MAGIC@20

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Financiado por la Unión Europea
NextGenerationEU

Plan de Recuperación, Transformación y Resiliencia

INSTITUTO D ASTROFISICA D CANARIAS · IAC ·

AGENCIA ESTATAL DE INVESTIGACIÓN

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Novae with MAGIC

Alicia López Oramas
(Instituto de Astrofísica de Canarias)

20 MAGIC Years Symposium, October 2023

Credit: Superbossa/MPP

Novae

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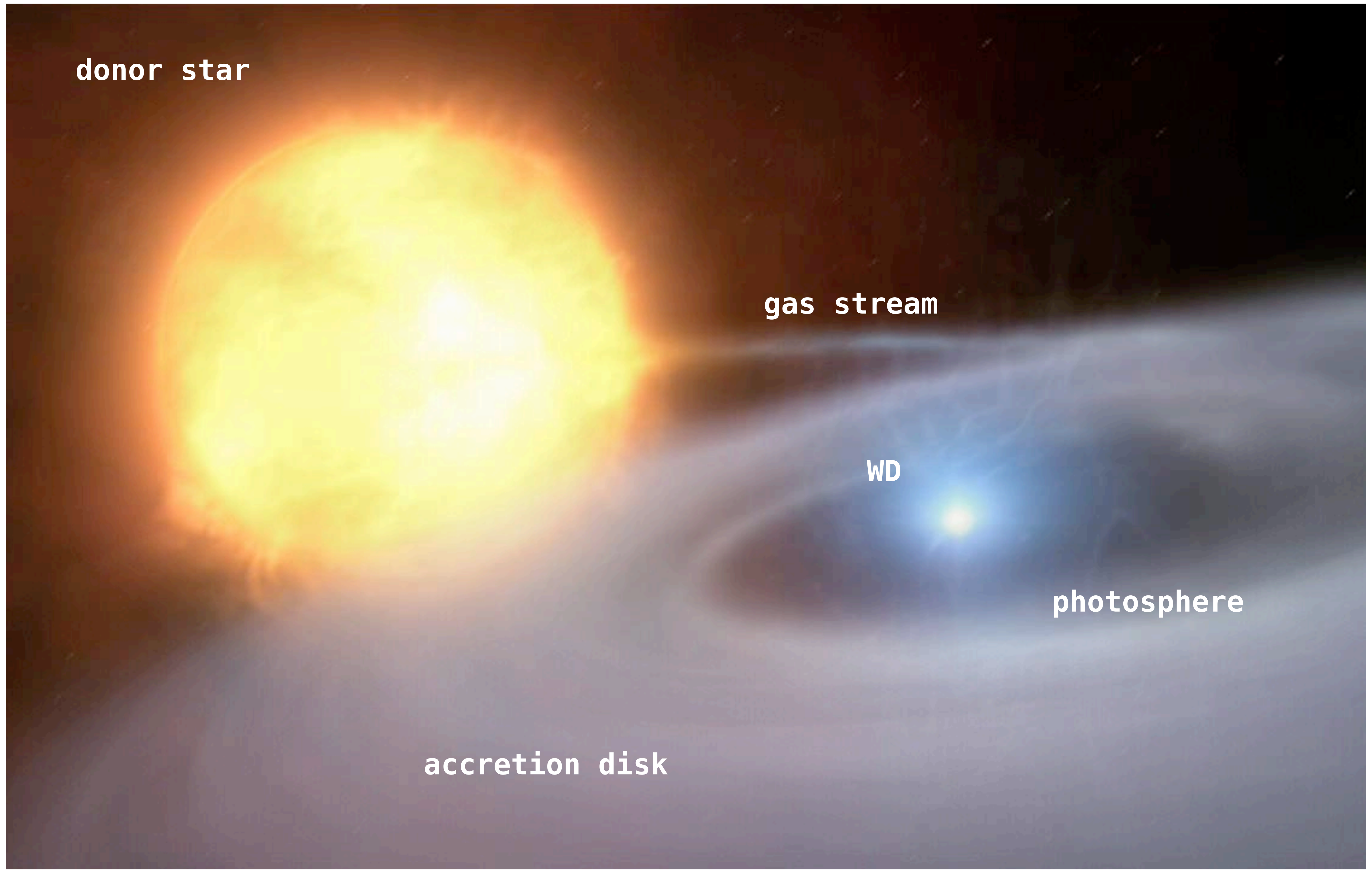
Classical novae

main sequence star+WD



Credit: ESO / M. Kornmesser

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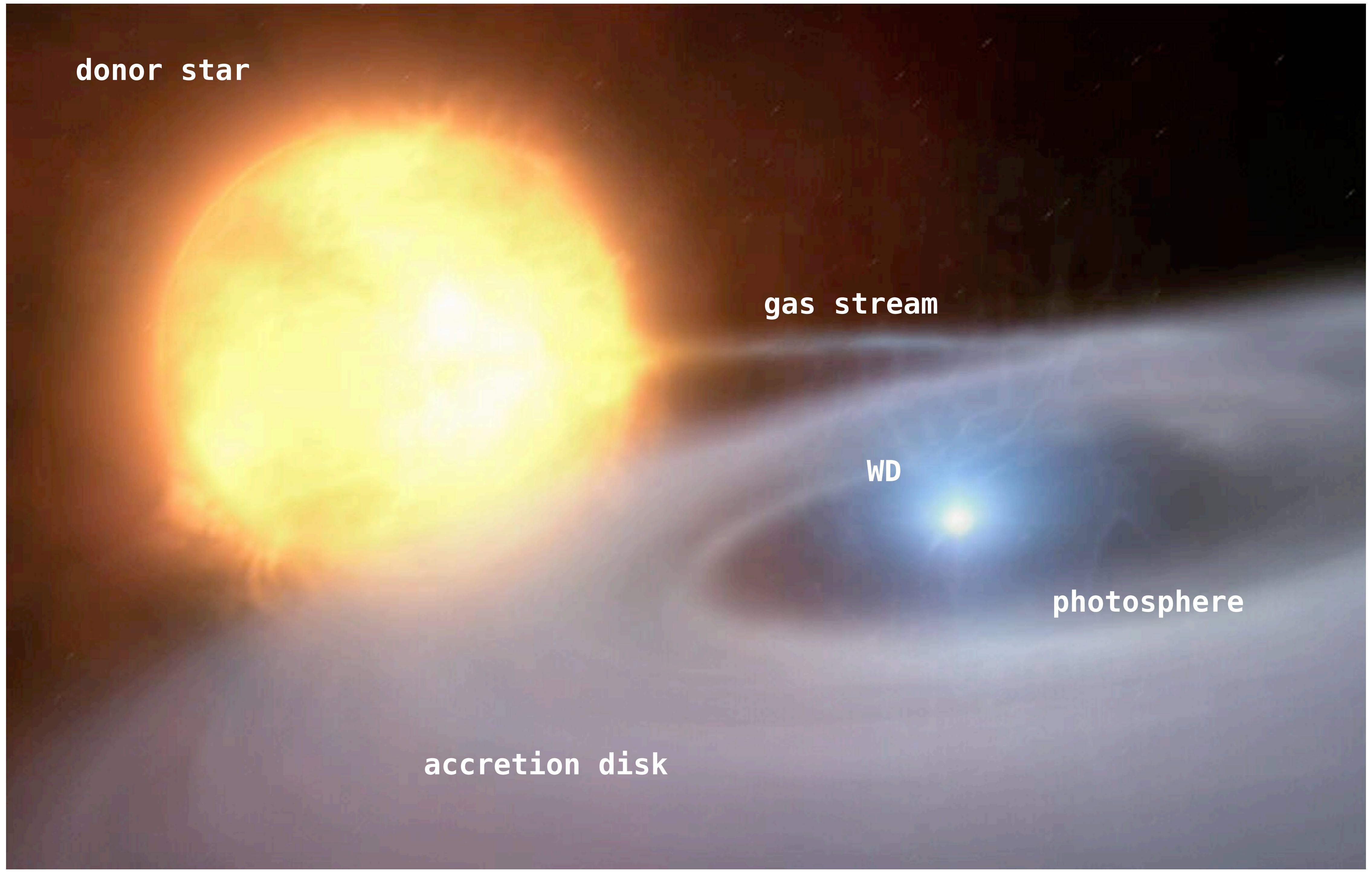

