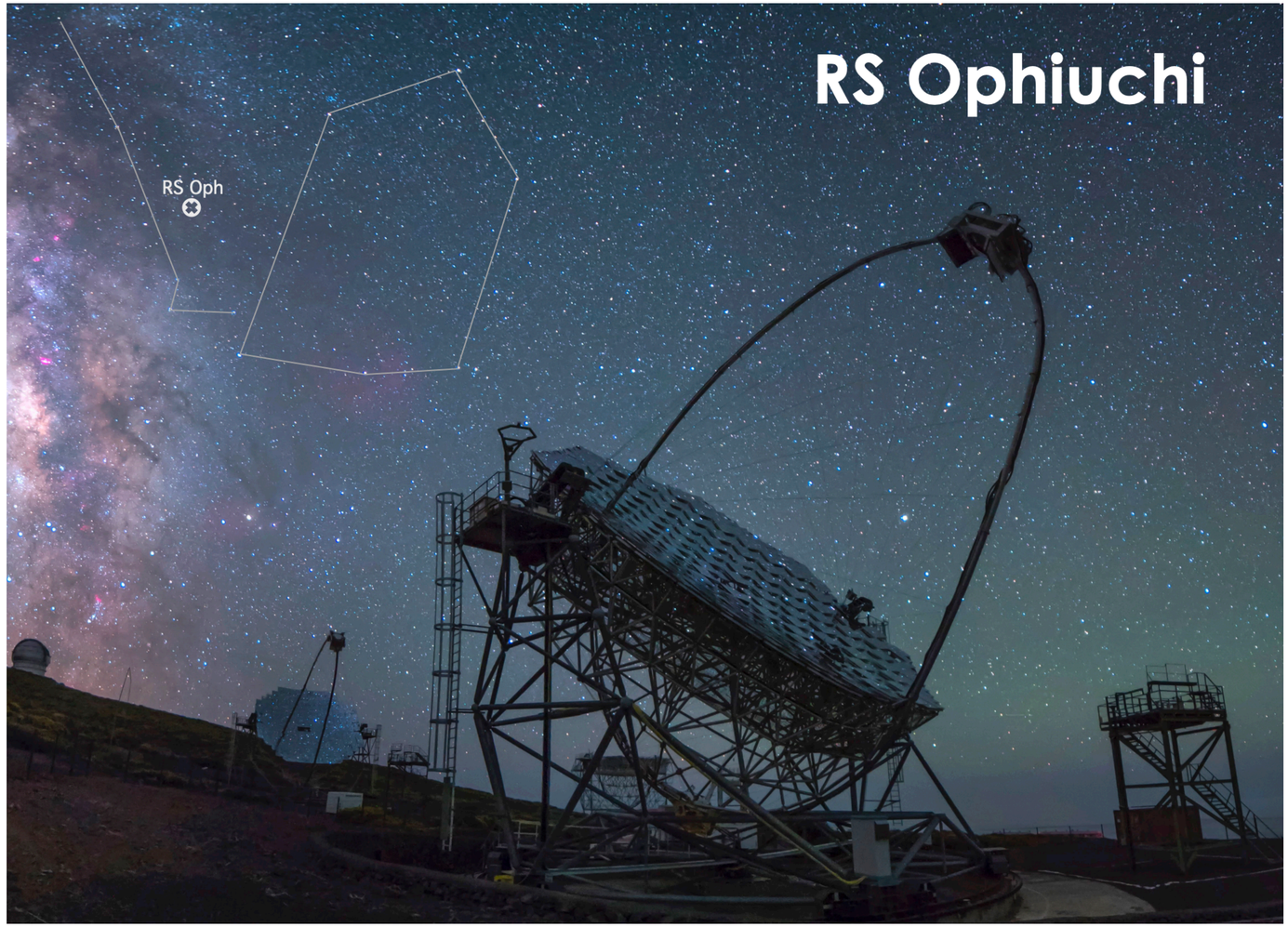


Fig. 3. Fermi-LAT >100 MeV average γ-ray spectra of the four novae over the full 17−27 day durations. Vertical bars indicate 1σ uncertainties for data points with significances $> 2\sigma$; otherwise, arrows indicate 2σ limits. The best-fit hadronic and leptonic model curves are overlaid.

(Fermi-LAT, Science 2014)

MAGIC Telescopes

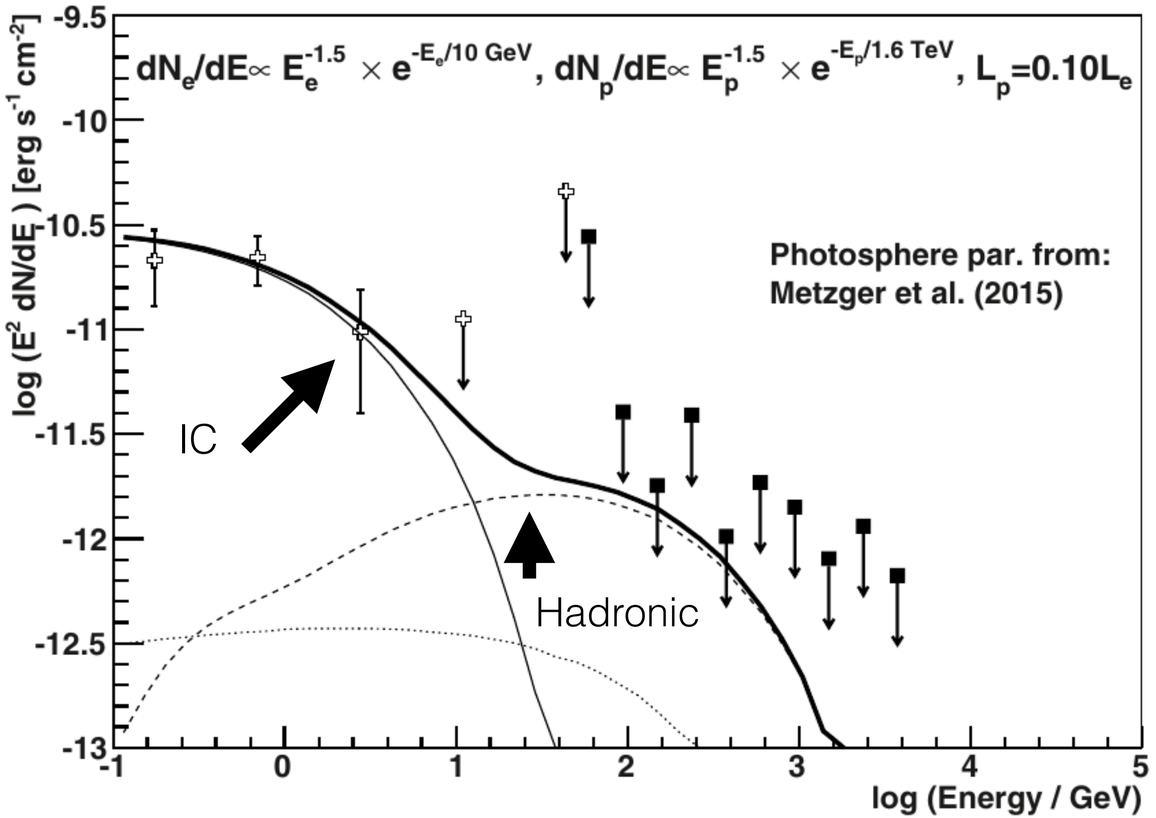
- Located Roque de los Muchachos observatory at La Palma, Canary Islands, Spain
- Two 17m diameter imaging atmospheric telescopes
  - Specially designed to measure the lowest energies of the VHE regime (~50 GeV) and up to 10s of TeV
  - Light design to allow fast slewing to follow-up observation of fast transients



