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

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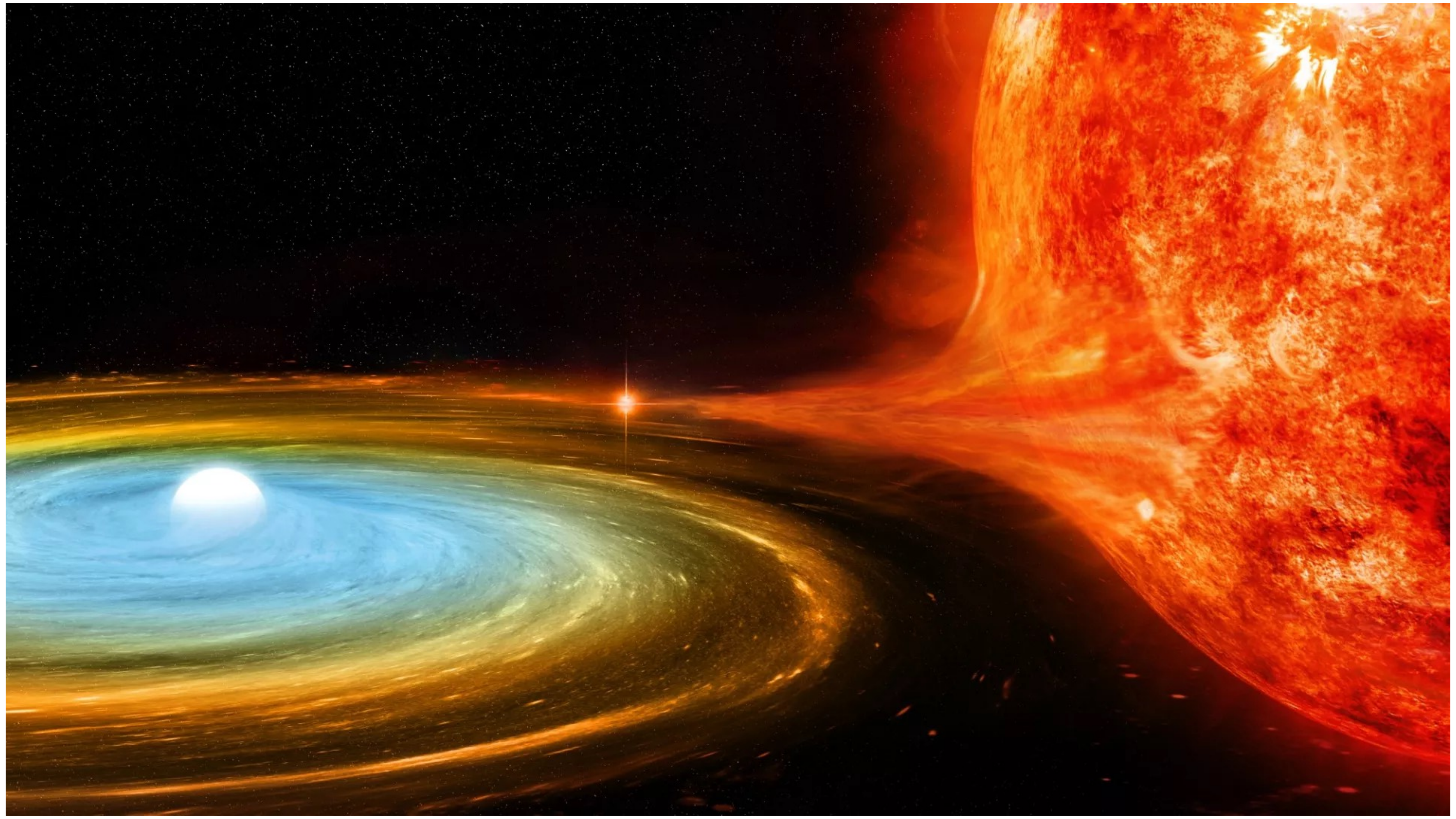
on behalf of the MAGIC Collaboration

Credit: Dan Lopez IAC

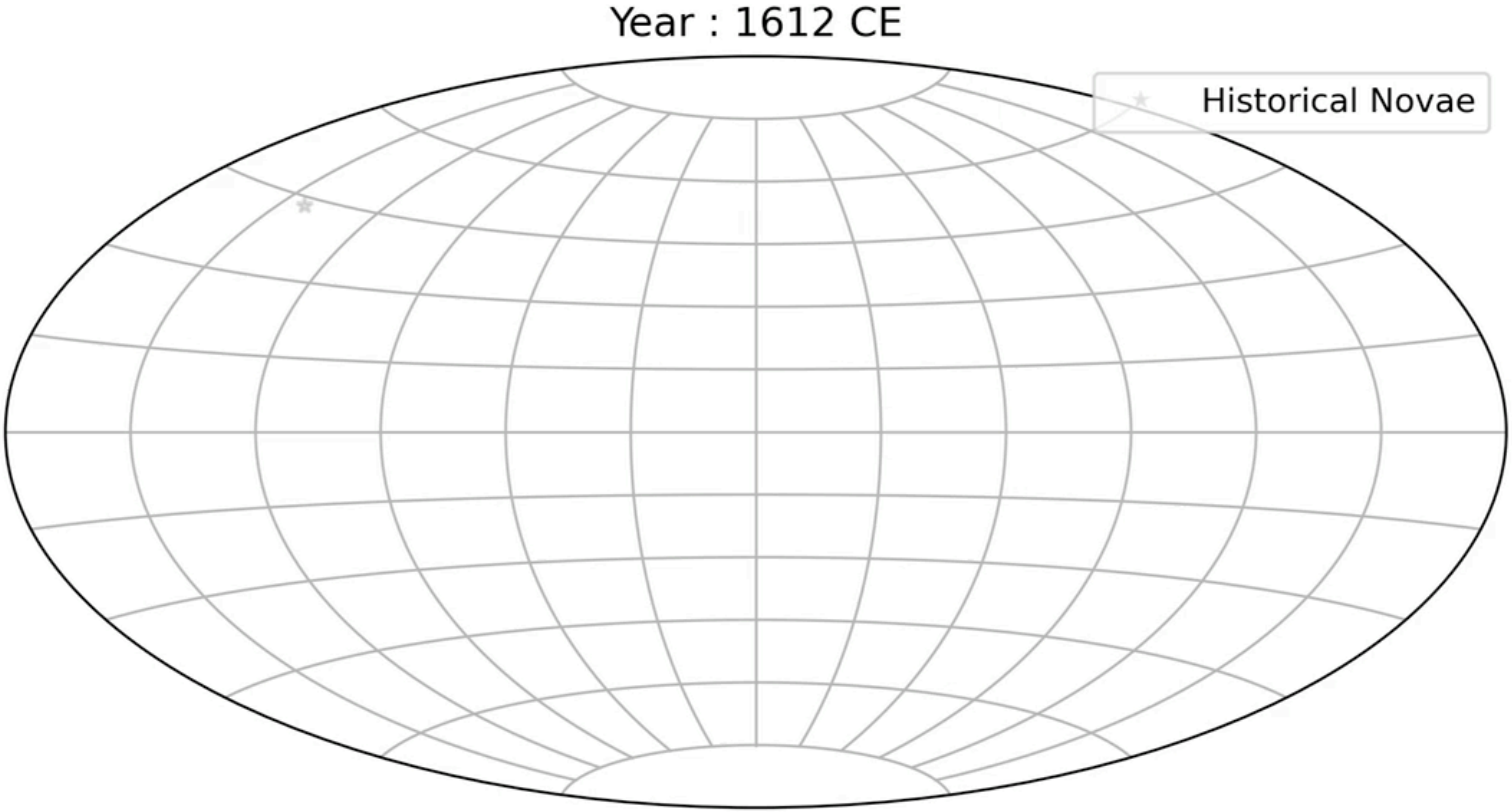
Novae

- Thermonuclear explosions caused by matter from a donor star collecting on a white dwarf surface in a binary system
- Matter on surface is in thermal equilibrium and eventually reaches fusion flashpoint
- Novae have been extensively studied in every wavelength
- Various Classifications are adopted, in particular:
  - Recurrent -> Outbursts observed multiple times
  - Classical -> Outburst only observed once
  - Symbiotic -> Evolved donor star/RG



An illustration of a binary system in which a white dwarf is feeding on material stripped from a companion star. (Image credit: NASA/CXC/M.Weiss)