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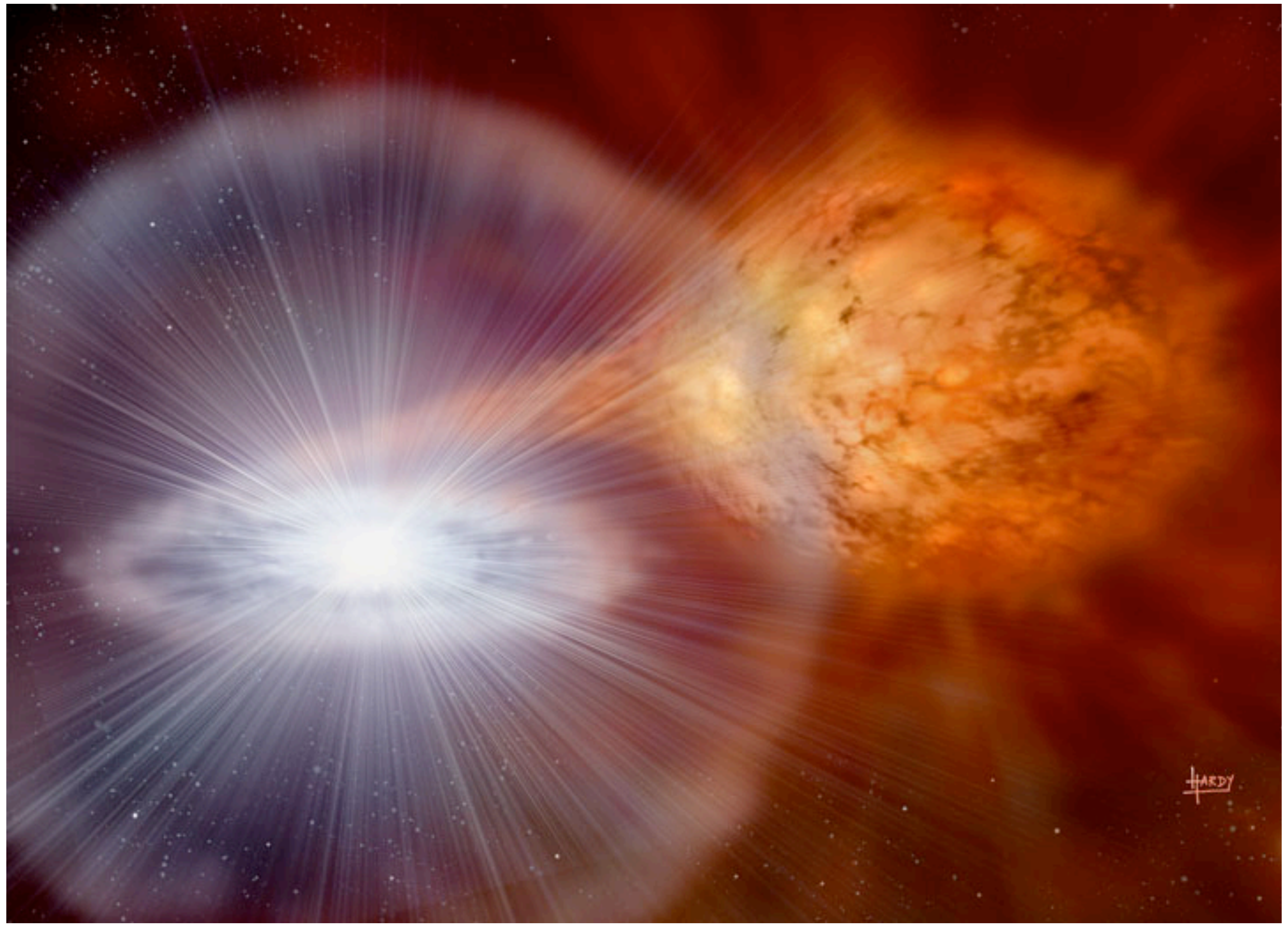
Symbiotic novae
red giant + WD