Picture credit: Antonio González

Novae with MAGIC

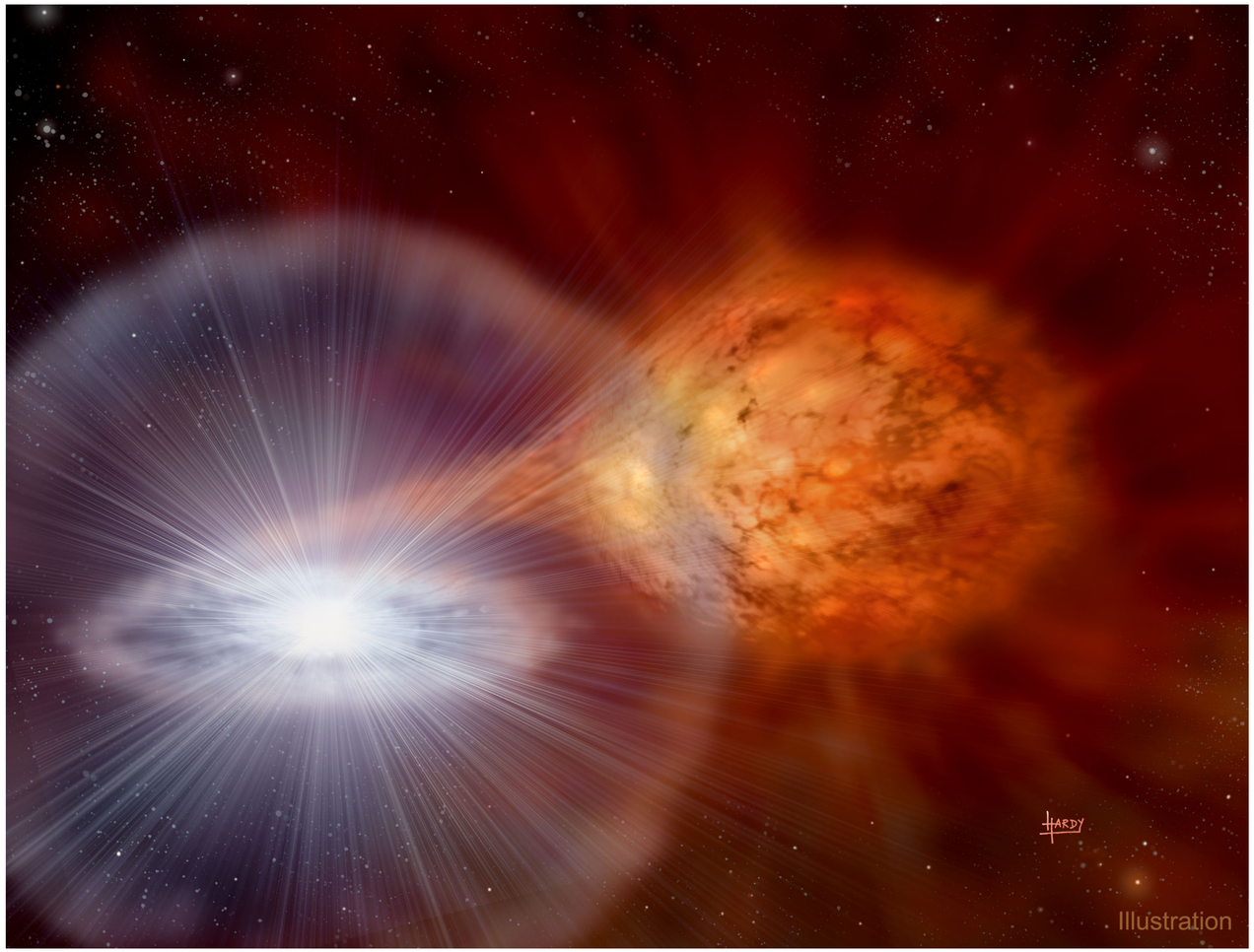
- MAGIC initiated a follow up program on novae since 2012
- VHE (>100 GeV) data is critical to understand emission mechanisms
- Constraining upper limits V339 Del
- No detection until RS Oph



MAGIC Coll., A&A, 582 (2015)

RS Ophiuchi

- Recurrent nova in a symbiotic binary
- Has major outburst every ~ 15 years
- WD (1.2–1.4$M_\odot$) + M0-2 III RG star (0.68–0.80$M_\odot$) Schaefer Astrophys. J. Suppl. Ser. 187, 275–373 (2010).
- Distance debated, range from 1.4 – 4.3 kpc with caveats for each
  - We used 2.45 kpc, derived from Rupen et. al. 2008
  - Although recent Gaia DR3 reports parallax distance of 2.69 ± 0.18 kpc