Historical Novae



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

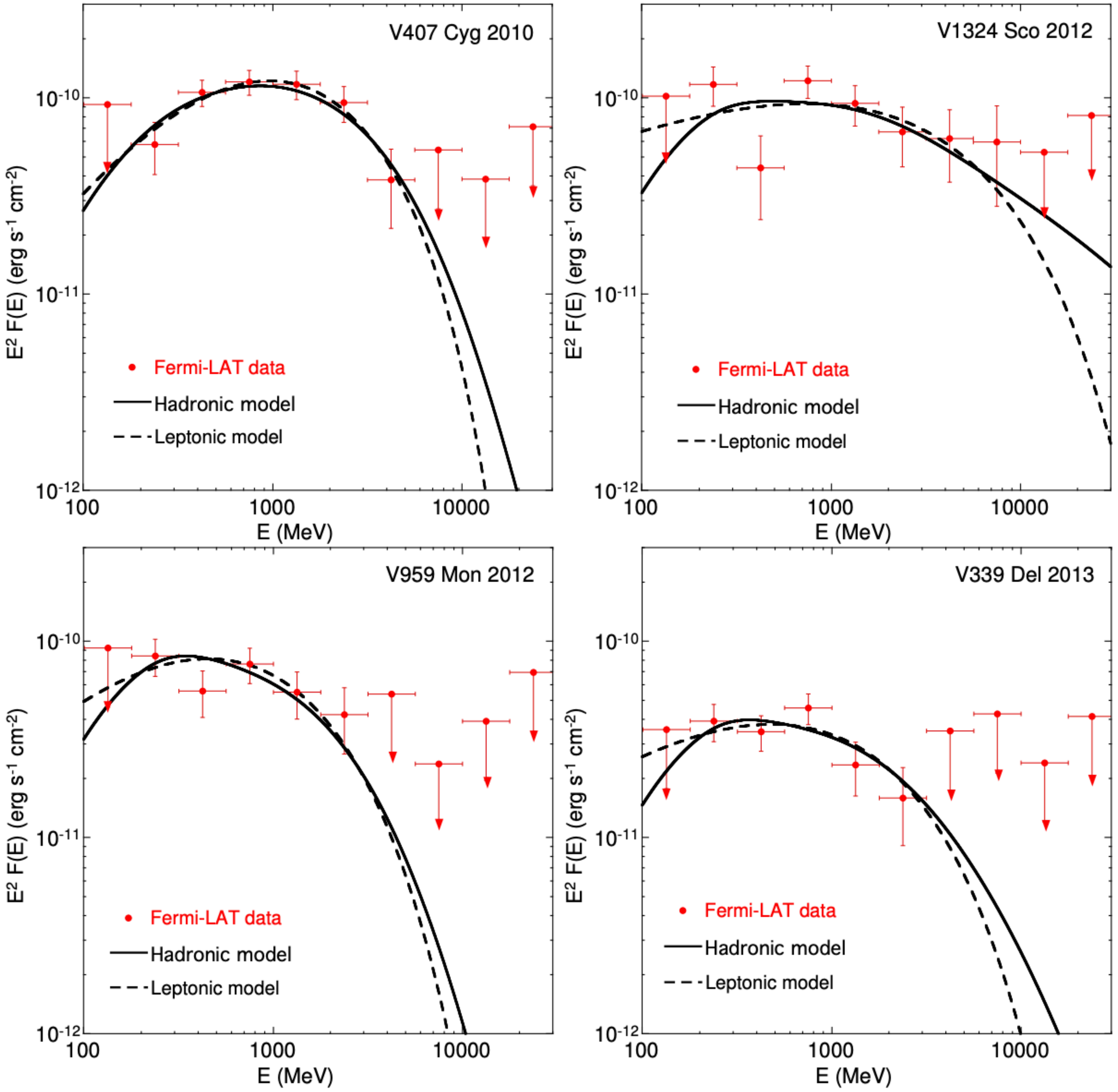
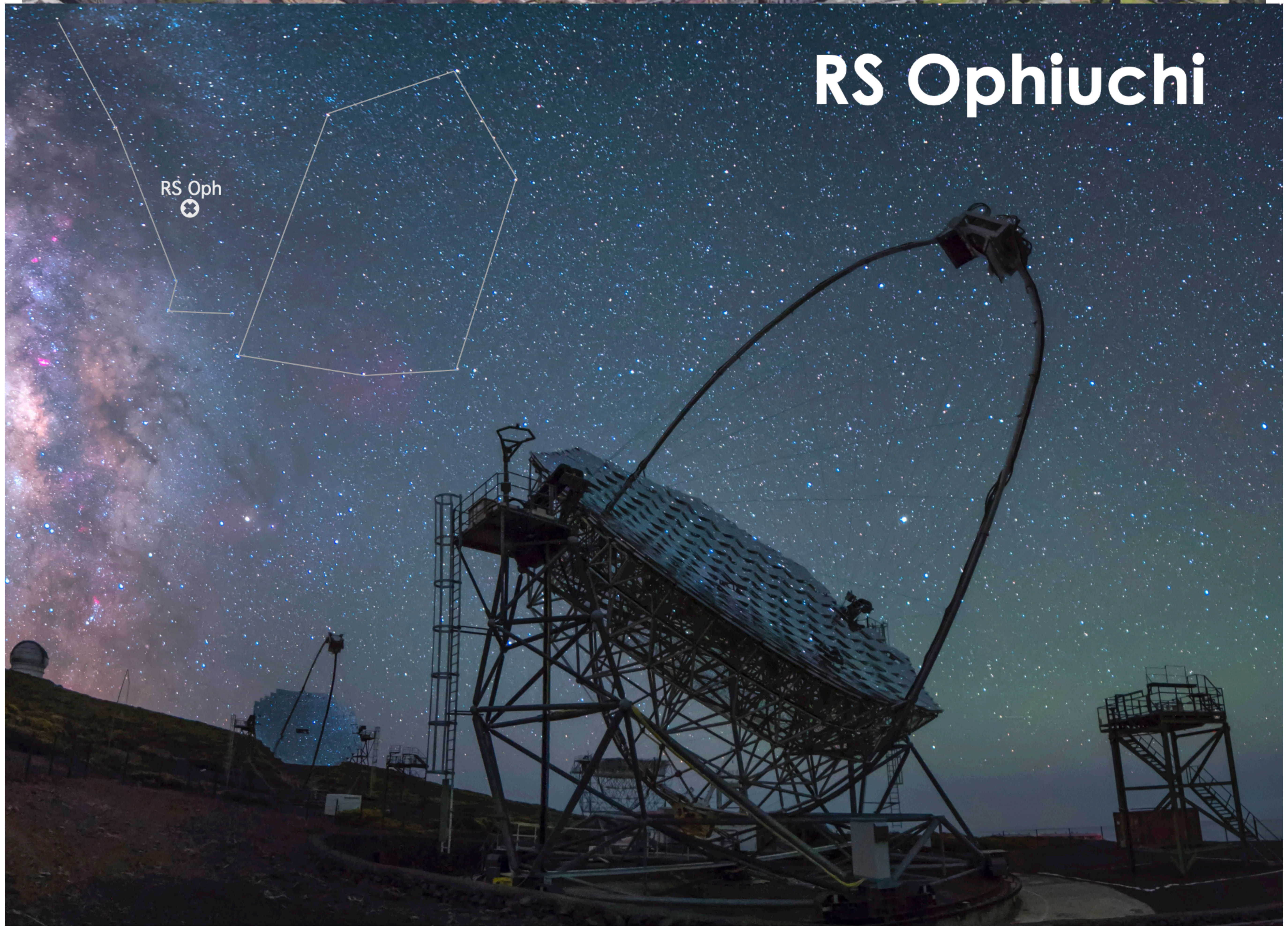


Fig. 3. Fermi-LAT >100 MeV average γ-ray spectra of the four novae over the full 17−27 day durations. Vertical bars indicate 1σ uncertainties for data points with significances $> 2\sigma$; otherwise, arrows indicate 2σ limits. The best-fit hadronic and leptonic model curves are overlaid.

(Fermi-LAT, Science 2014)

MAGIC Telescopes

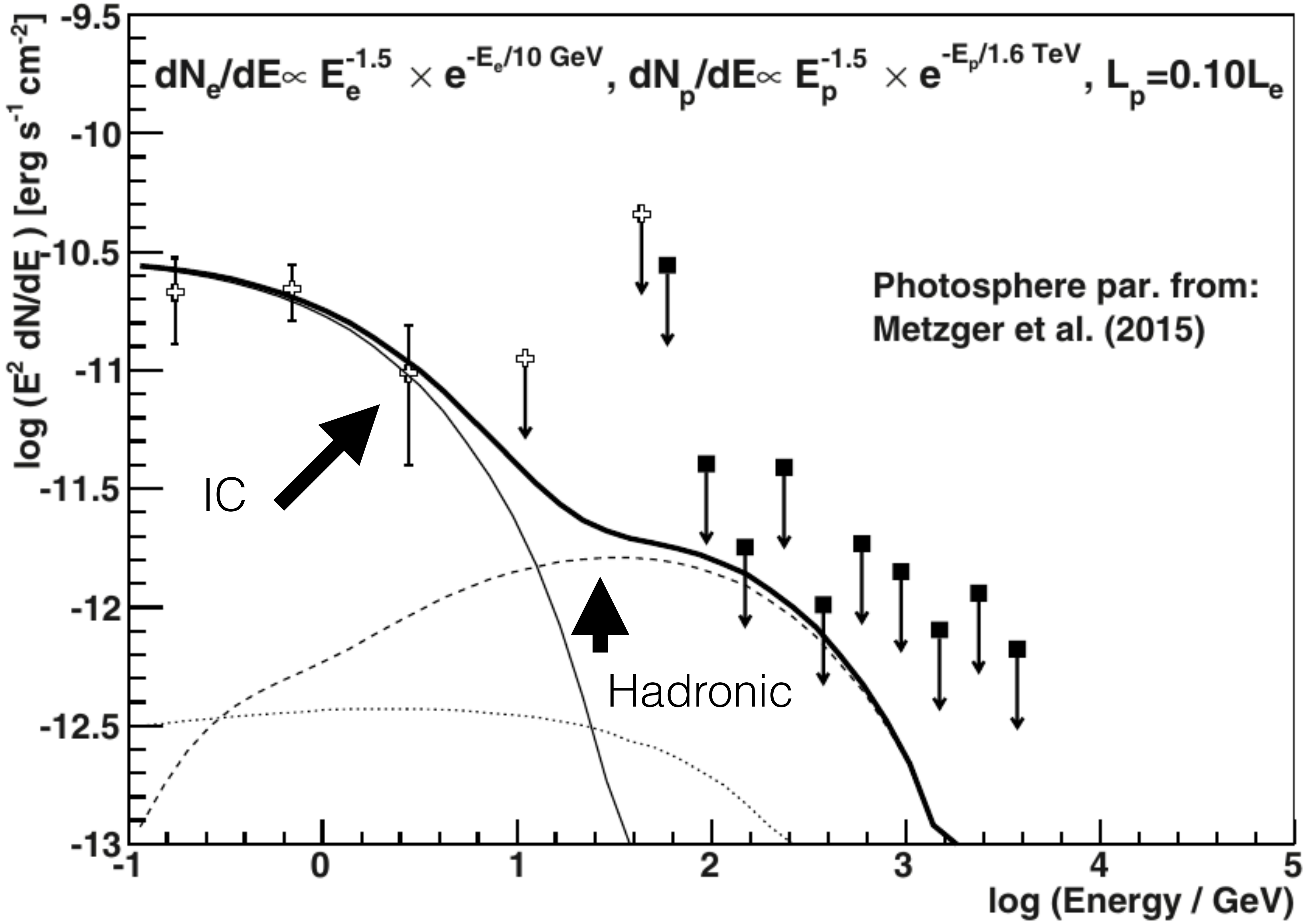


Picture credit: Antonio González

- 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

Novae with MAGIC

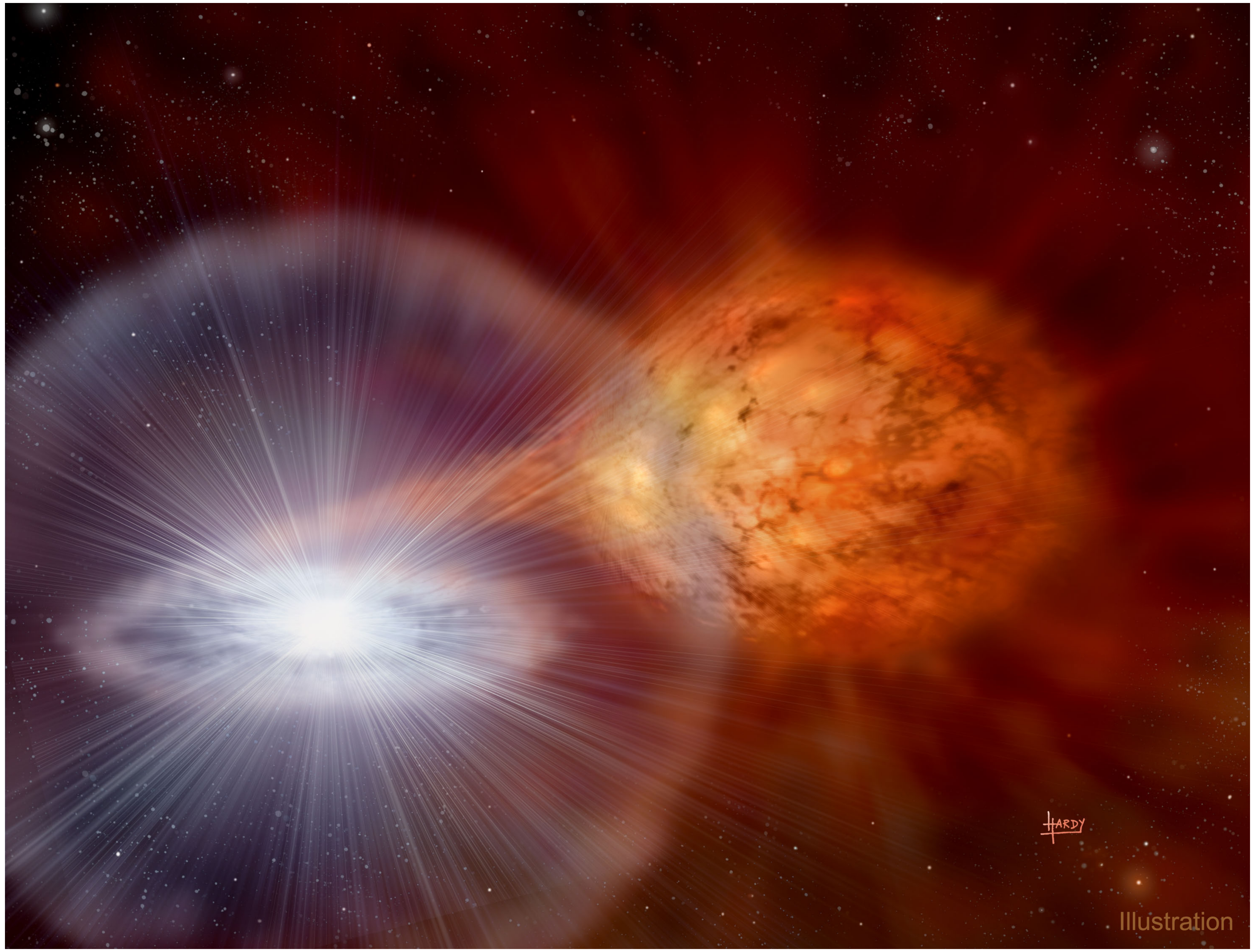
- MAGIC initiated a follow up program on novae in 2012
- VHE (>100 GeV) data is critical to understand emission mechanisms
- Constraining upper limits from V339 Del
- No detection until RS Oph