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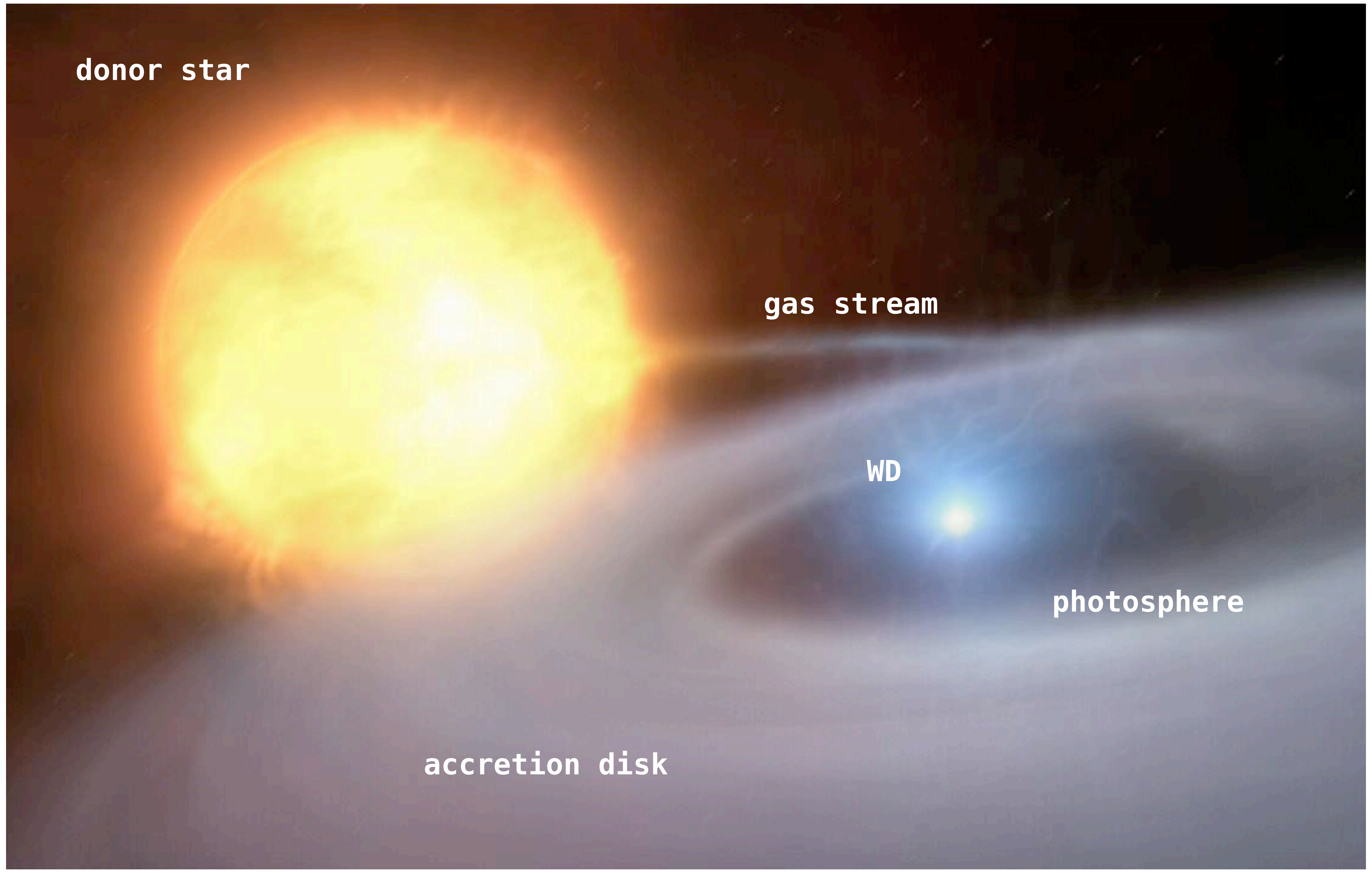
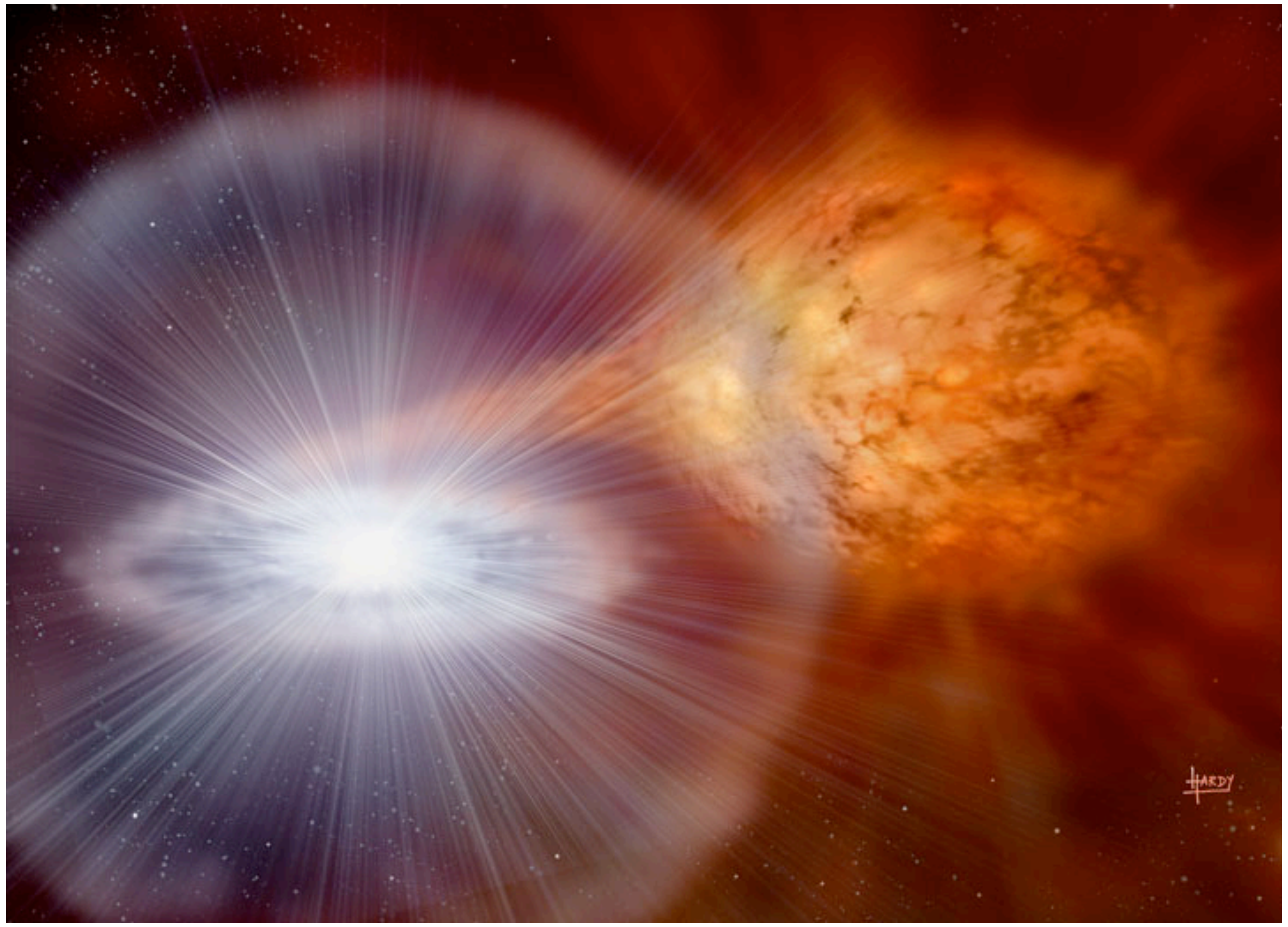