Credit: David A. Hardy

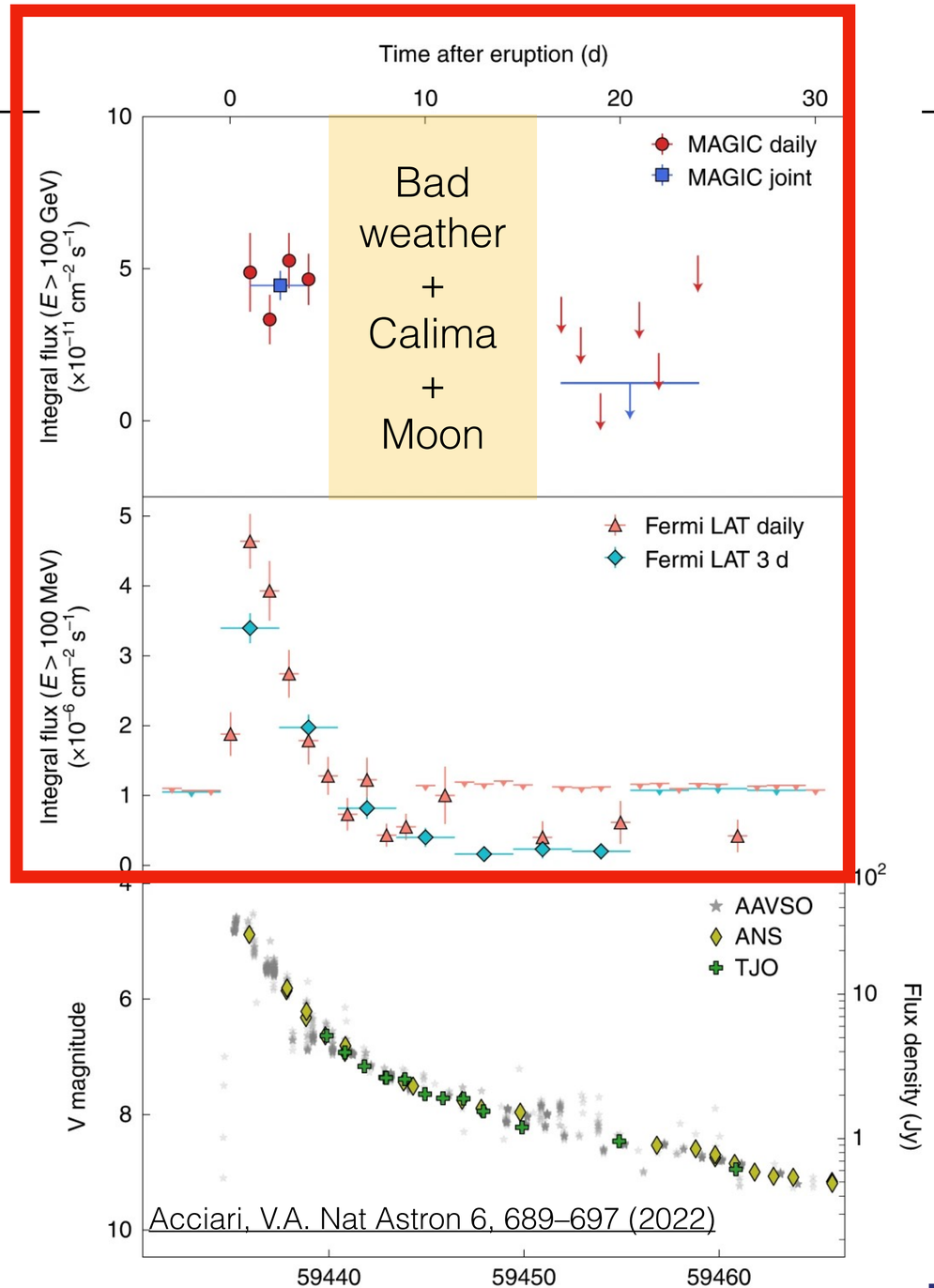
RS Ophiuchi in VHE Gamma-rays

- 9 Aug 00:35 UT – optical discovery (vsnet-alert 26131)
- 9 Aug 05:05 UT – ATel #14834 by Fermi-LAT
- 9 Aug 18:17 UT – H.E.S.S. starts observations
- 9 Aug 22:30 UT – MAGIC starts observations
- 10 Aug 18:34 UT – ATel #14844 by H.E.S.S.

Picture credit: Giovanni Ceribella

RS Ophiuchi in Gamma-rays

- HE shows rapid rise (brightest nova to date) and fall (exponential halving time (2.20 ± 0.18 days)
- The first four days of MAGIC observations (August 09-12) yield a VHE signal with a significance of 13.2σ
- No MAGIC detection as after August 25th
- VHE photon flux > 100 GeV constant over first 4 days while HE signal decreases by factor of <2



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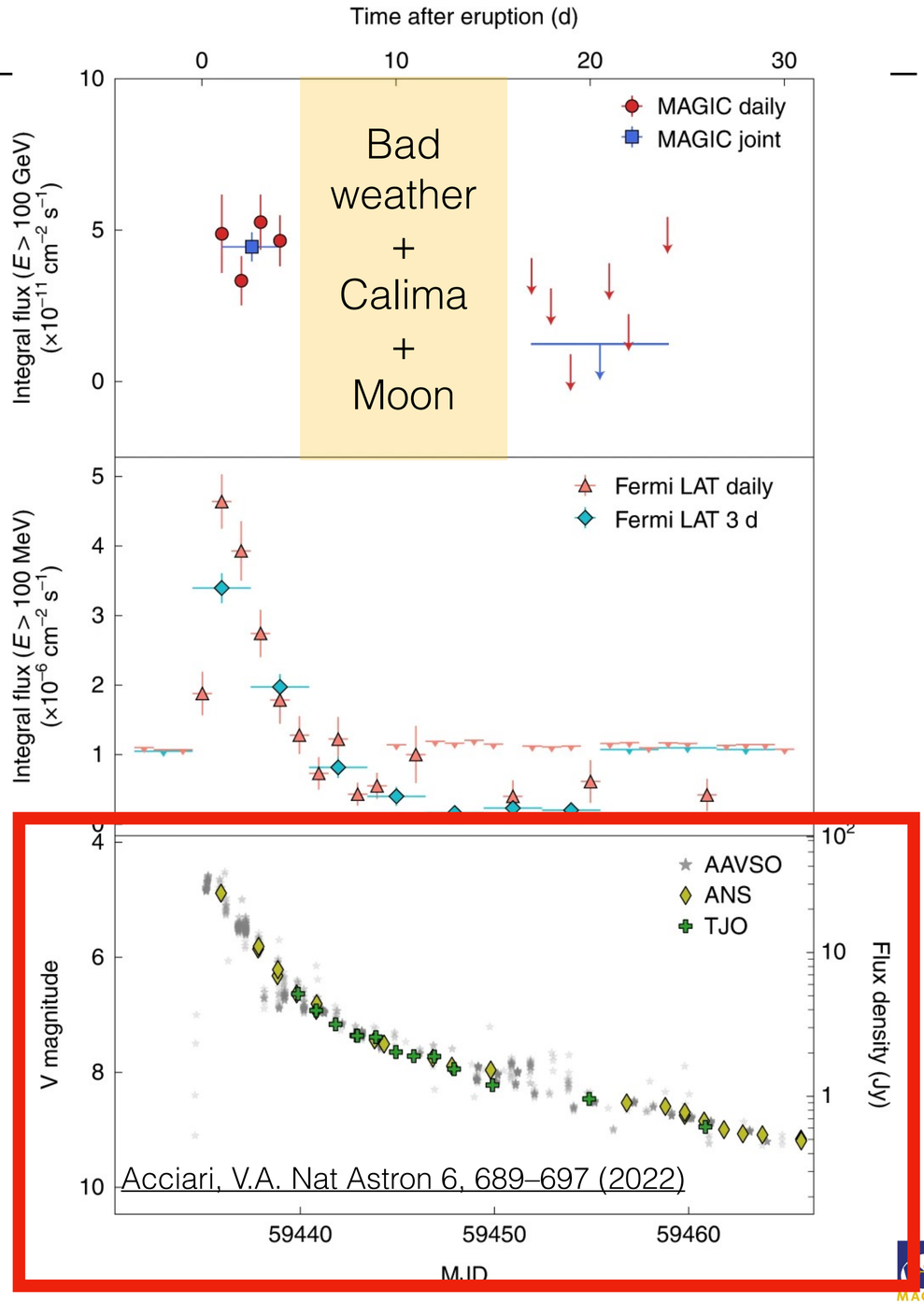
RS Ophiuchi in Optical

- Photometry:
  - TJO and ANS simultaneous data with MAGIC
  - Emission described with T_{ph} 10800K -> 7680 K and R_{ph} = 200 $R_{\odot}$
- Spectroscopy:
  - Varese 0.84 m and Catania 0.91 m telescopes
  - 4500 ± 250 km/s for ejecta expansion during first 4 days



Gamma-ray Modeling

- Time dependent modeling based from MAGIC Coll., A&A, 582 (2015)
- Hadronic model favored over leptonic model
- Hadronic model has natural CR index ~2
- Leptonic requires ad hoc break and fits poorly