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

RS Ophiuchi

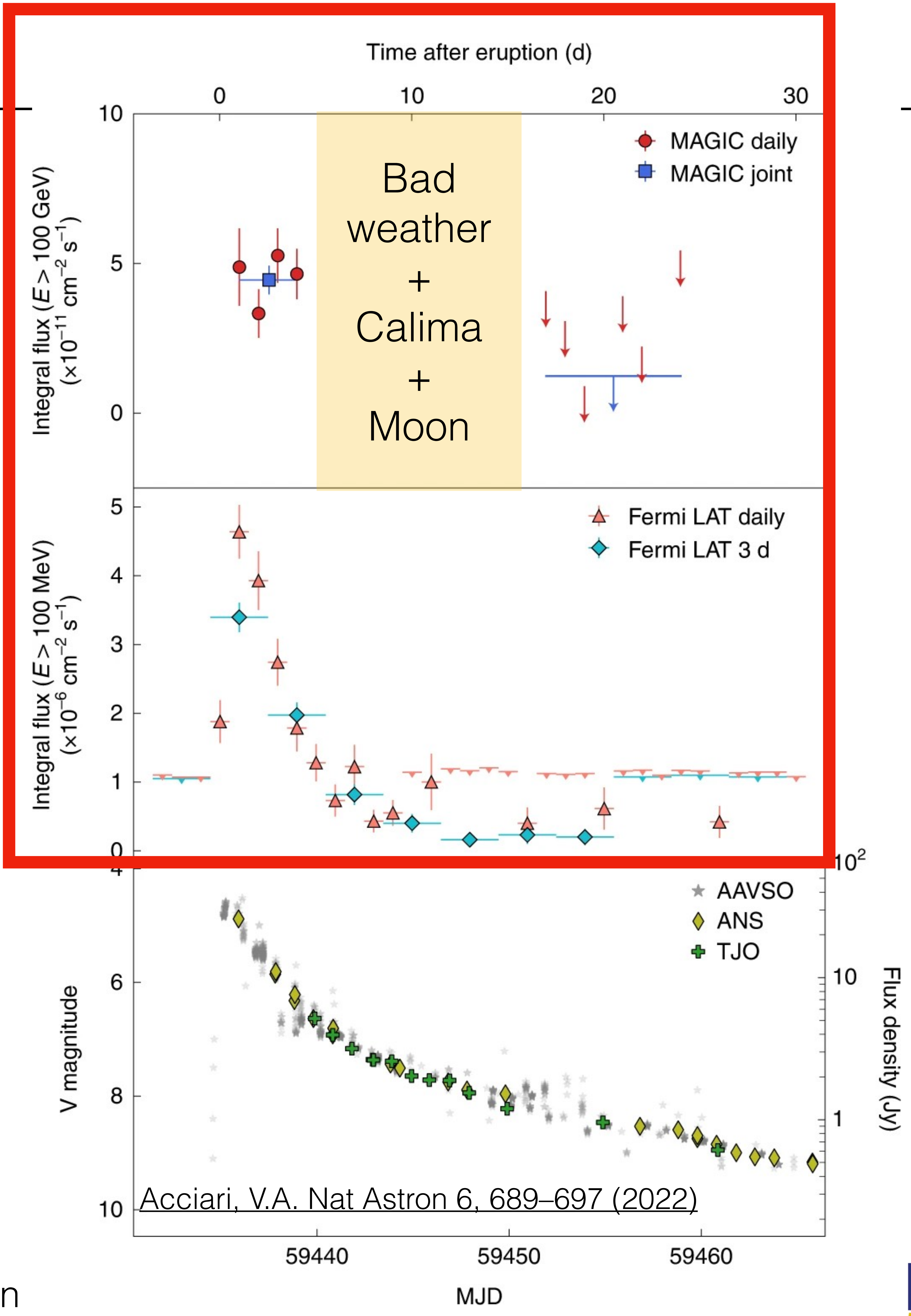
- Recurrent nova in a symbiotic binary
- Has major outburst every ~ 15 years
- WD (1.2–1.4$M_\odot$) + M0-2 III RG star (0.68–0.80$M_\odot$) Schaefer Astrophys. J. Suppl. Ser. 187, 275–373 (2010).
- Distance debated, range from 1.4 – 4.3 kpc with caveats for each
    - We used 2.45 kpc, derived from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



Credit: David A. Hardy

RS Ophiuchi in Gamma-rays

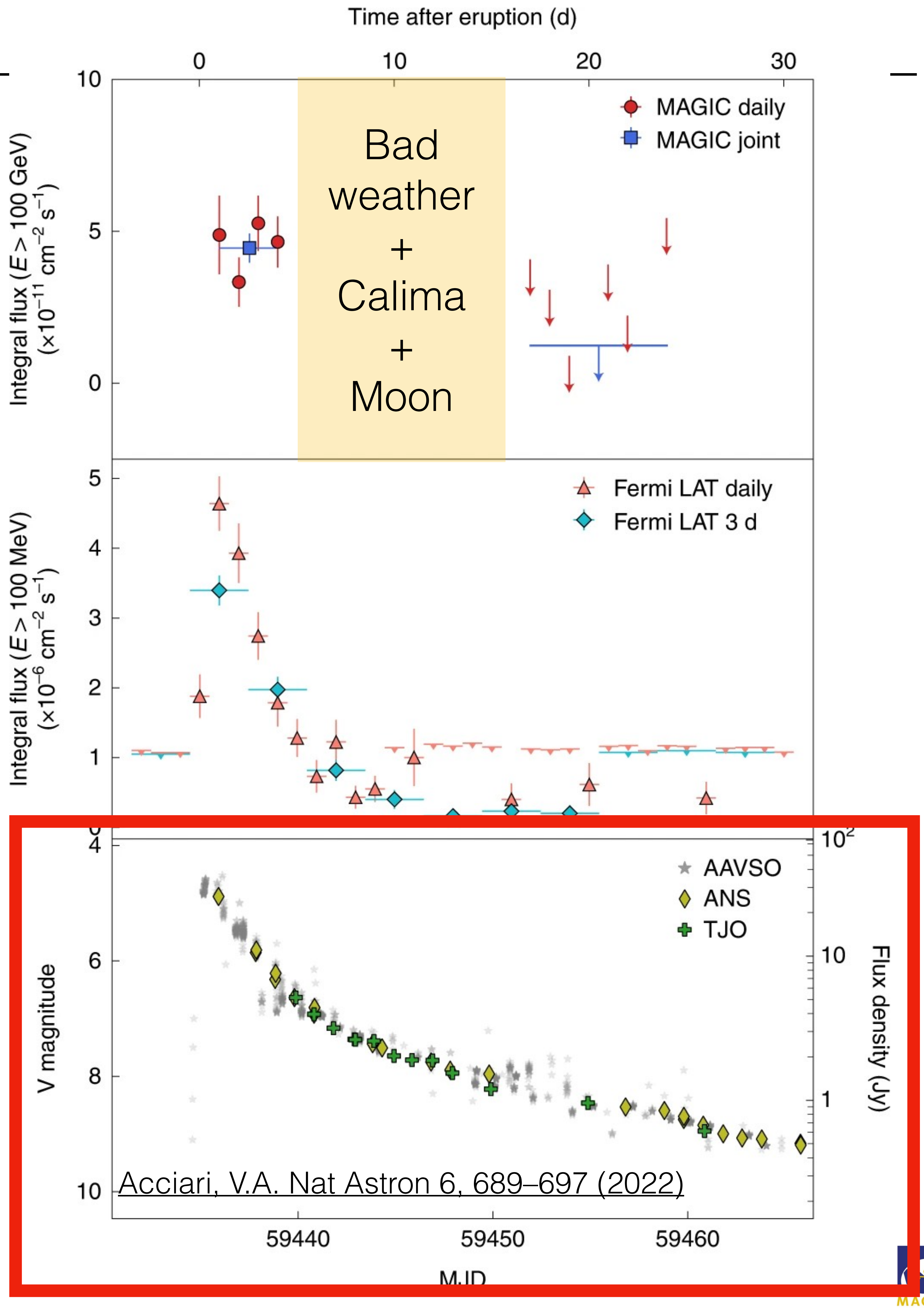
- HE shows rapid rise (brightest nova to date) and fall (exponential halving time (2.20 ± 0.18 days)
- The first four days of MAGIC observations (August 09-12) yield a VHE signal with a significance of 13.2σ
- No MAGIC detection as after August 25th
- VHE photon flux > 100 GeV constant over first 4 days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



Acciari, V.A. Nat Astron 6, 689–697 (2022)