Credit: ESO / M. Kornmesser

- Roche-lobe overflow
- Long (no) recurrency : > 10^4 years

Symbiotic novae

red giant + WD



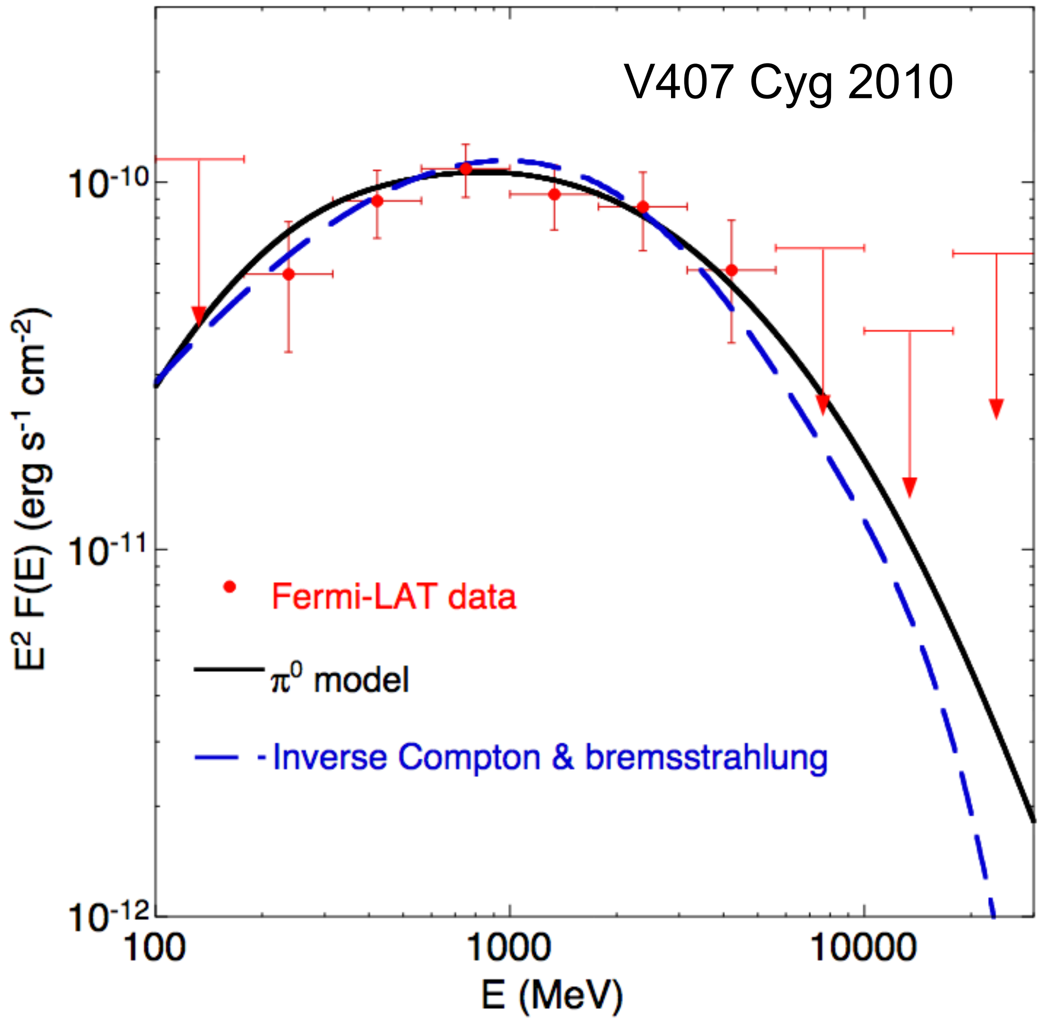
Credit: Hardy

- Accretion from stellar wind
- Some novae show repeated outbursts within a human lifetime: **recurrent novae (RN)**

The quest

Novae: sources of HE gamma rays

- The **first nova** to be detected by *Fermi*-LAT was the **symbiotic** system V407 Cyg (*Fermi*–LAT, Science, 2010)
- **Novae established as HE emitters (HE, E>100 MeV)**



Fermi–LAT, Science, 2014

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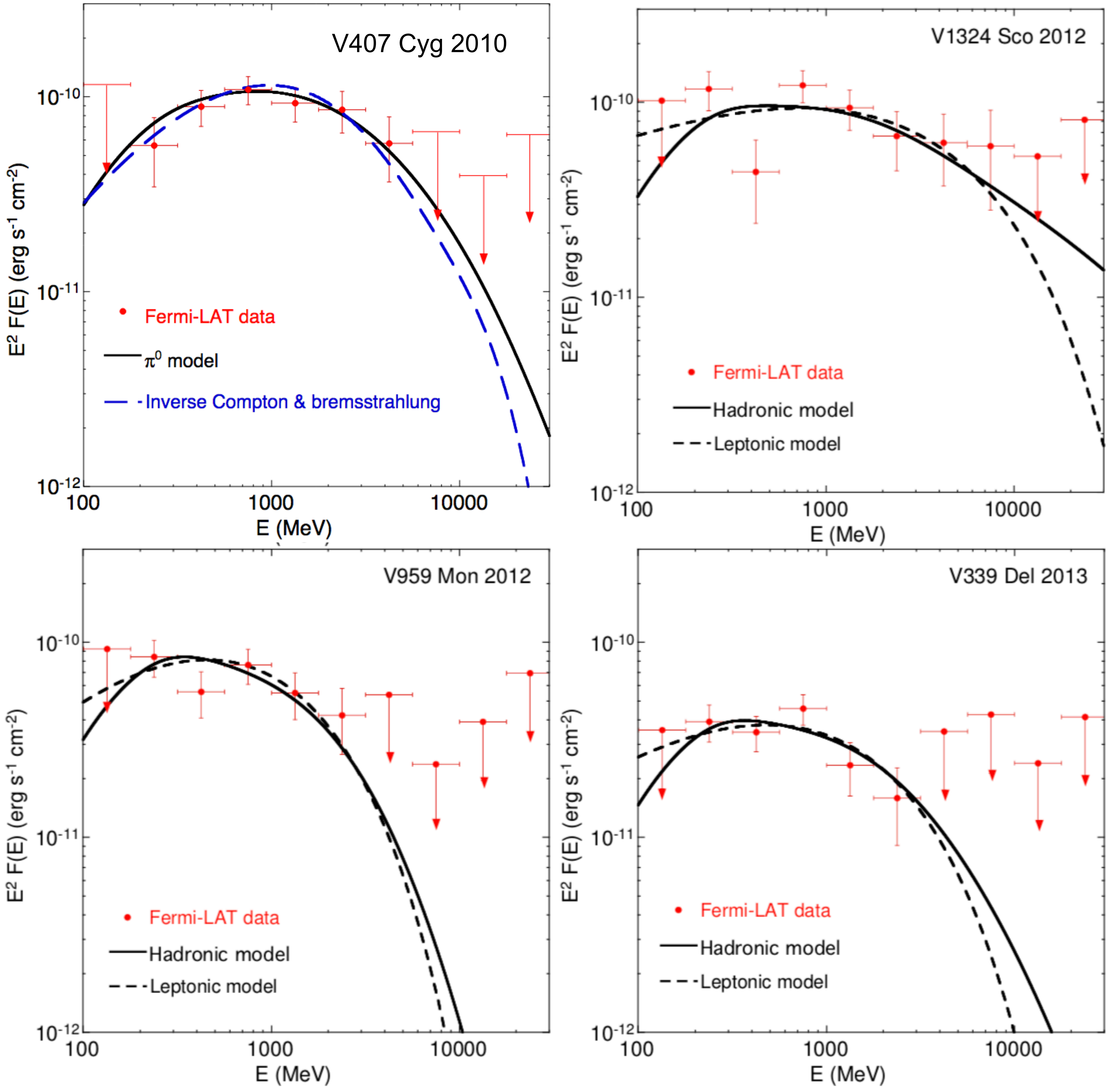
- **Novae established as HE emitters (HE, E>100 MeV)**
- **Classical** novae (WD+low-mass star) are also **sources of HE gamma rays** `(Fermi–LAT, Science, 2014)`
- Emission could be explained with either **pp interaction** or **leptonic models** (IC+Brems.)
- They **show a cut-off** in their SED
    - SED measured up to 6 – 10 GeV