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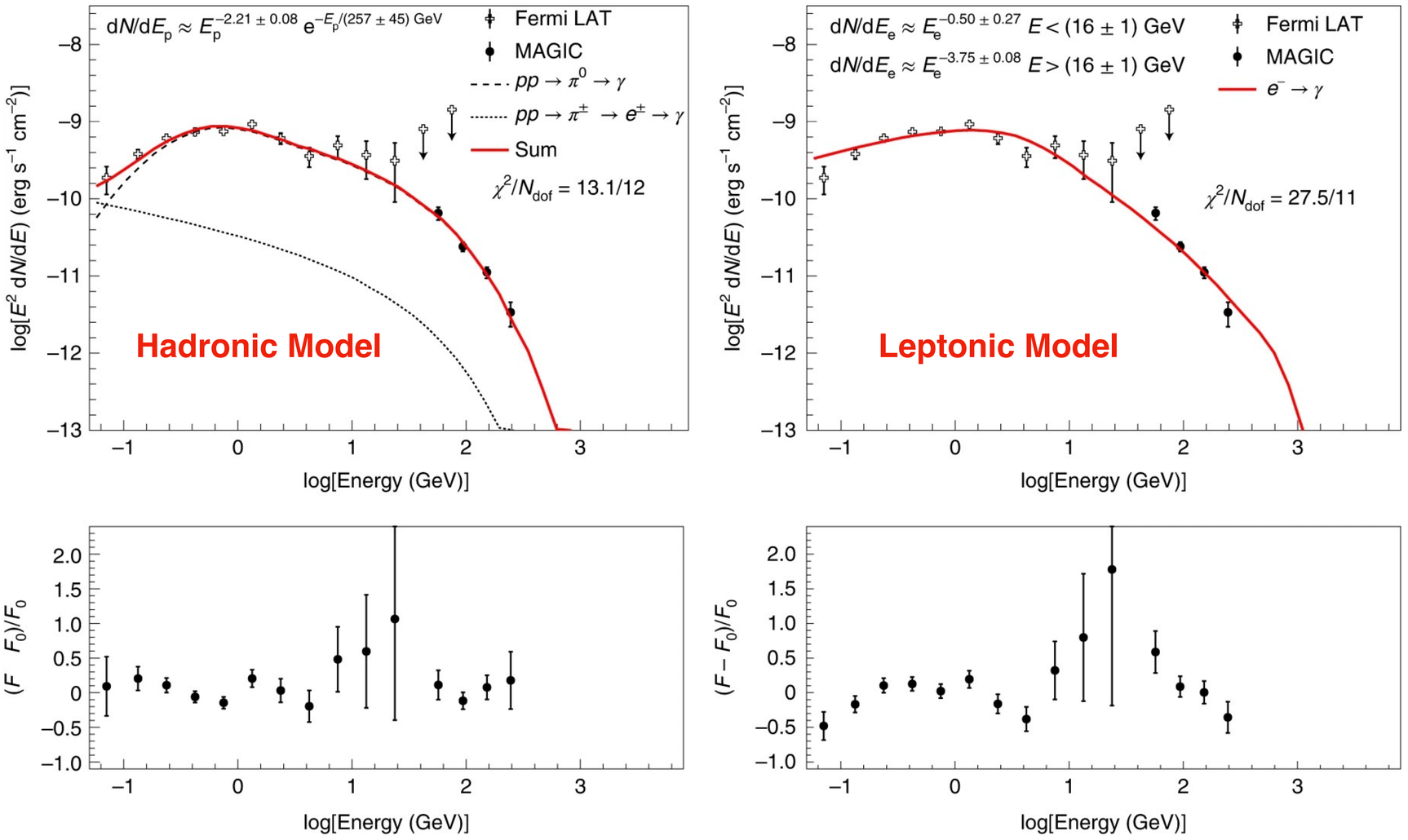

Daily Gamma-ray Modeling

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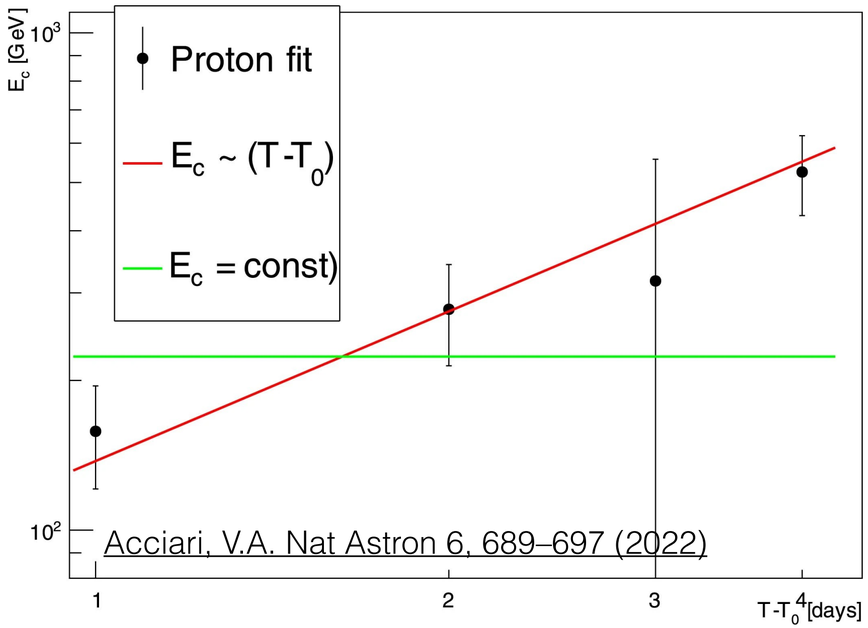
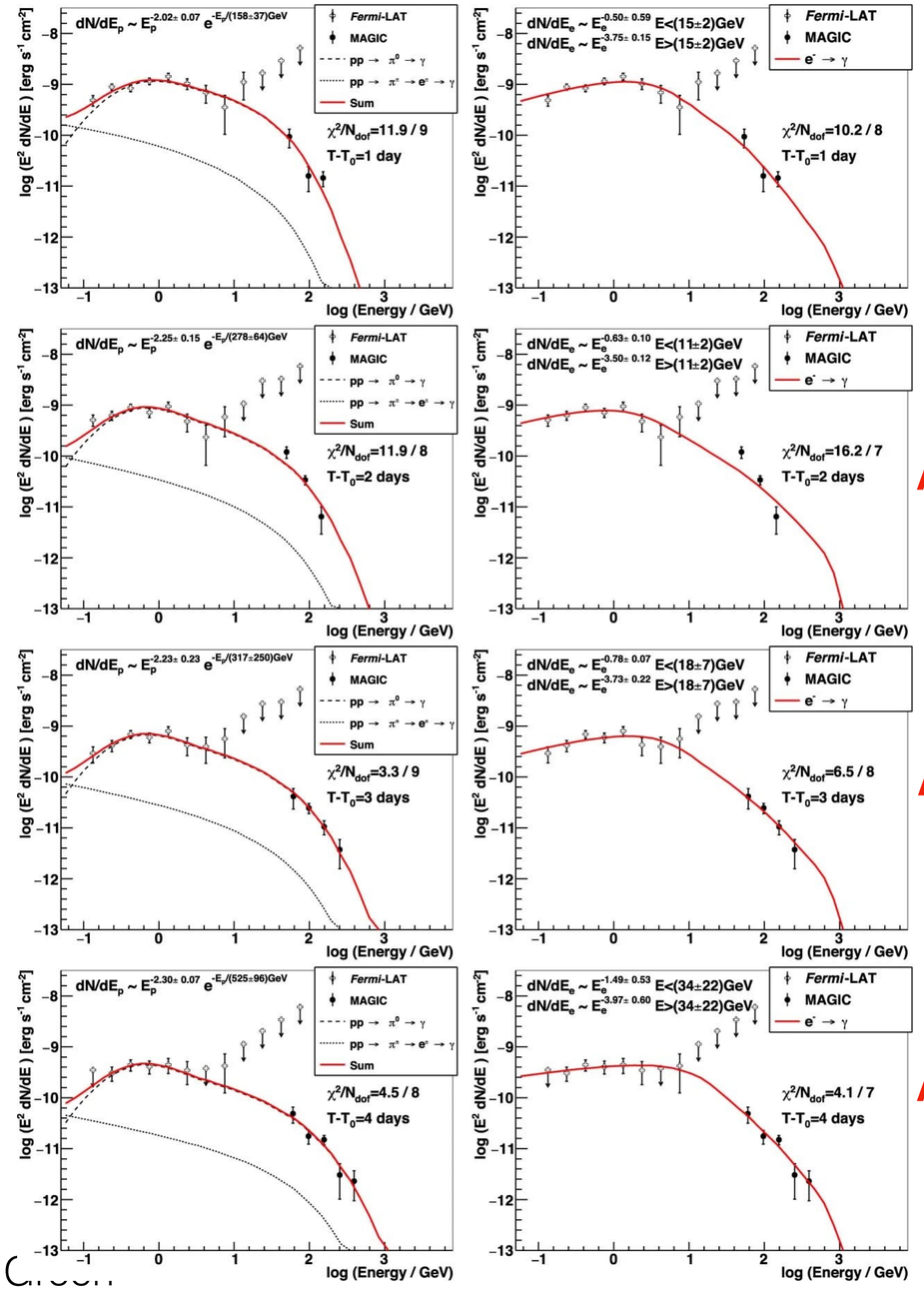
- Hadronic model preferred on the daily fits
- Slight indication of hardening (increase in maximum energy) vs time
- Inline with electrons cooling quickly while protons don't