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

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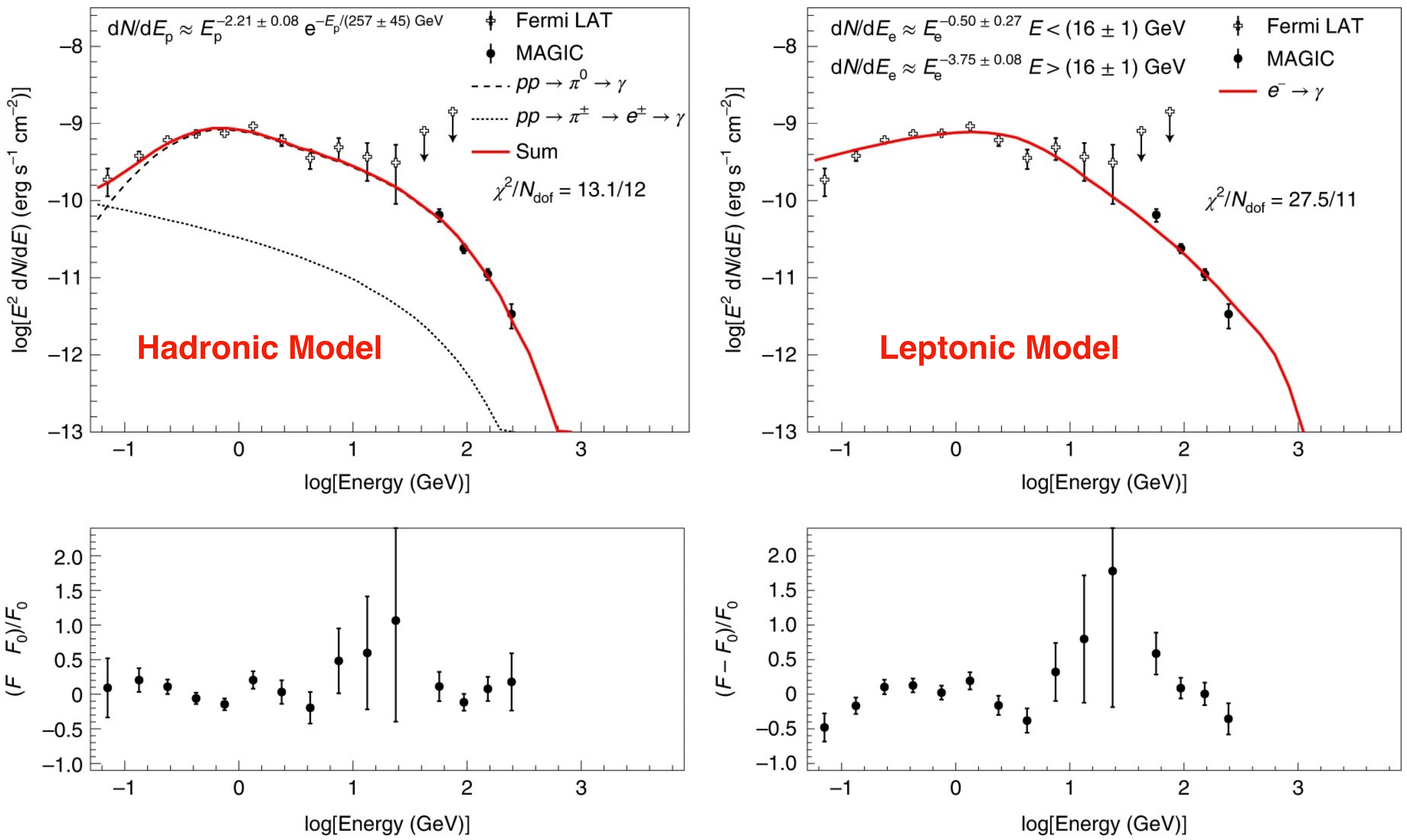
- Time dependent modeling based from MAGIC Coll., A&A, 582 (2015)
- Hadronic model favored over leptonic model
- Hadronic model has natural CR index ~2
- Leptonic requires ad hoc break and fits poorly



Daily Gamma-ray Modeling

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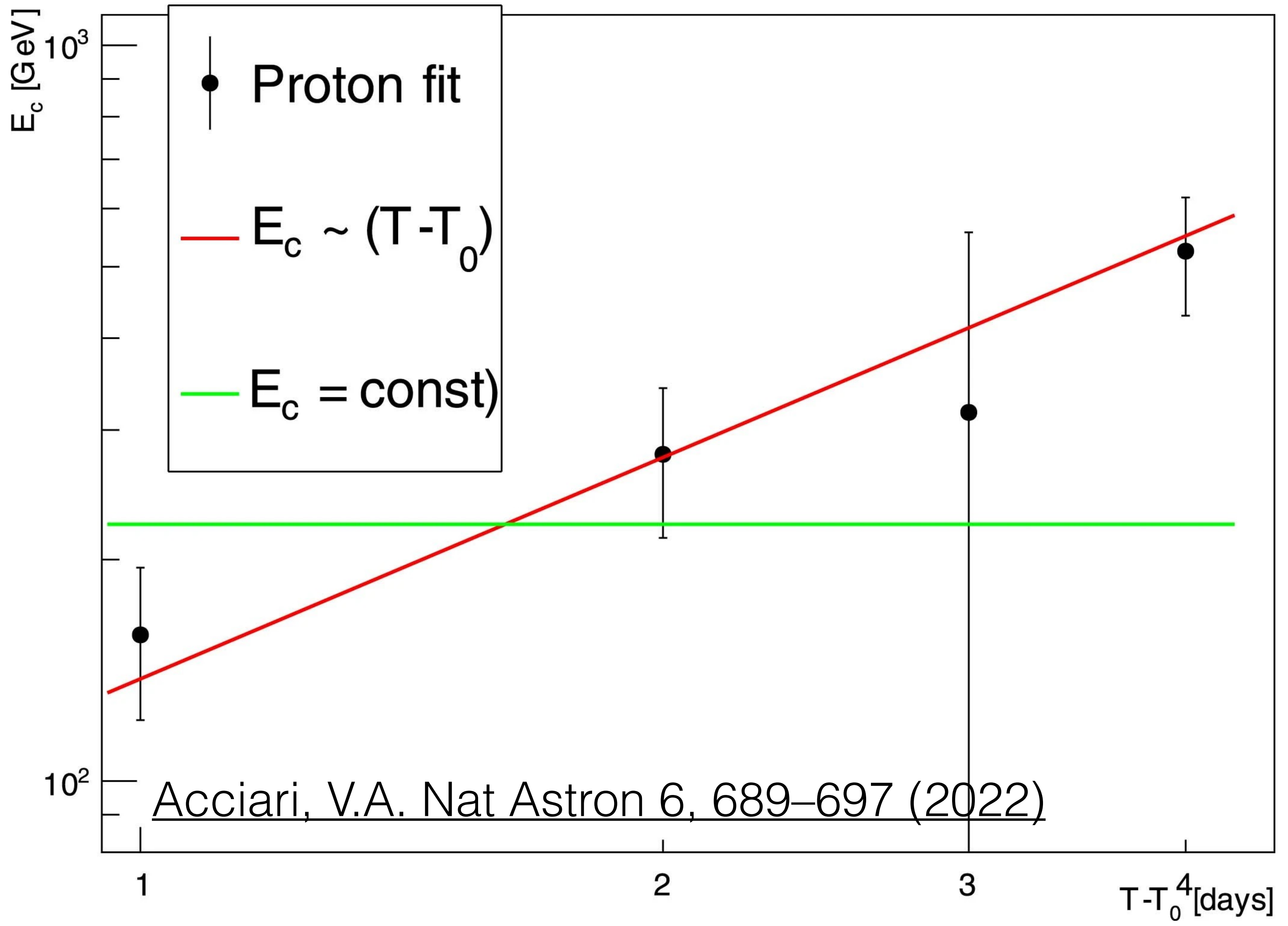
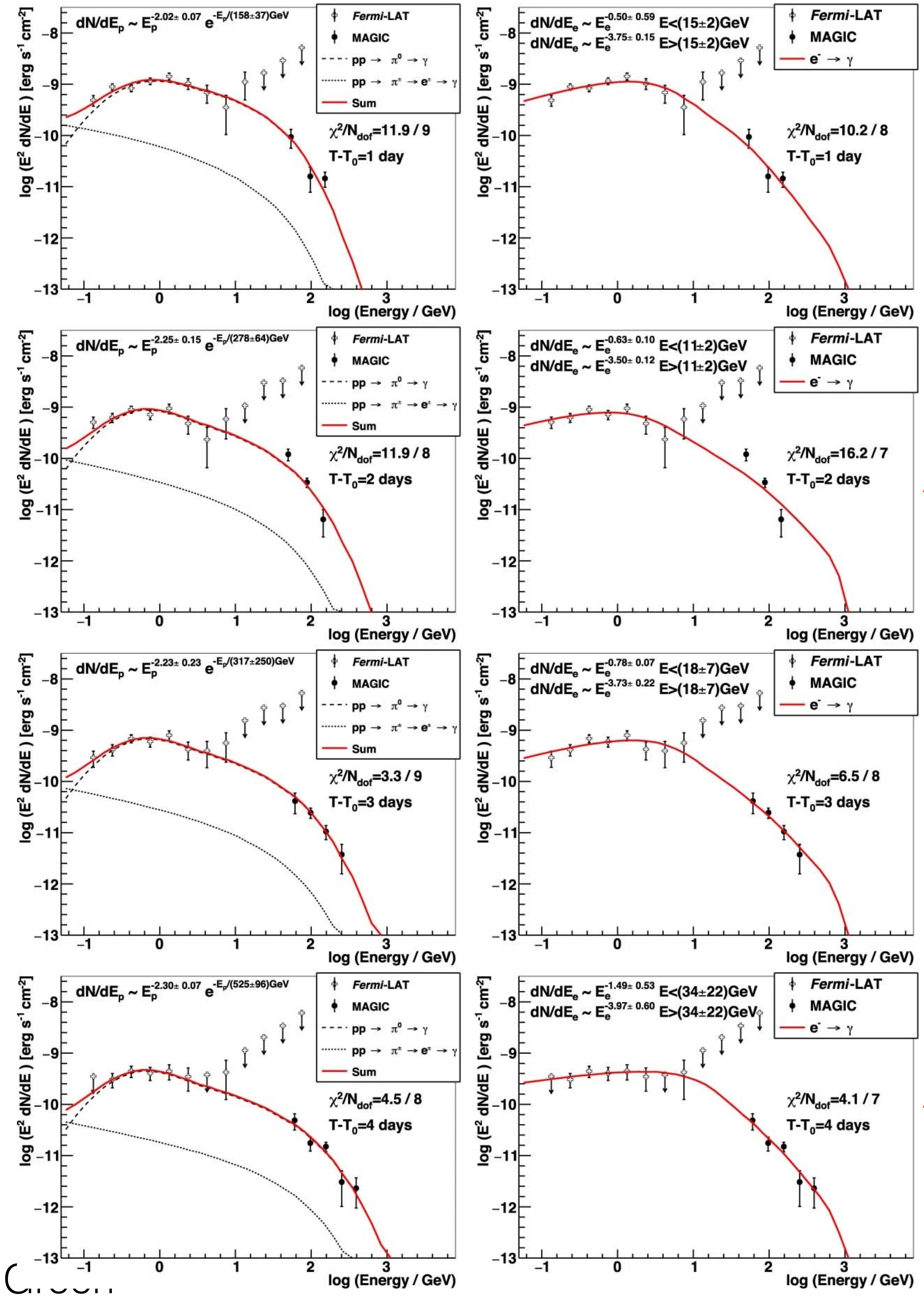
- Hadronic model preferred on the daily fits
- Slight indication of hardening (increase in maximum energy) vs time
- Inline with protons cooling slowly



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 shock expansion
- VHE emission seems stable
    - Hint of spectral hardening
    - Protons cool slowly + delayed emission