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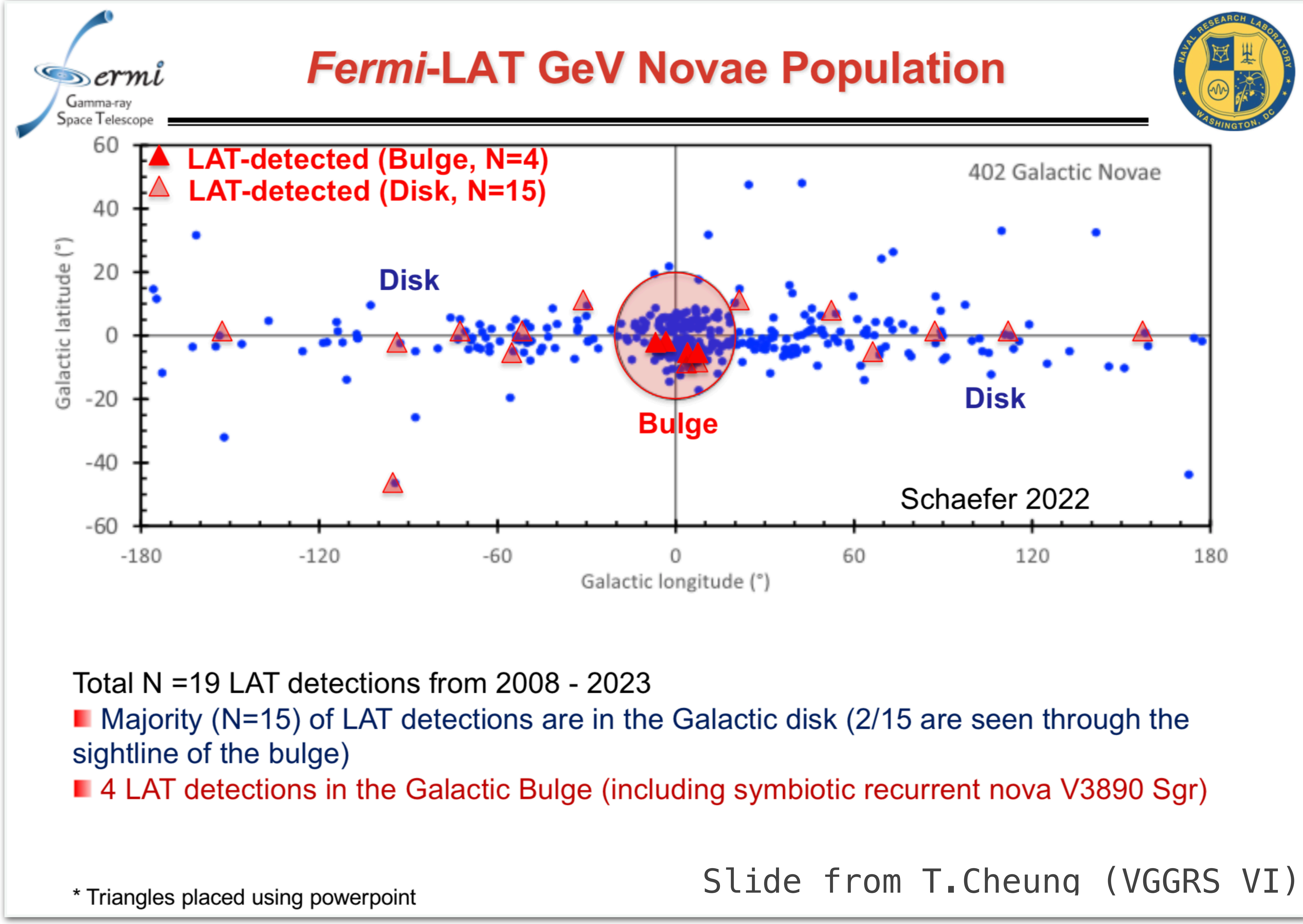
Novae: sources of HE gamma rays

- 402 optical novae `(Schaefer 2022)`
  - Estimated eruption rate: 20-70 /year
  - Discovery rate: 5-15 /year `(Chomiuk et al. 2021)`
- *Fermi*-LAT average ~1 per year `(Cheung, VGGRS VI)`
  - Up to know, total of 19 HE novae* (+6 hints)
    `https://asd.gsfc.nasa.gov/Koji.Mukai/novae/latnovae.html`
  - Most Fermi-LAT novae by detected up to 4.5 kpc
    - subset of bulge detections (up to 8kpc)



Fermi-LAT GeV Novae Population

Total N =19 LAT detections from 2008 - 2023

- Majority (N=15) of LAT detections are in the Galactic disk (2/15 are seen through the sightline of the bulge)
- 4 LAT detections in the Galactic Bulge (including symbiotic recurrent nova V3890 Sgr)

* Triangles placed using powerpoint

`Slide from T.Cheung (VGGRS VI)`

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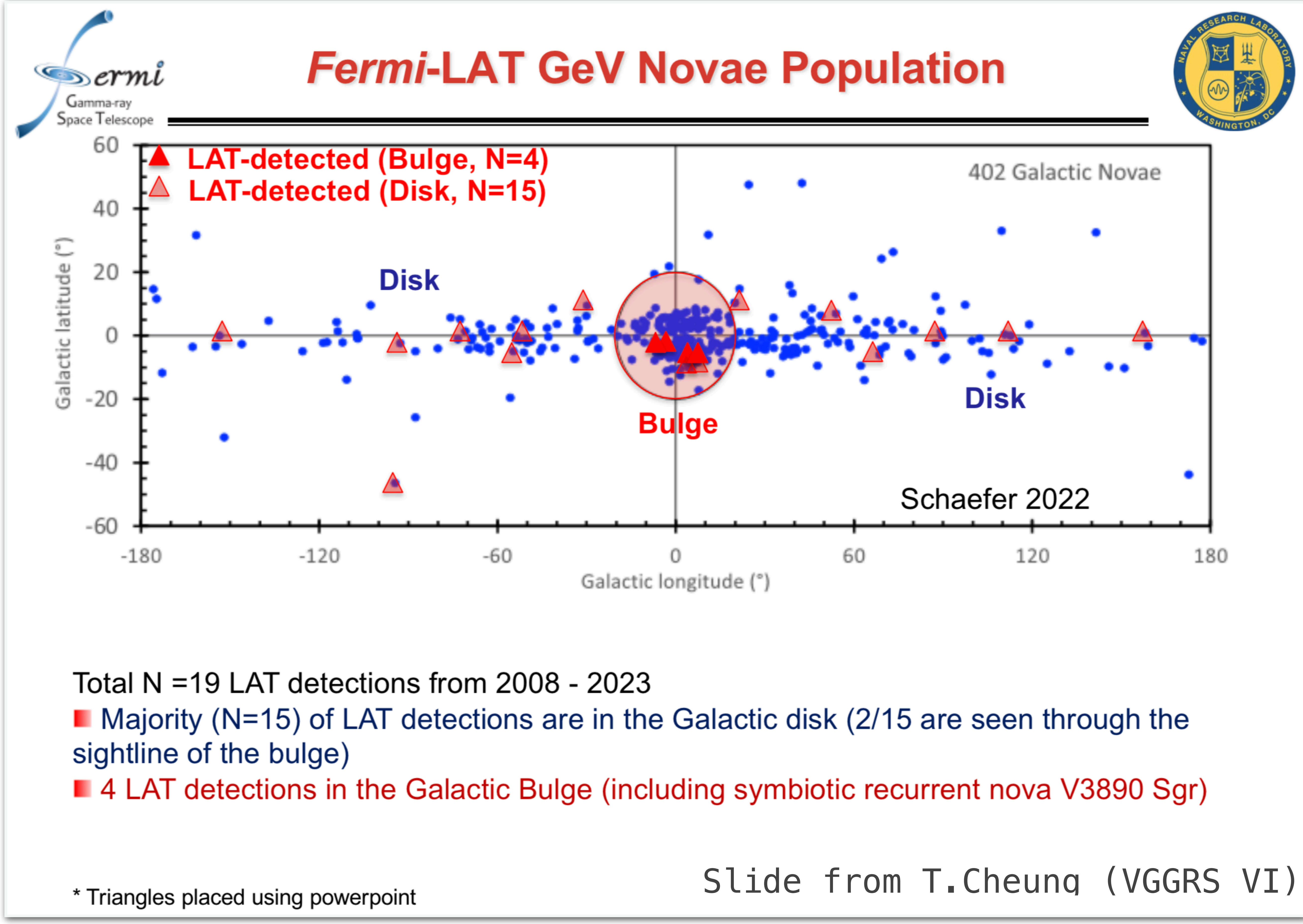