Hadronic Model **Leptonic Model**



Aug 9th

Aug 10th

Aug 11th

Aug 12th

More Evidence for Protons

- Optical and HE emission follow similar decay
  - IC emission should decay fast due to photosphere expansion
- HE emission seems stable
  - Hint of spectral hardening
  - Protons cool slowly + delayed emission

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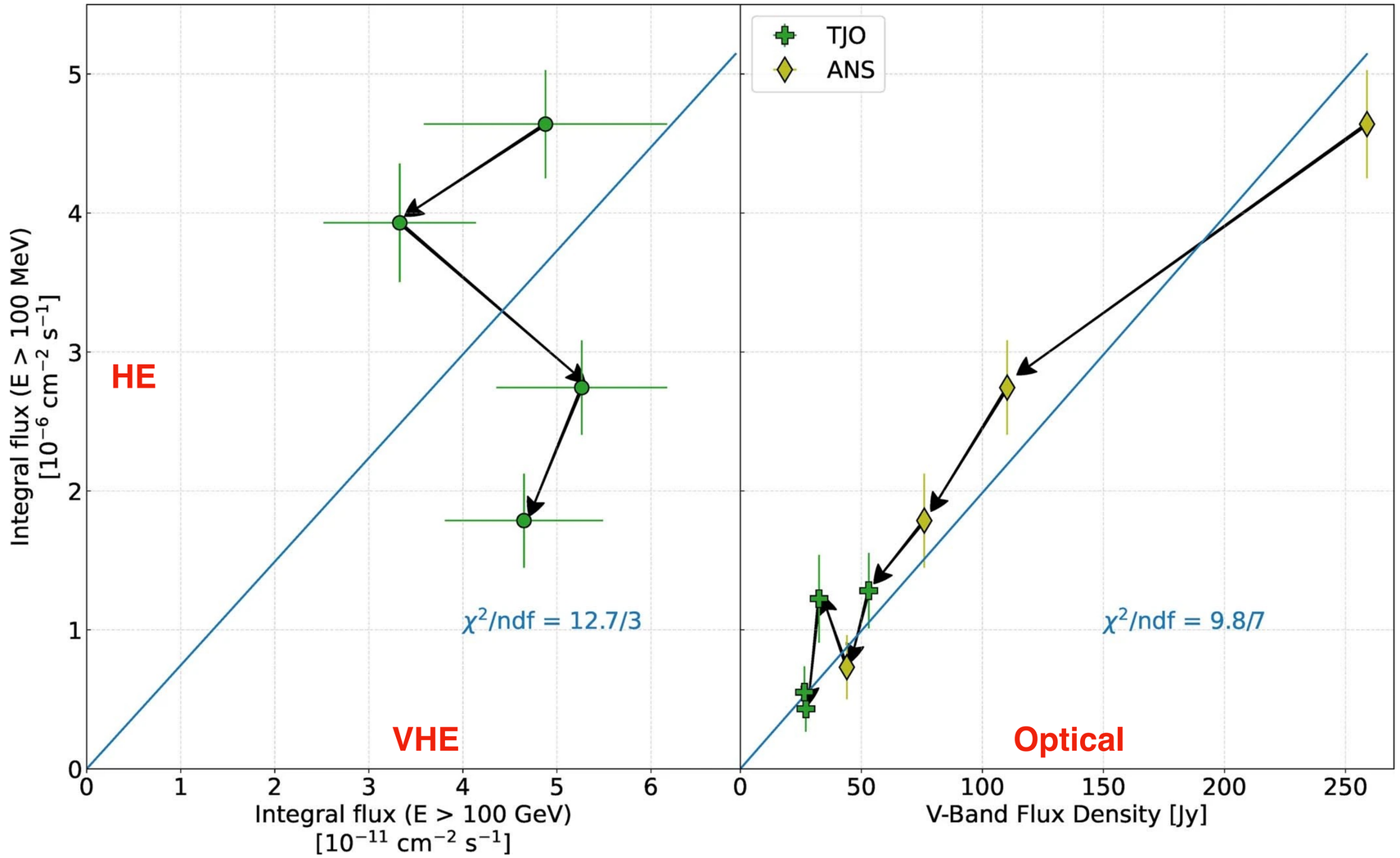
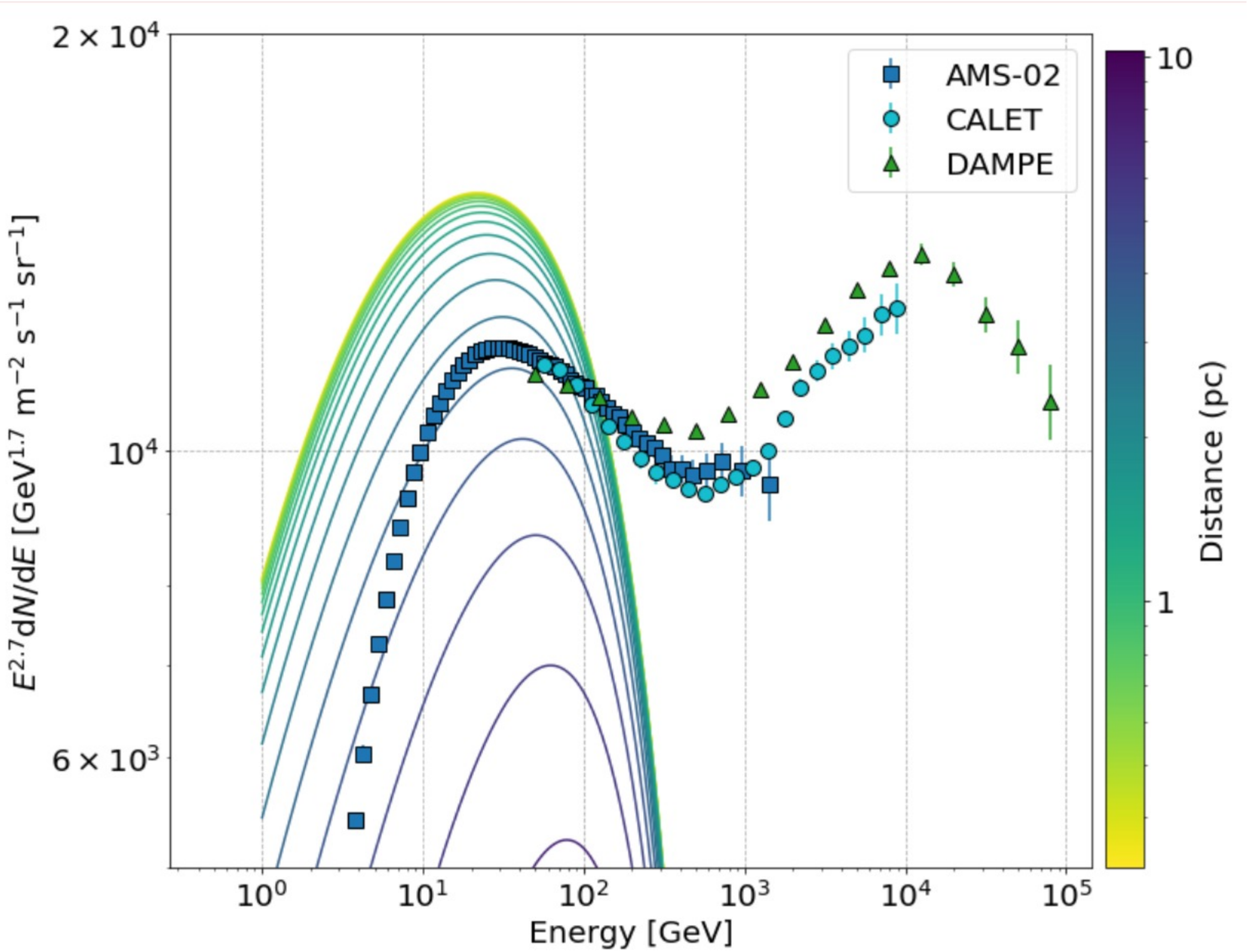