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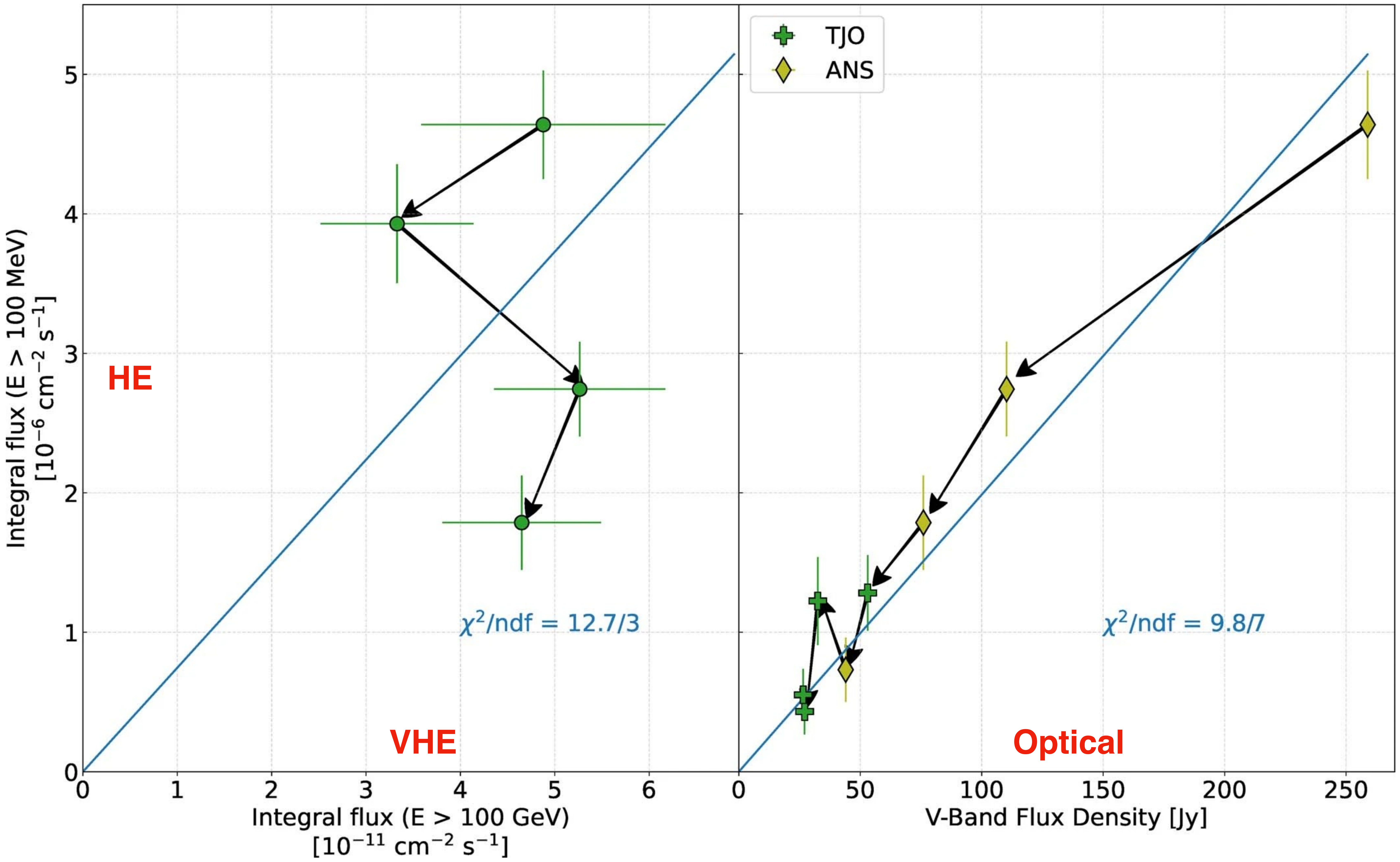

Context of other Gamma-ray Novae

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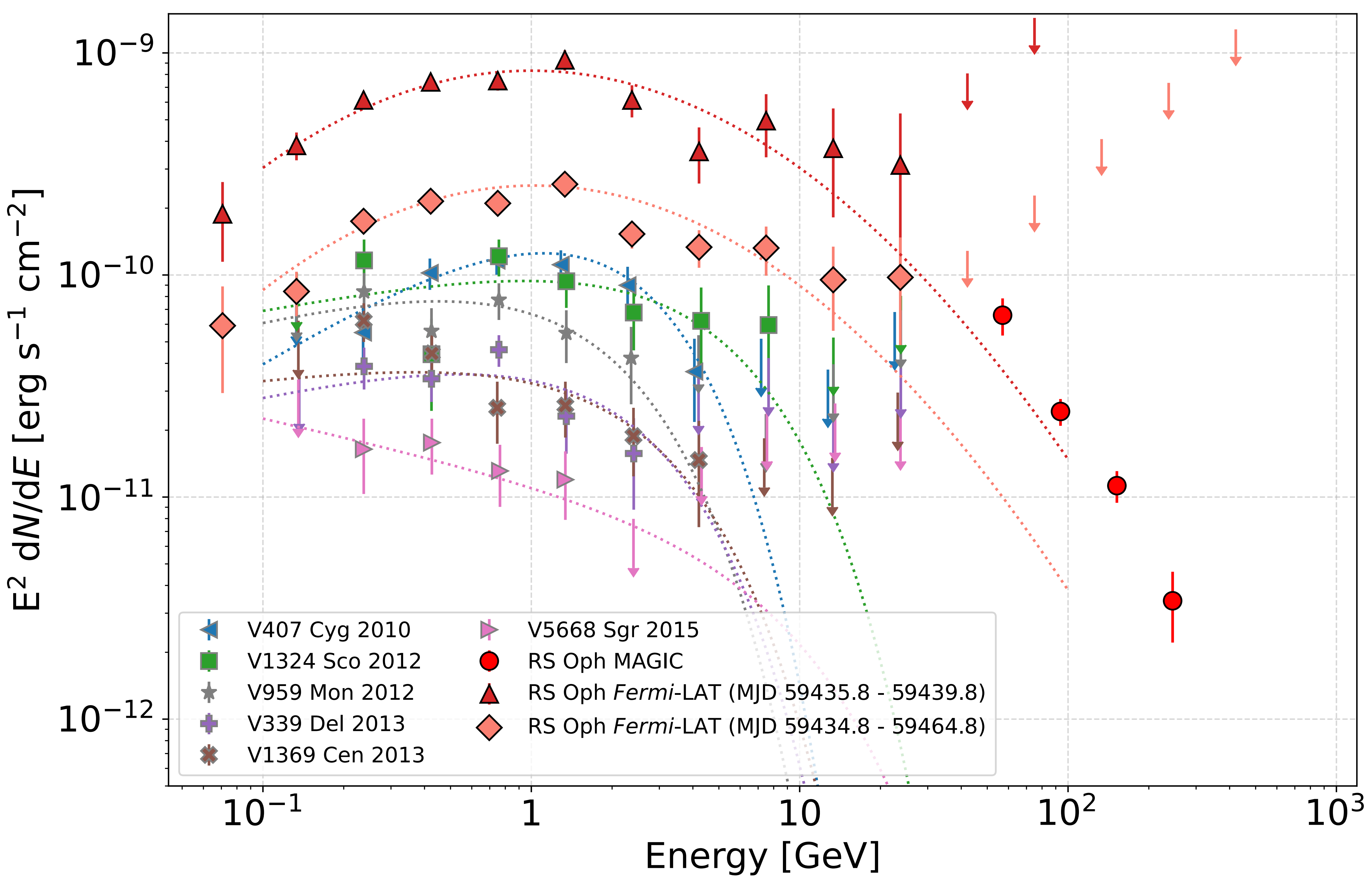