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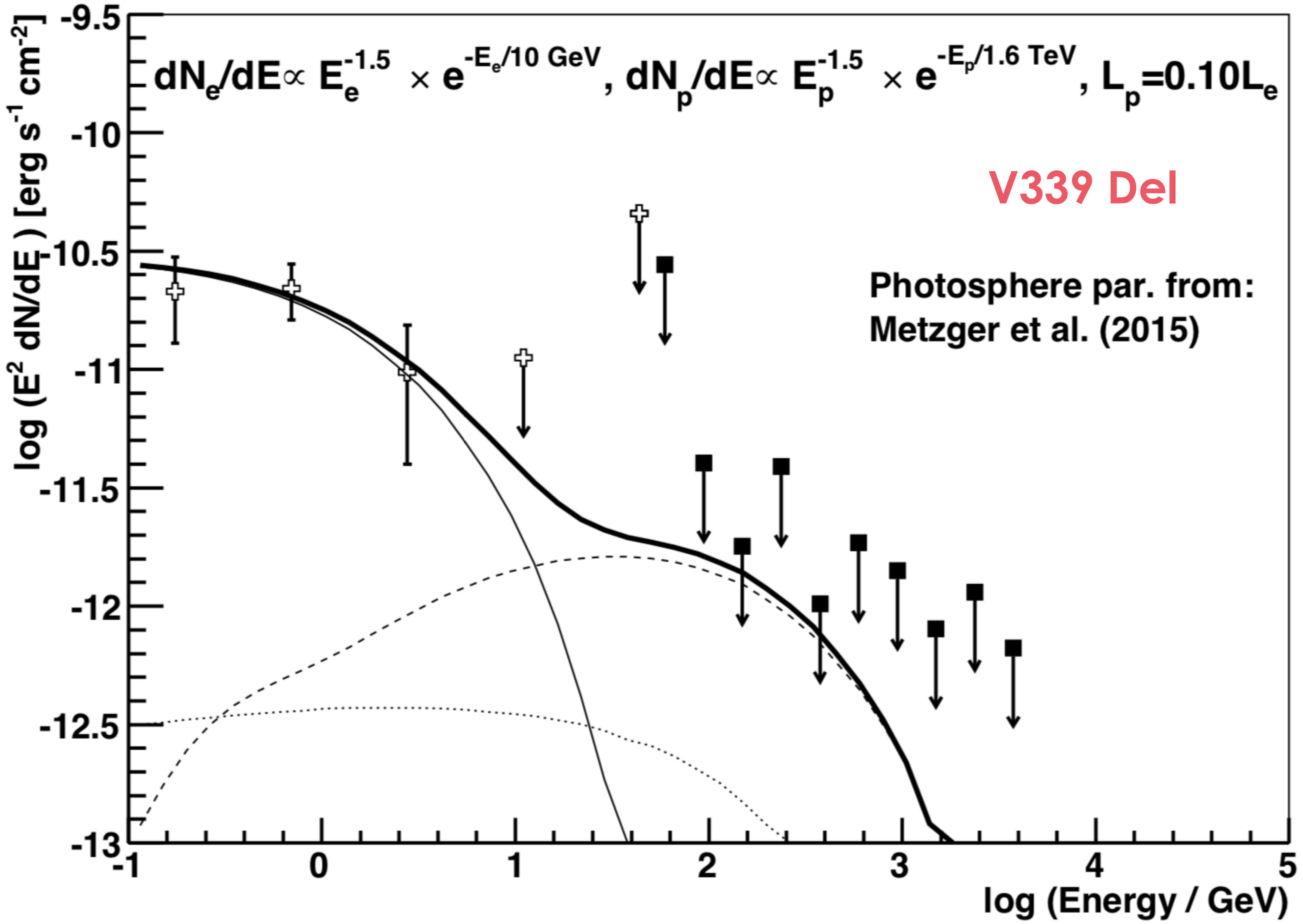
Are novae very-high-energy (VHE, E>100 GeV) emitters?

Search for VHE emission: motivation

- **HE data alone is not enough** to disentangle electron and proton **acceleration models**
- Particles are accelerated in nova shock, **non-thermal processes** are at work
- **Protons can reach much higher energies due to lower energy losses**
- IACTs had searched for a VHE component in novae for more than a decade (Aliu et al. 2012, Ahnen et al. 2015)



Ahnen et al. 2015

RS Ophiuchi

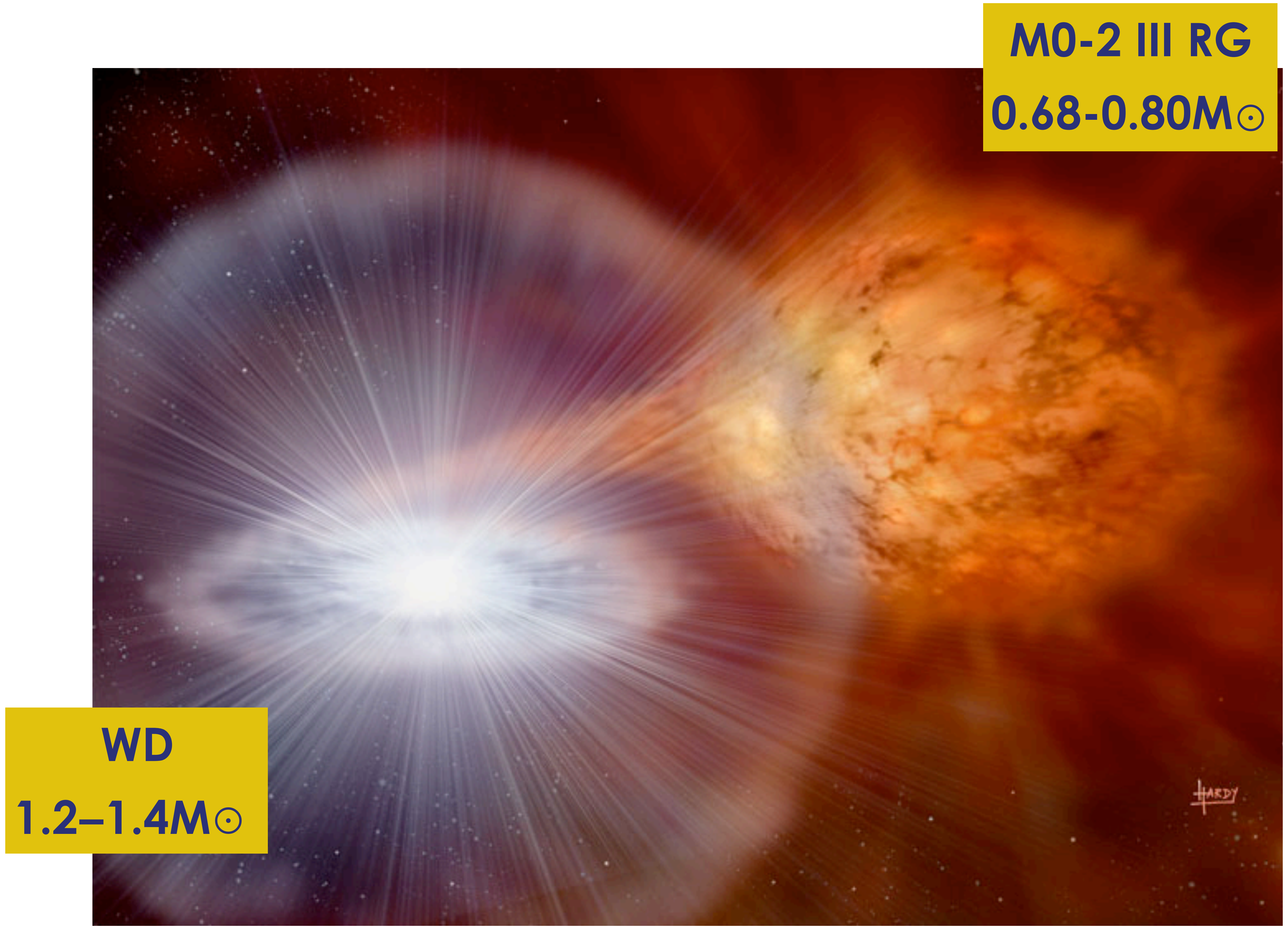
Antonio González (Cielos-LaPalma.com)