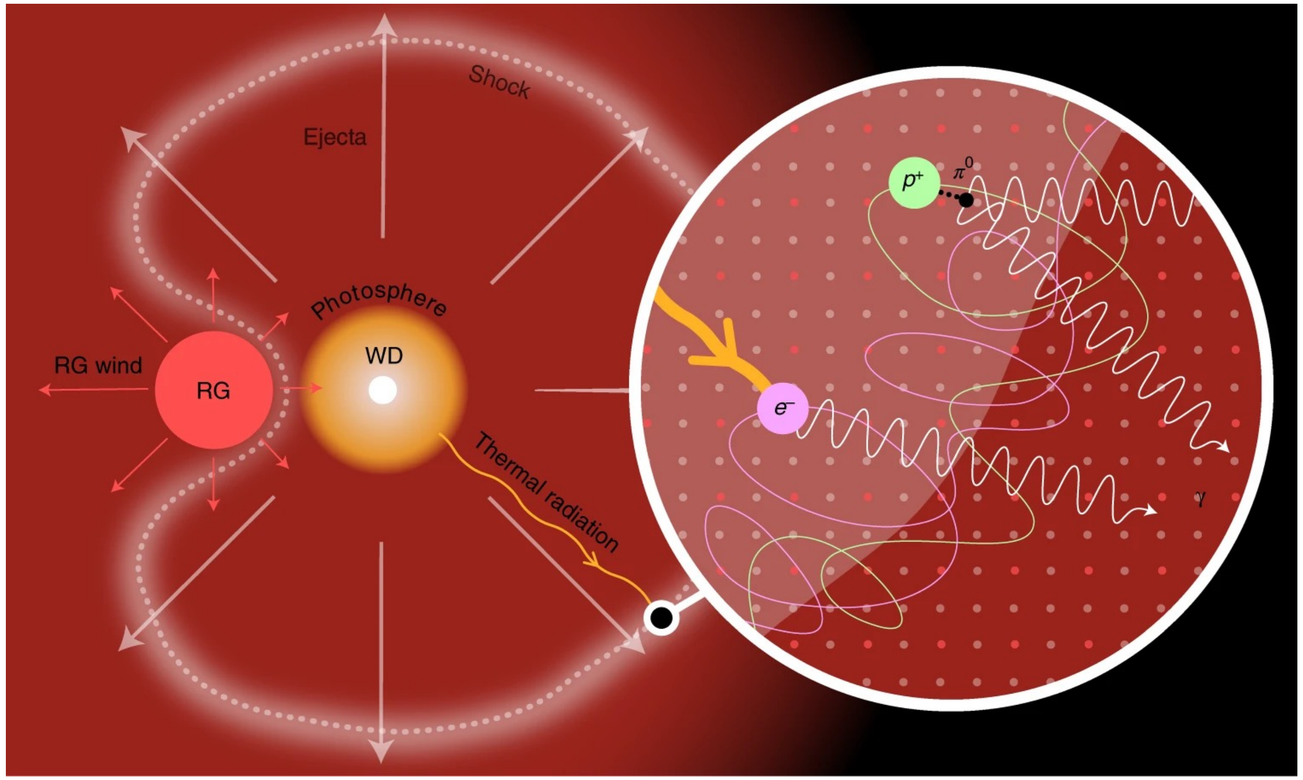
Galactic Cosmic Rays

- Protons can contribute to cosmic-ray population
  - Total contribution is < 0.2% compared to Supernova remnants
- Can dominate over ~ 1 pc radius
  - For frequent recurrent eruptions create a bubble with ~10 pc radius
  - Chances novae contribute significantly to the CR spectrum we measure are extremely small



Conclusions

- August 2021 outburst of RS Oph creates a new class of VHE emitters
- Hadronic emission favored by Optical + Fermi-LAT + MAGIC modeling
- First evidence for hadronic origin of gamma-rays in novae