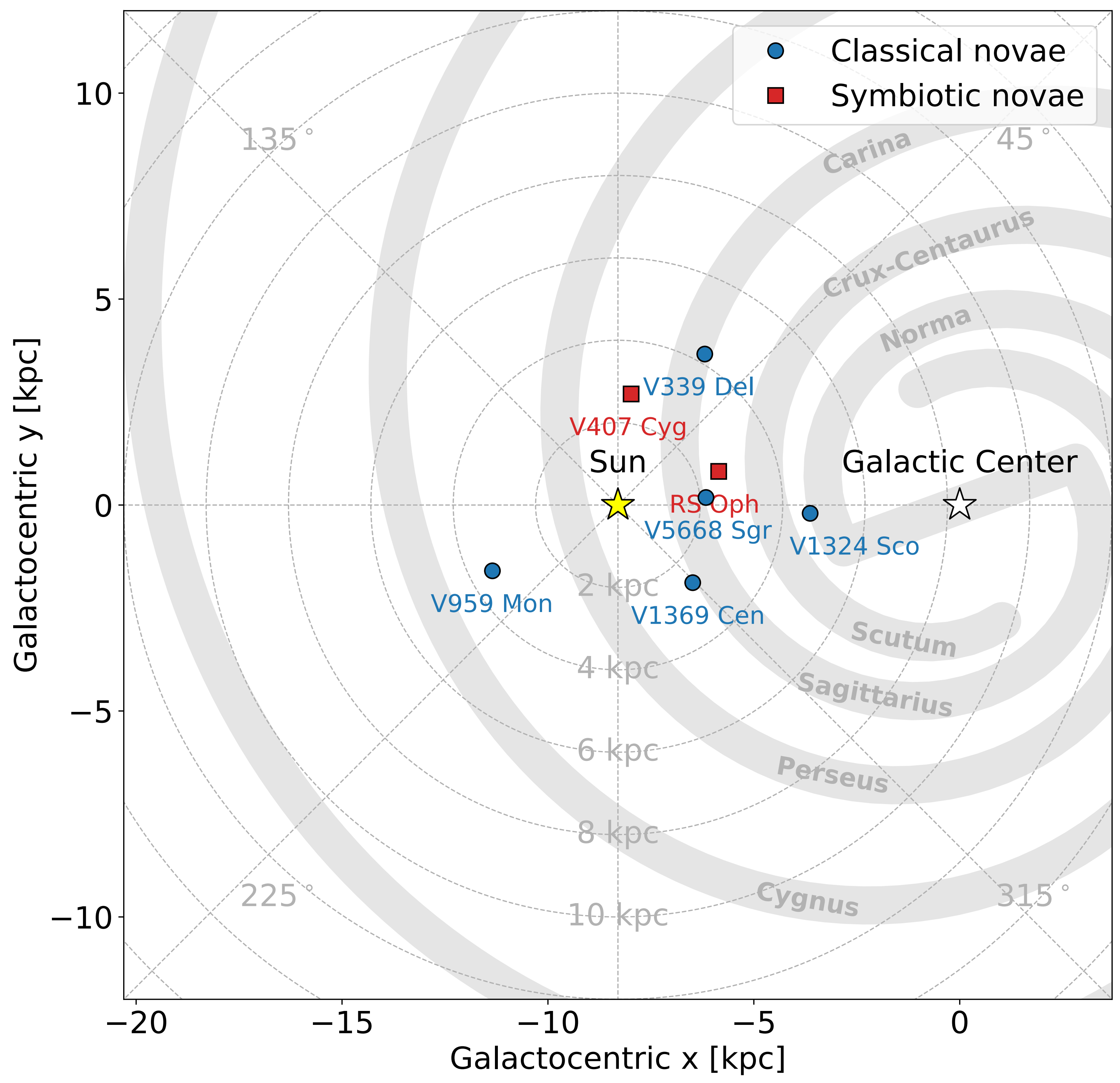

- RS Oph is of the highest flux of other gamma-ray novae

Context of other Gamma-ray Novae

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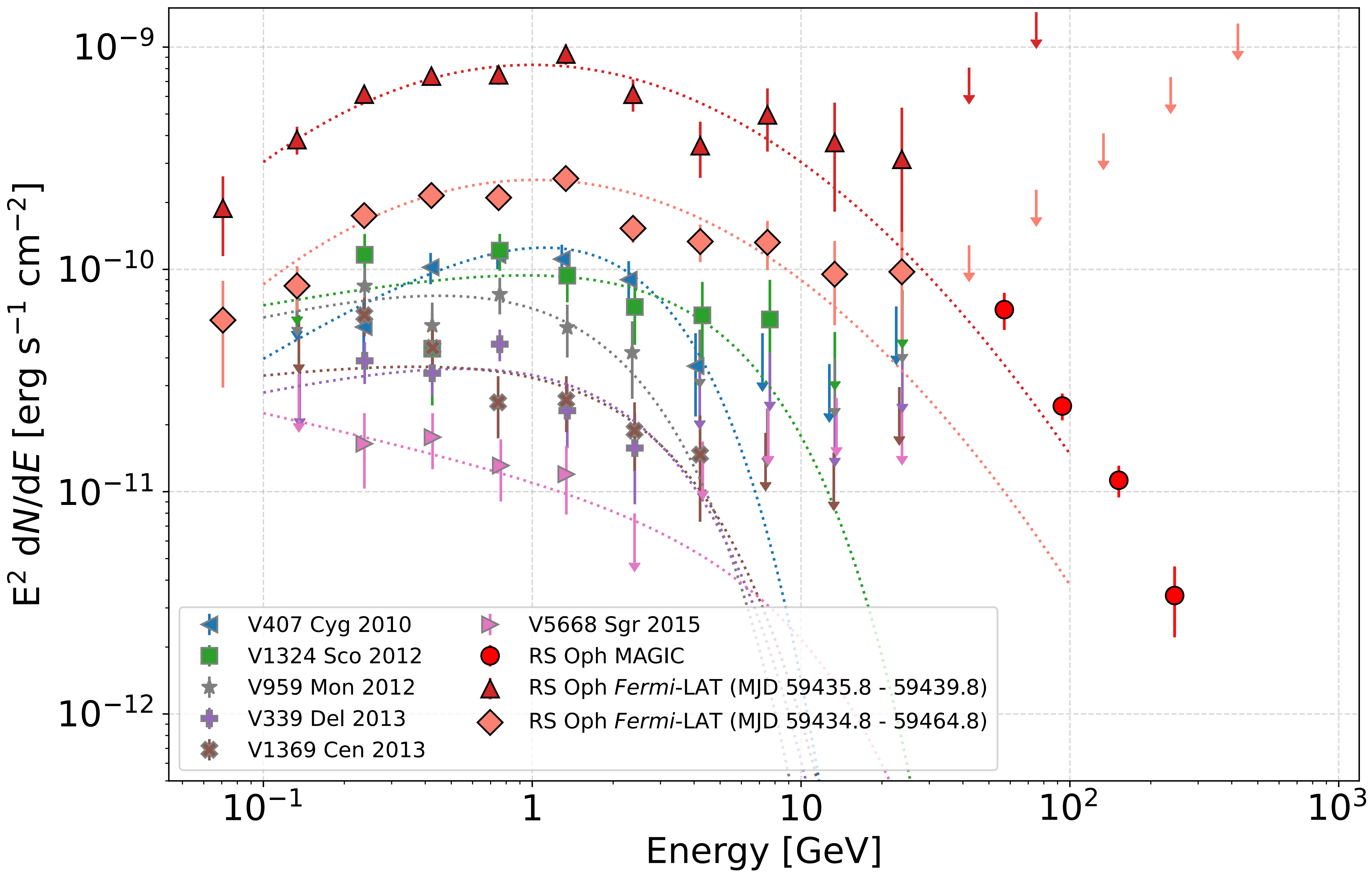