RS Ophiuchi

- RS Oph is a **recurrent symbiotic nova** which displays major **outbursts every 14.7 years**
  - WD + M0-2 III RG star `(Anupama 1999)`
    - M_{WD} = 1.2–1.4M⊙ and M_{RG} = 0.68–0.80M⊙
  - Nine eruptions between 1898 and 2021
    - **Latest outburst: August 2021**
  - Distance: 2.45 kpc `(Rupen 2008)`

- Type Ia SN progenitor candidate

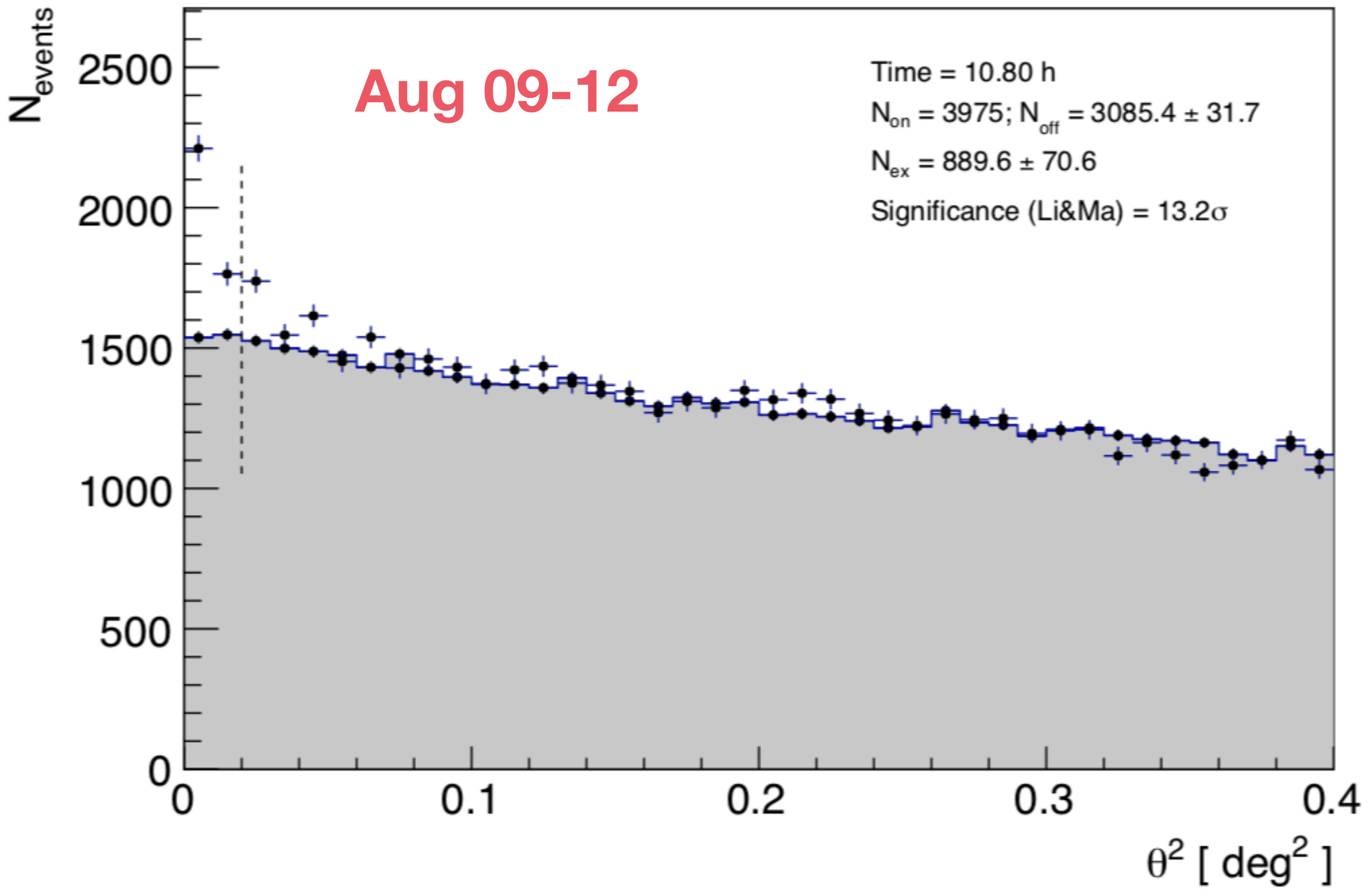
- 2006 outburst: **GeV emitter candidate**:
  - 2006 outburst of RS Oph detected by Swift/BAT could not be accounted by the decay of radioactive isotopes
  - Emission could be explained **via the production of non-thermal particles by diffuse shock acceleration** `Tatischeff et al. 2007)`