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Backup Slides

Context of other Gamma-ray Novae

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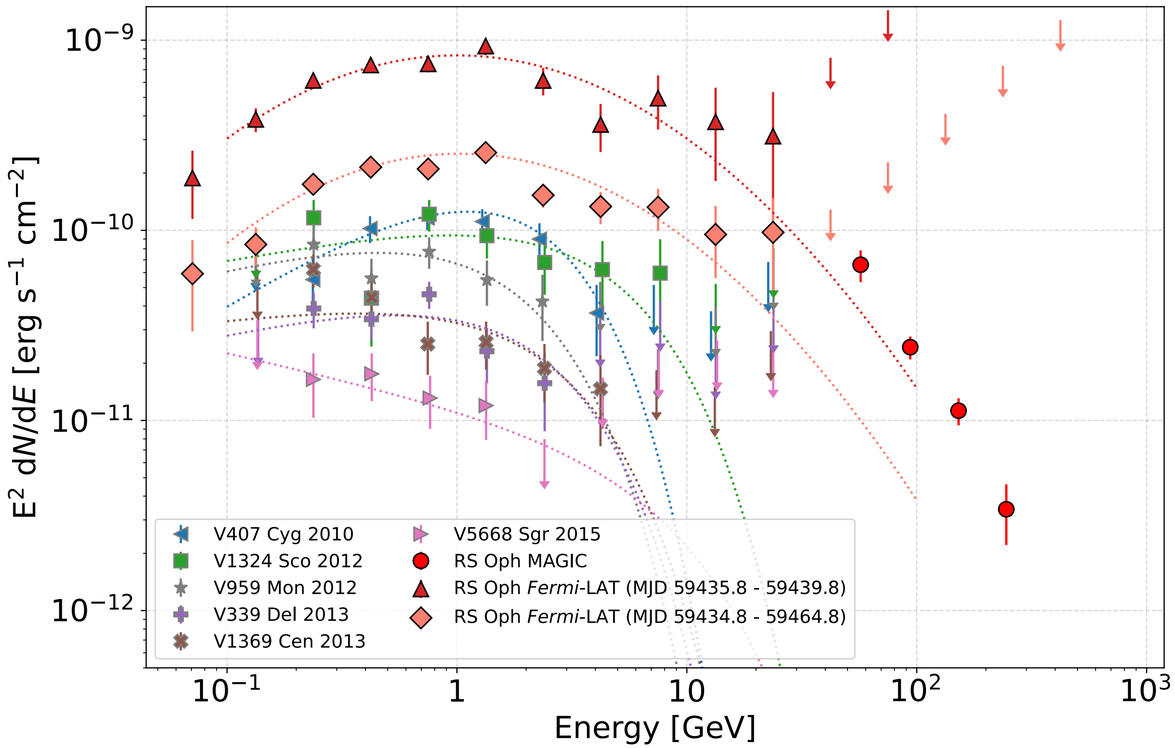
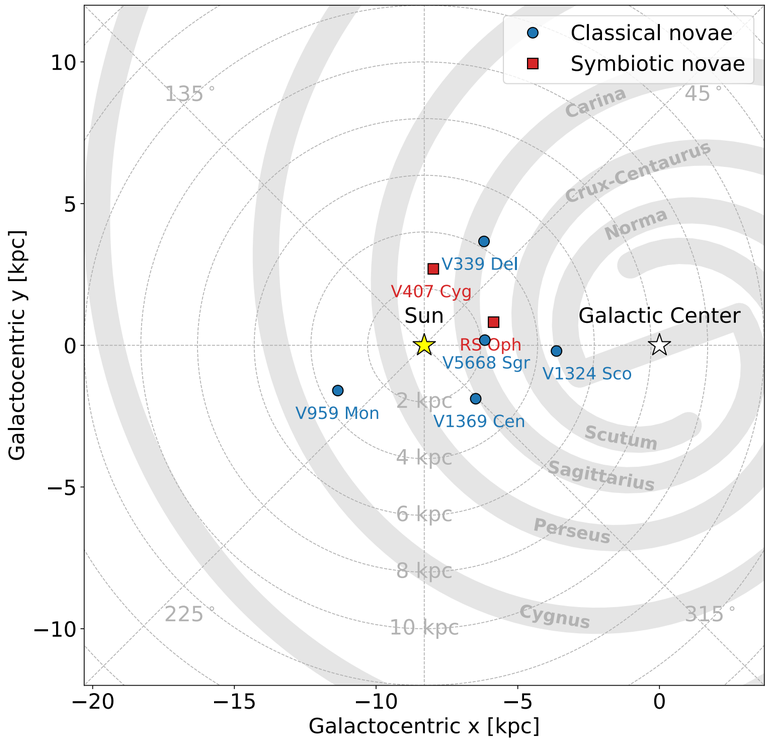
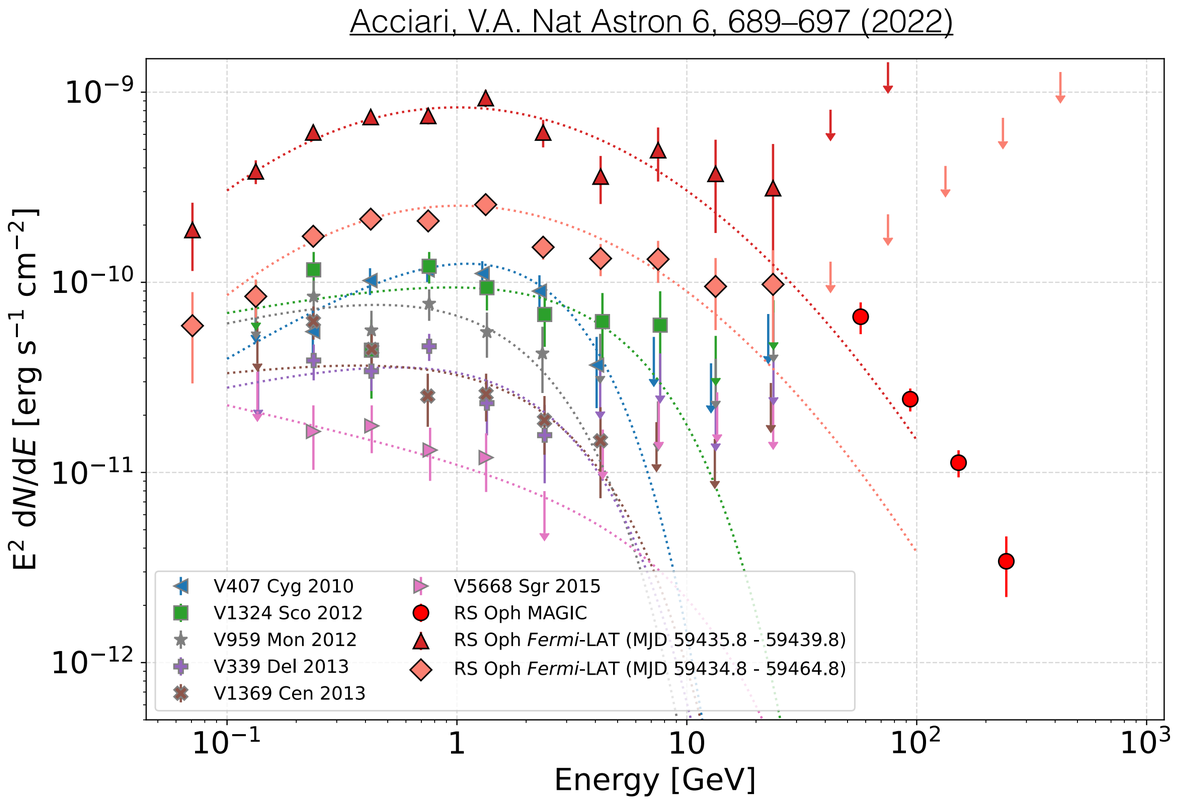
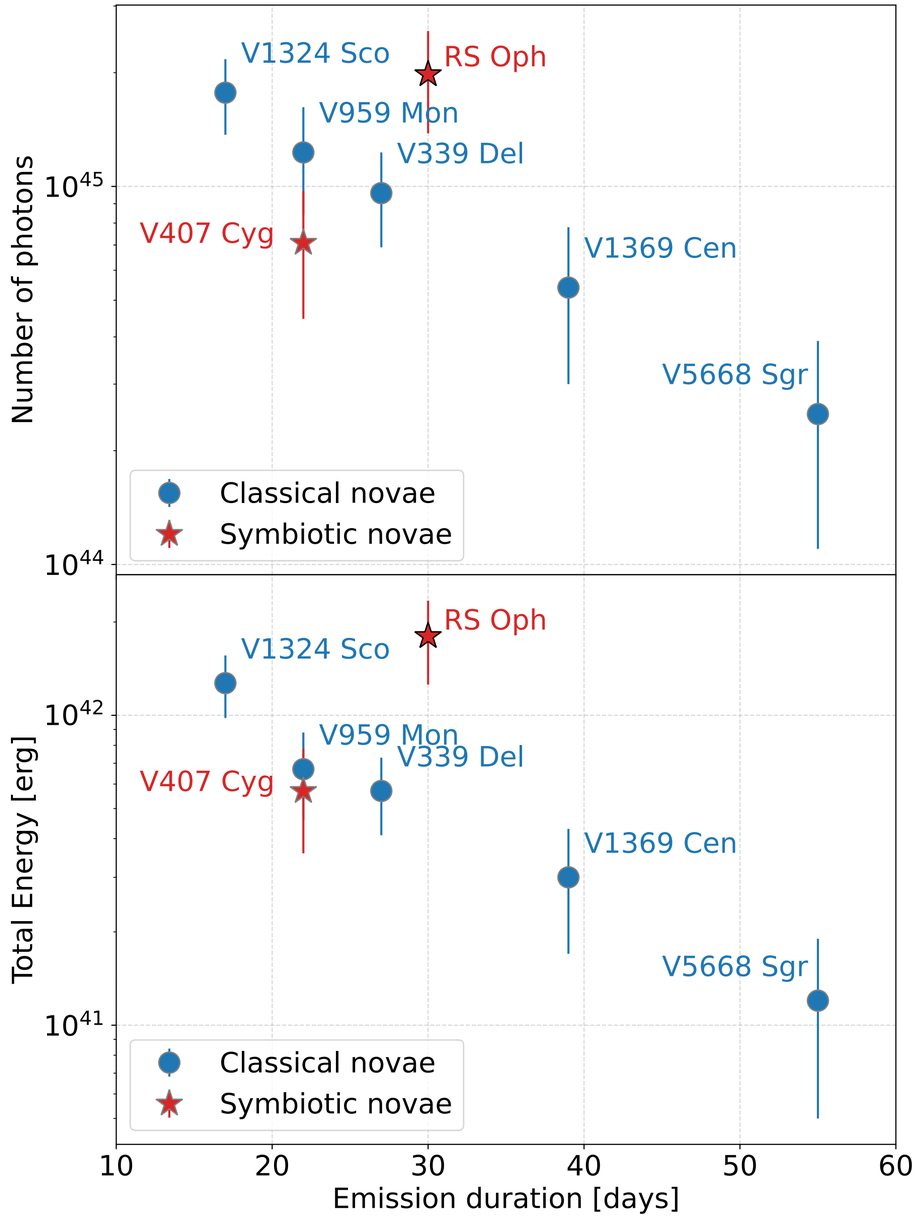