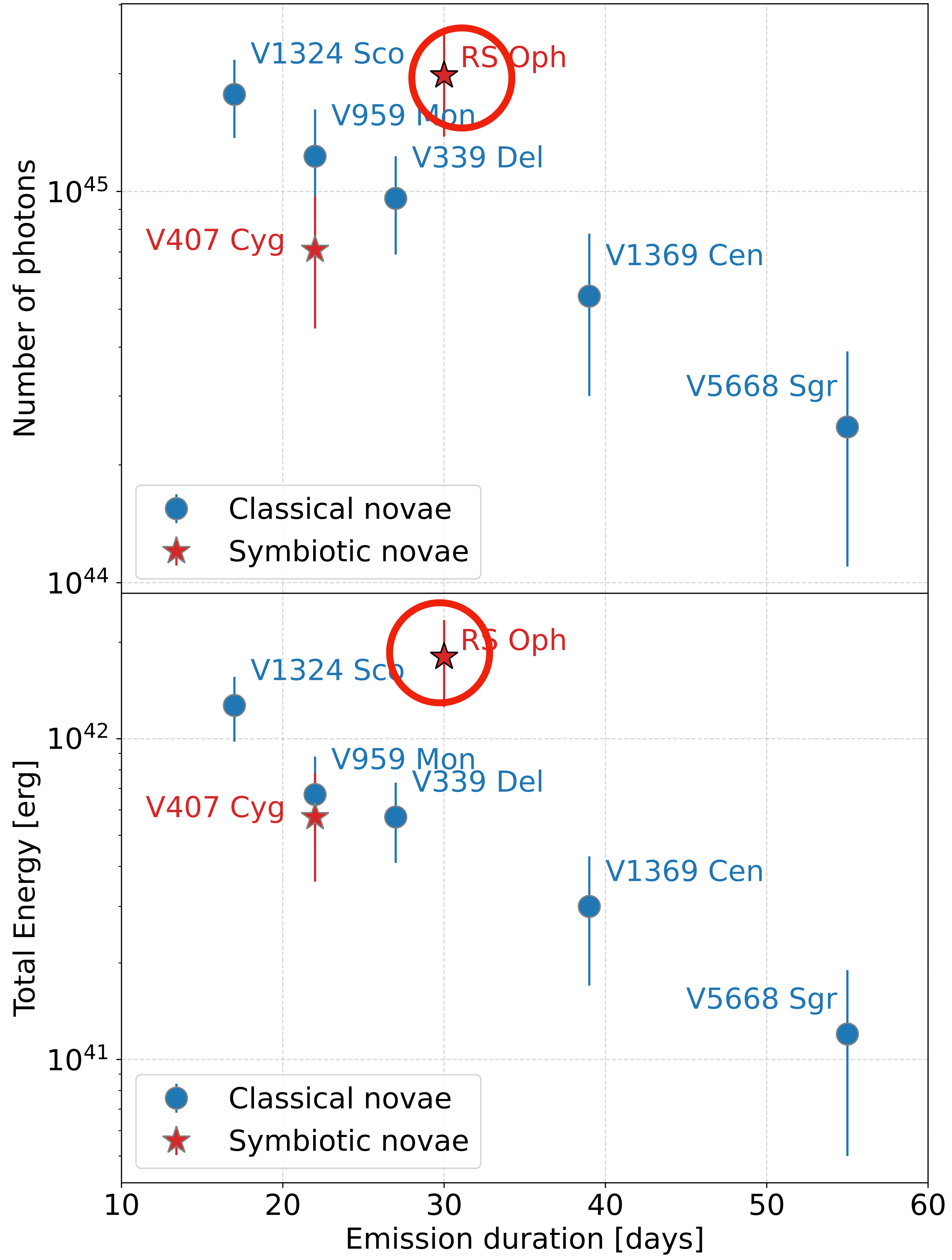

- Also intrinsically the brightest

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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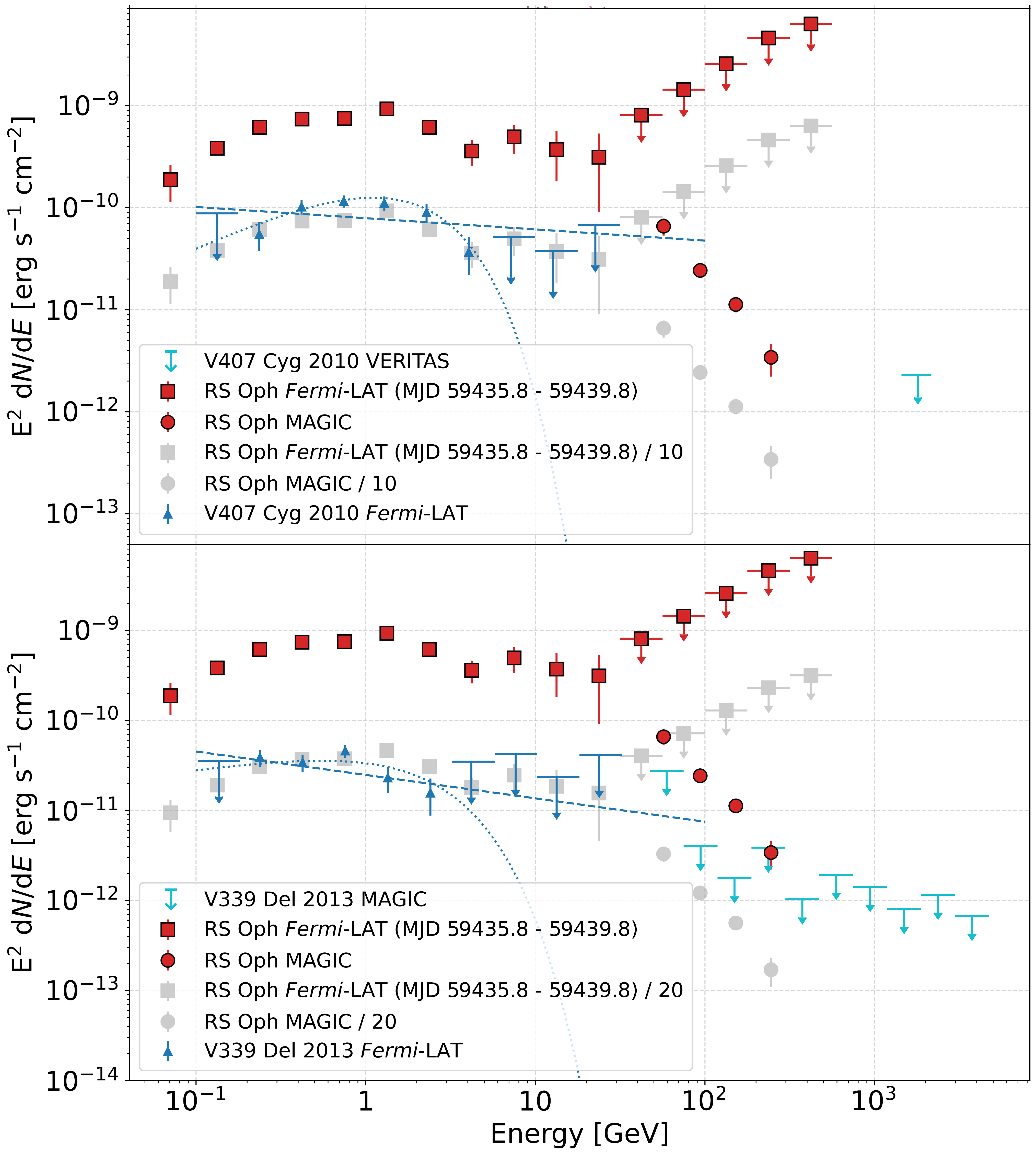
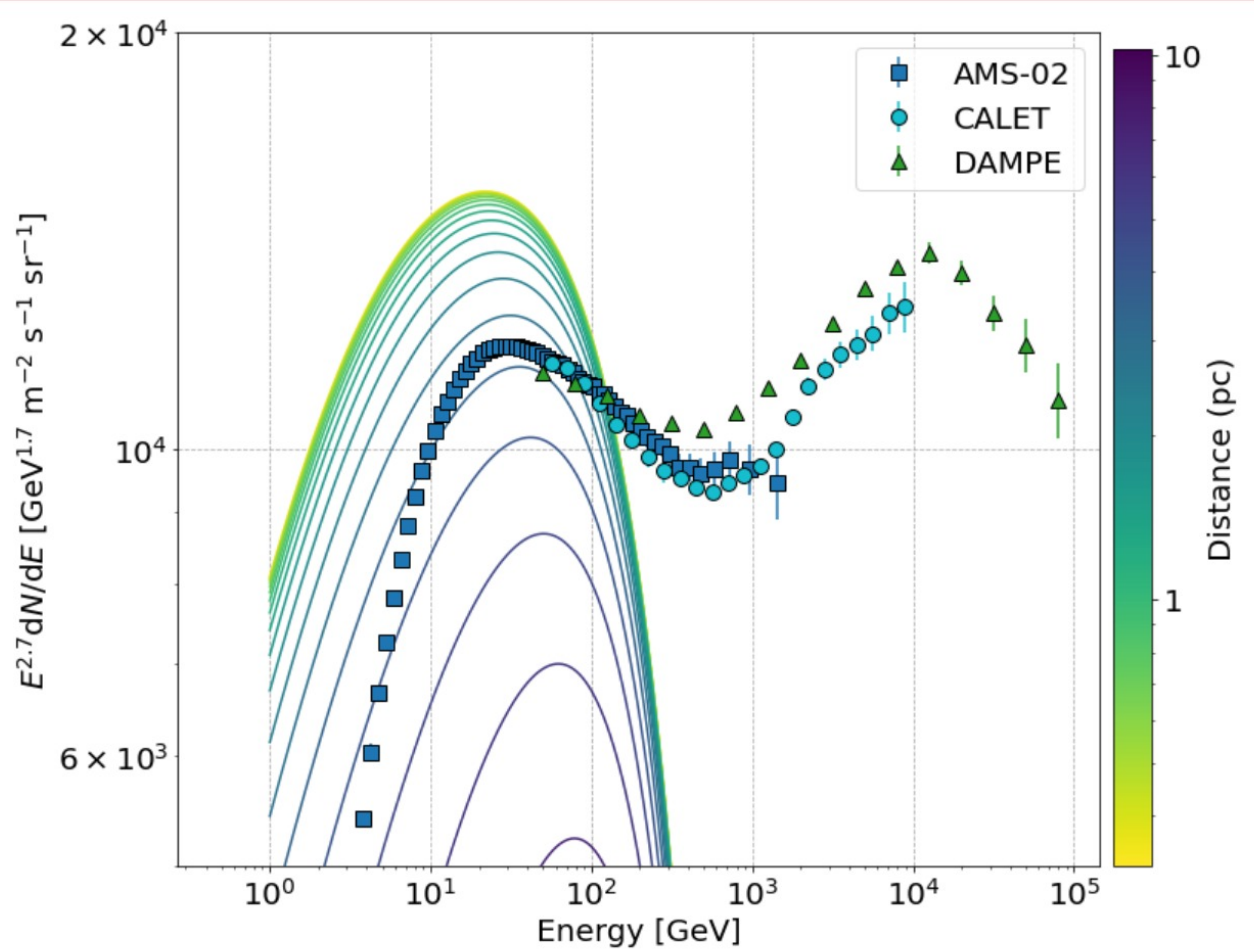


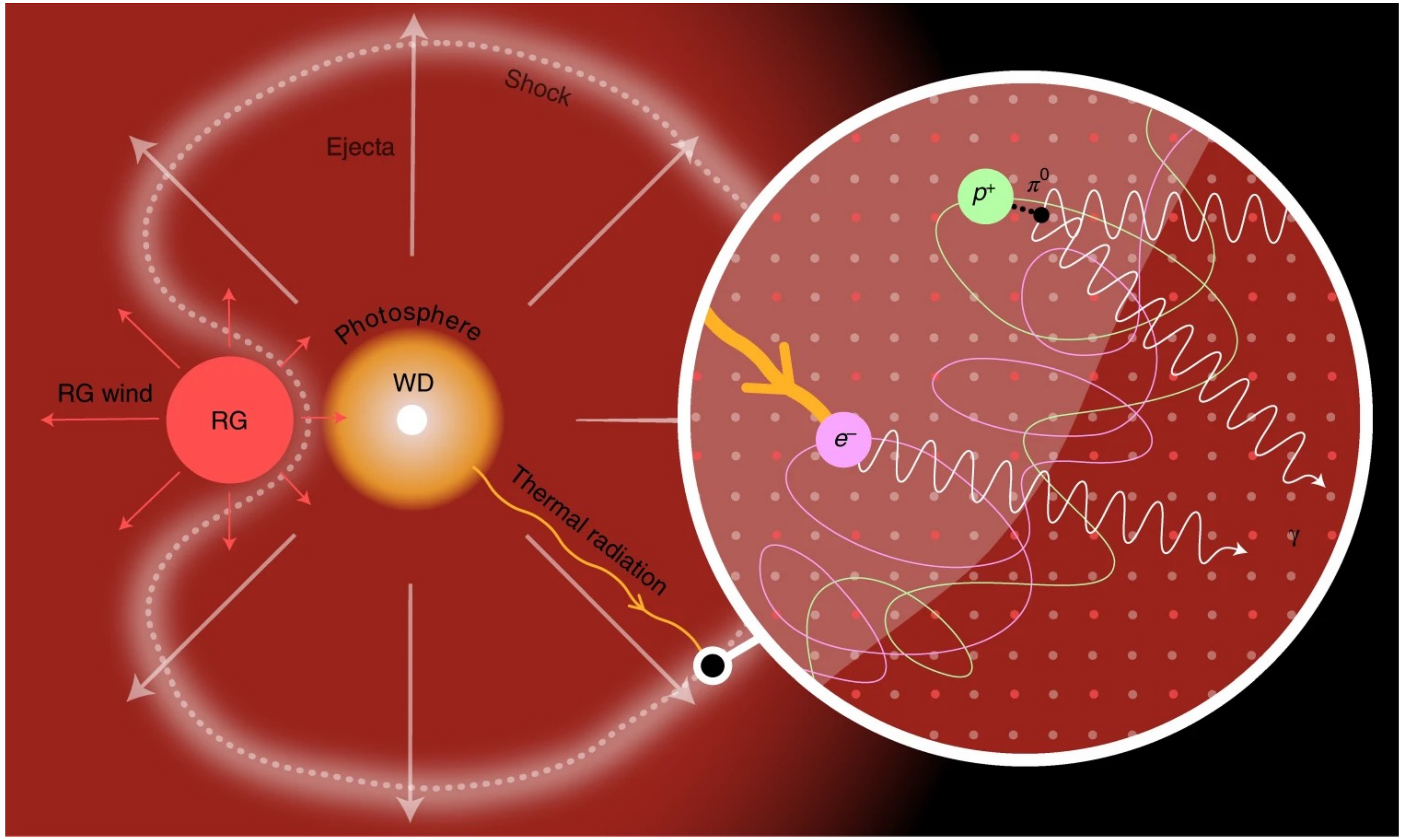
Galactic Cosmic Rays

- 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
  - Novae are not expected to contribute significantly to the measured CR spectrum