- RS Oph is of the highest flux of other gamma-ray novae

Context of other Gamma-ray Novae





- Also intrinsically the brightest

Context of other Gamma-ray Novae

- Tricky to detect other novae
- Scaling RS Oph to V339 Del brightness, would have been below detection threshold
- More sensitive instruments required like the future CTA

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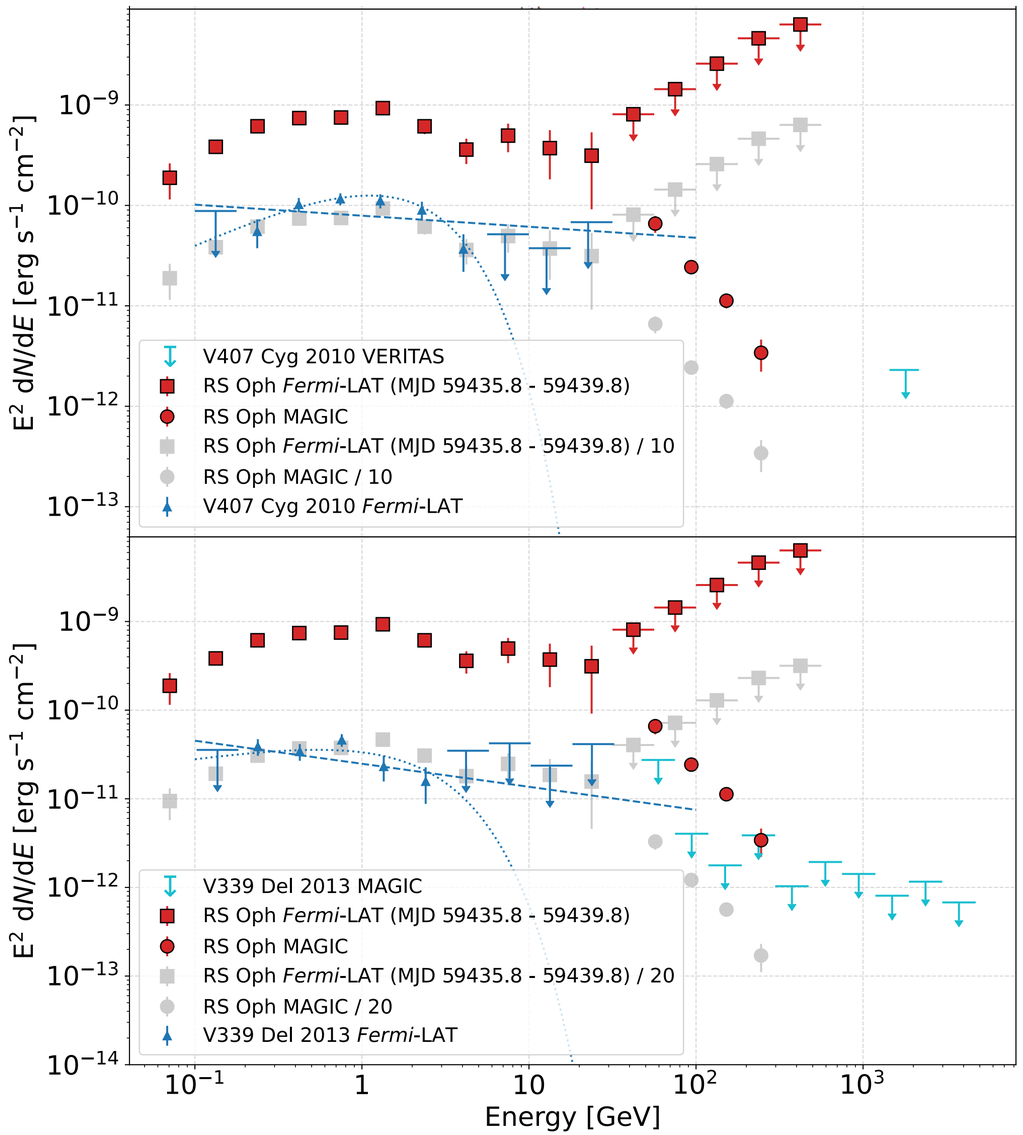

RS Oph Distance Estimates

Distance (kpc)	Method	
1.6	H I absorption measurements	Hjellming, R.M et. al. Astrophys. J. Lett. 305, 71 (1986).
$1.4^{+0.6}_{-0.2}$	Several estimations	Barry, R.K et. al. Astronomical Society of the Pacific Conference Series, vol. 401, p. 52 (2008)
2.45 ± 0.37	Expansion velocity	Rupen, M.P et. al. Astrophysical Journal 688(1), 559–567 (2008).
3.1 ± 0.5	Requirement of RG filling its Roche lobe	Barry, R.K et. al. Astronomical Society of the Pacific Conference Series, vol. 401, p. 52 (2008)
4.3 ± 0.7	Light curve	Cheung, C. C. et. al. Astrophys. J. 826, 142 (2016).
2.69 ± 0.18	Parallax	

- Lower estimates (1.4 and 1.6) greatly underfill RG Roche lobe
- Parallax measurements suffer from RS Oph long period orbit larger than parallax
- Requiring that RG fills Roche Lobe increases distance to ~ 3 kpc