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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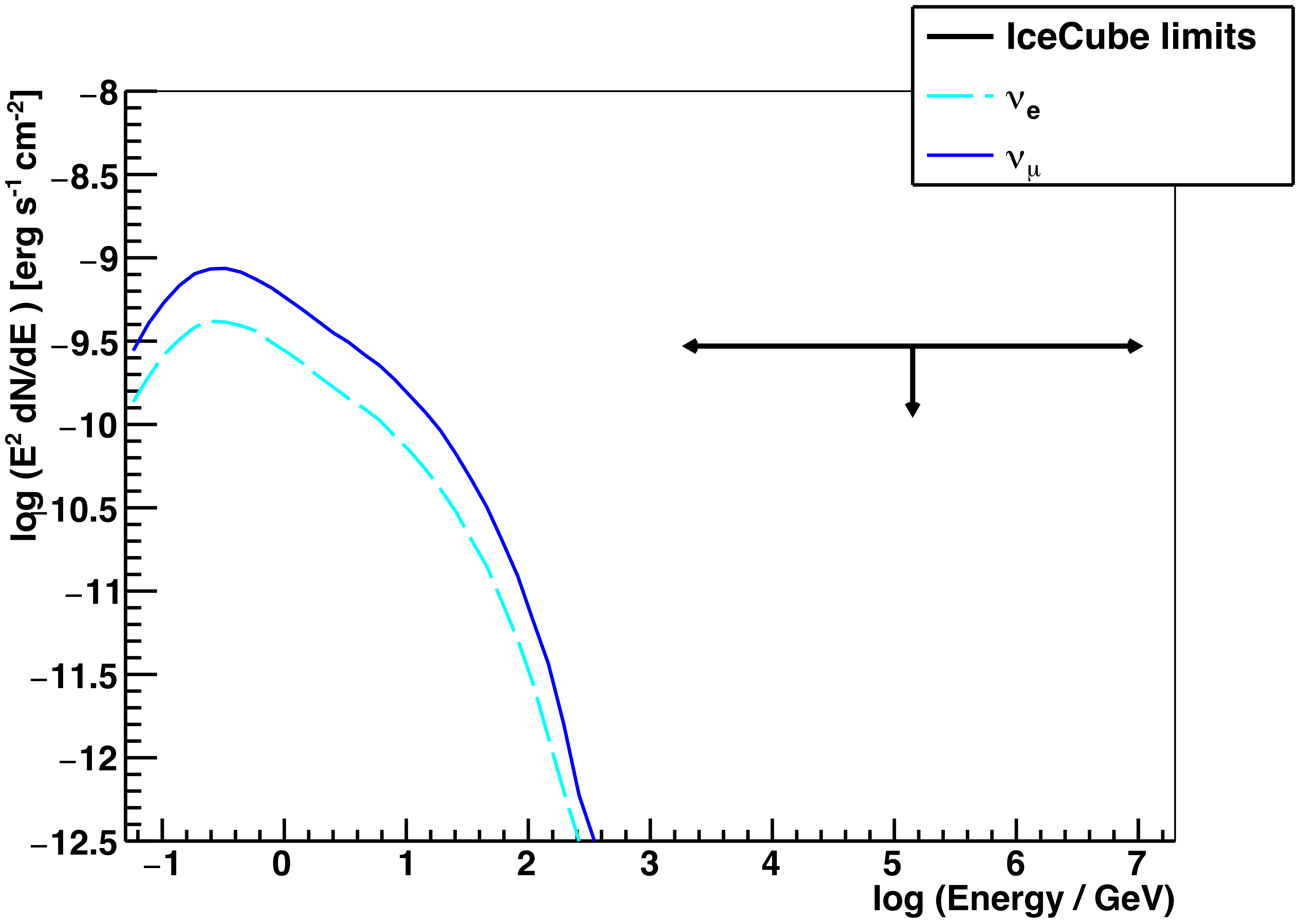
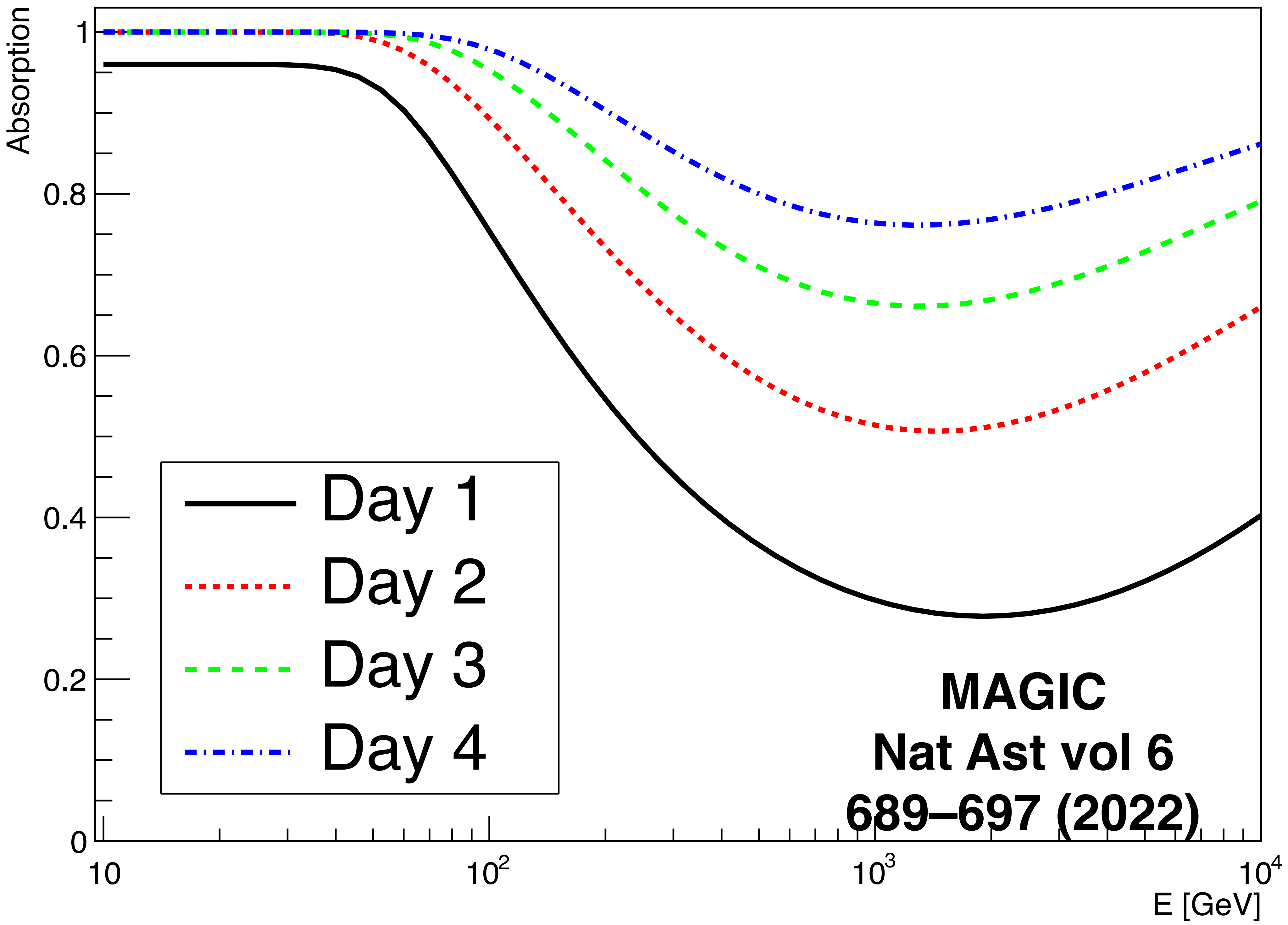
Backup Slides

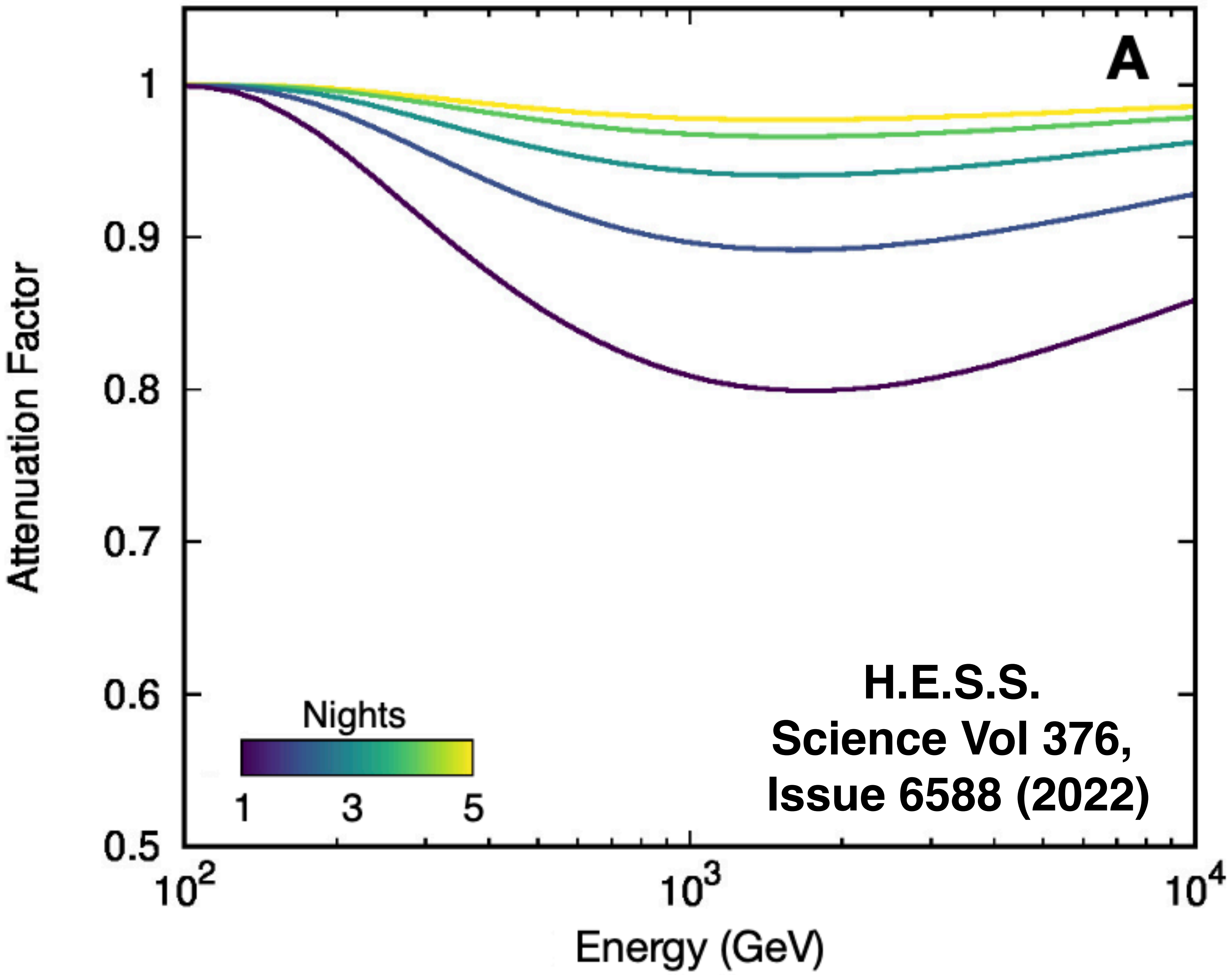
Neutrino Emission?



- IceCube ULs from Atel 14851
    - 2021-08-08 12:00:00 UTC
      2021-08-11 12:00:00 UTC
    - Coverage of MAGIC observations
- Unfortunately, IceCube ULs not constraining given MAGIC hadronic model

Absorption





- MAGIC estimates a stronger absorption than H.E.S.S.
- Consistent in strongest effects on the first day and at highest energies
- Likely due to different distances used between MAGIC and H.E.S.S.

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 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

RS Viewing from La Palma

RS Oph Outburst Begins

	Period 230																								Period 231										
UT↓ -Day&rarr	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2
19:00	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
19:30	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
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21:30	38	37	37	37	37	36	36	36	36	36	36	35	35	35	35	35	35	36	36	36	36	36	36	37	37	37	37	38	38	38	39	39	40	40	40
22:00	36	36	36	36	35	35	35	35	35	36	36	36	36	36	36	36	37	37	37	38	38	38	39	39	39	40	40	41	41	42	42	43	43	44	44
22:30	35	36	36	36	36	36	36	36	37	37	37	37	38	38	38	39	39	40	40	41	41	42	42	43	43	44	44	45	45	46	47	47	48	48	49
23:00	37	37	37	37	38	38	38	39	39	40	40	40	41	41	42	42	43	43	44	45	45	46	46	47	48	48	49	50	50	51	52	52	53	54	54
23:30	39	39	40	40	41	41	42	42	43	43	44	44	45	46	46	47	47	48	49	49	50	51	51	52	53	53	54	55	56	56	57	58	59	59	60
00:00(+)	42	43	44	44	45	45	46	47	47	48	48	49	50	50	51	52	52	53	54	55	55	56	57	57	58	59	60	61	61	62	63	64	64	65	66
00:30(+)	47	48	48	49	49	50	51	52	52	53	54	54	55	56	56	57	58	59	59	60	61	62	63	63	64	65	66	67	67	68	69	70	71	71	72
01:00(+)	52	53	53	54	55	56	56	57	58	58	59	60	61	62	62	63	64	65	65	66	67	68	69	69	70	71	72	73	74	74	75	76	77	78	79
01:30(+)	57	58	59	60	60	61	62	63	64	64	65	66	67	68	68	69	70	71	72	72	73	74	75	76	77	77	78	79	80	81	82	82	83	84	85
02:00(+)	63	64	65	66	66	67	68	69	70	71	71	72	73	74	75	75	76	77	78	79	80	80	81	82	83	84	85	86	86	87	88	89	90	90	-
02:30(+)	69	70	71	72	73	74	74	75	76	77	78	78	79	80	81	82	83	84	84	85	86	87	88	89	90	90	90	-	-	-	-	-	-	-	-
03:00(+)	76	77	77	78	79	80	81	82	82	83	84	85	86	87	88	88	89	90	90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
03:30(+)	82	83	84	85	86	86	87	88	89	90	90	90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
04:00(+)	89	89	90	90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
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06:00(+)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
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Day	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2
Dark hours	*3*	*3.5*	*4*	*4.5*	*4.5*	*4*	*4*	*4*	*4*	*4*	*4*	*3.5*	*2.5*	*2*	*1.5*	*1*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*1*	*1.5*	*2*	*2.5*	*3*	*3*	*3*	*3*	*3*
(+) Change of date		*Tot. dark hours in september 2021: 76*																																	