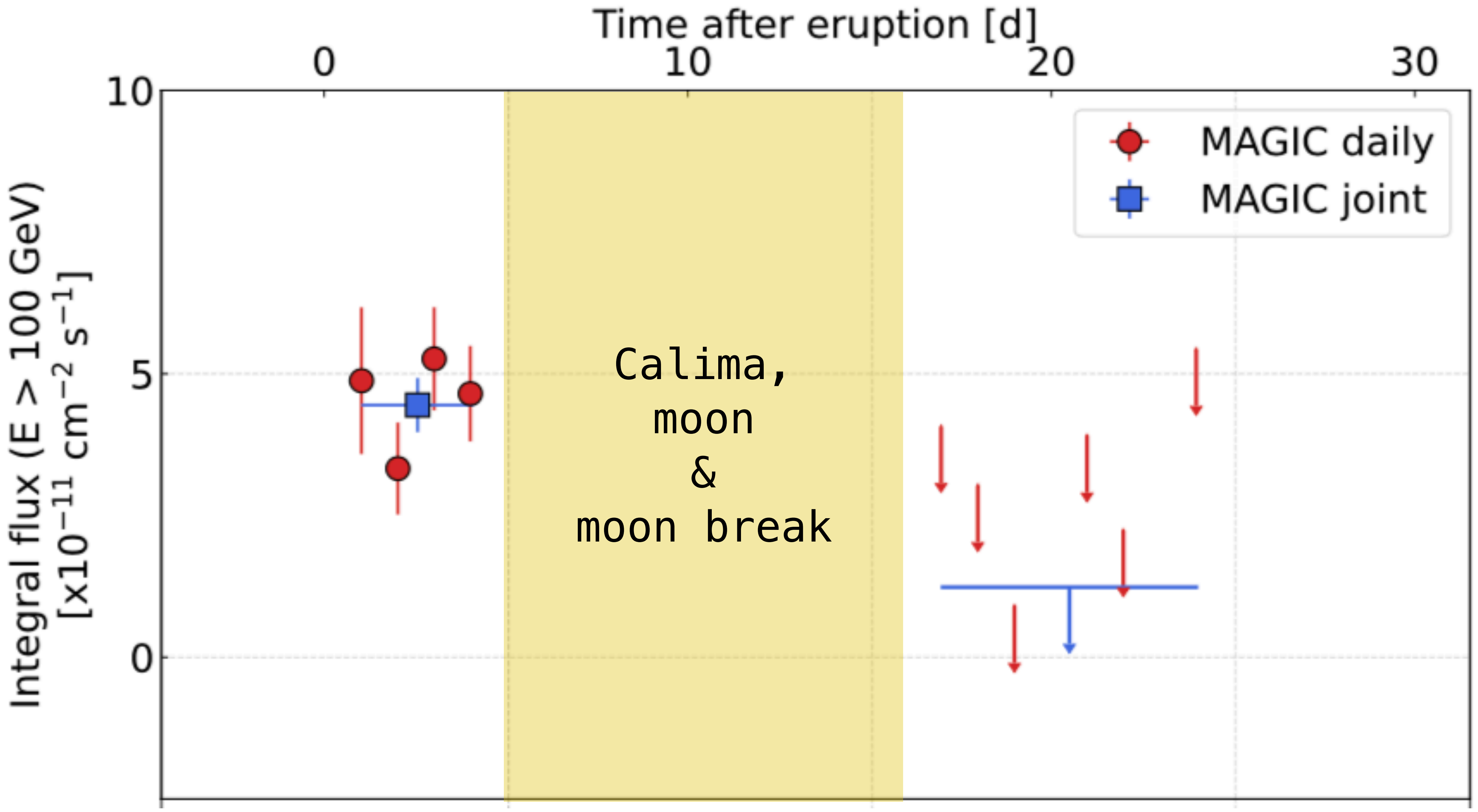


MAGIC detection

- The **first four days** of MAGIC observations (August 09-12) yield a **VHE signal** with a **significance of 13.2σ** `(Acciari et al. Nat. Astronomy, 2022)`
  - 34 h observed, 21.4 h after quality cuts (zenith angle range: 36° - 60°)
  - **Energy threshold of the analysis: ~60 GeV**
- **Decrease** below the VHE detection limit **two weeks later**
- VHE emission by H.E.S.S. `(H.E.S.S. coll, Science, 2022)` and LST `(CTA-LST Project, Pos(Gamma2022))`

Novae established as a new type of source of VHE gamma rays



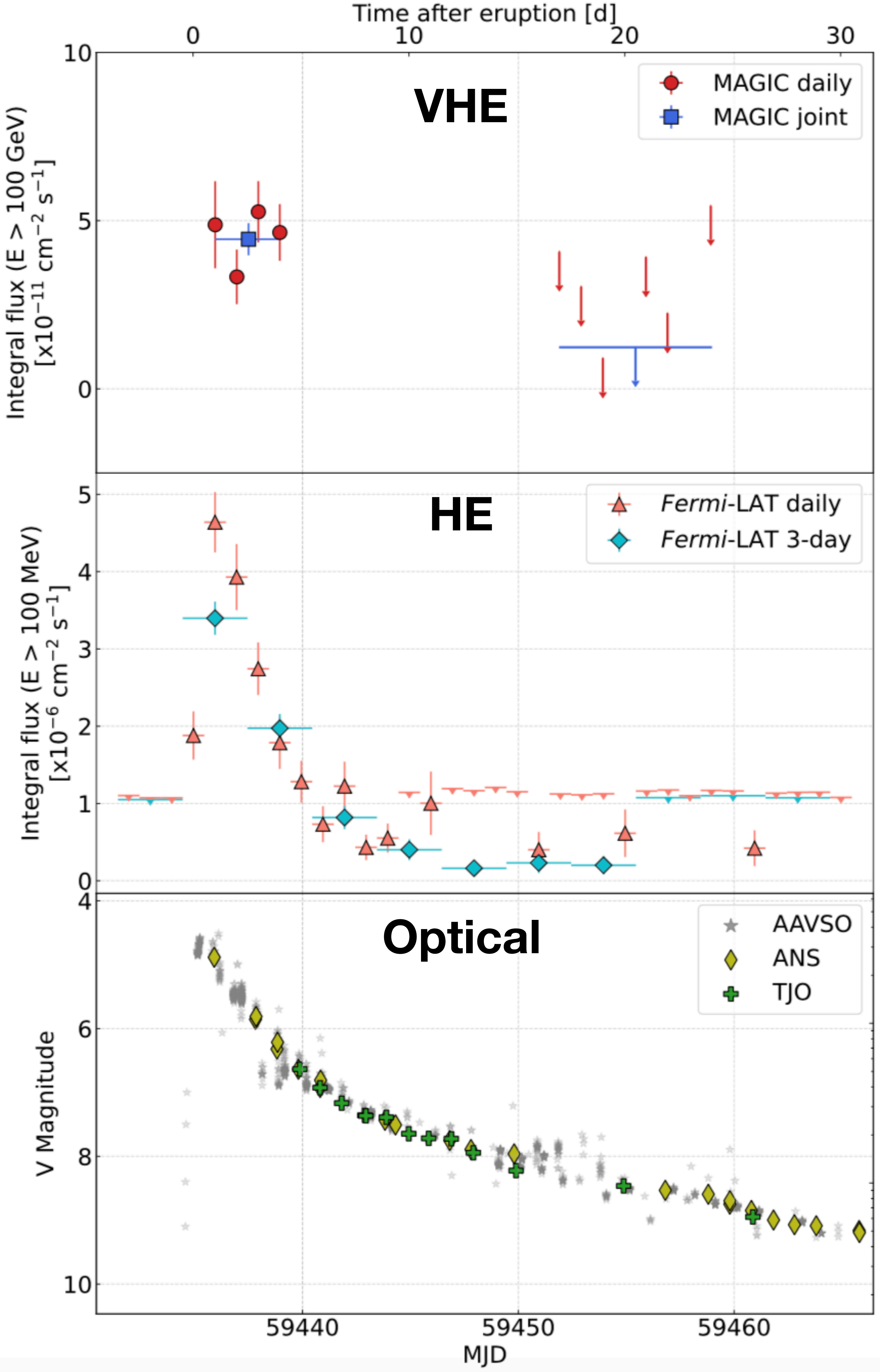


Acciari et al., Nature Astronomy, 2022
https://doi.org/10.1038/s41550-022-01640-z

MWL view

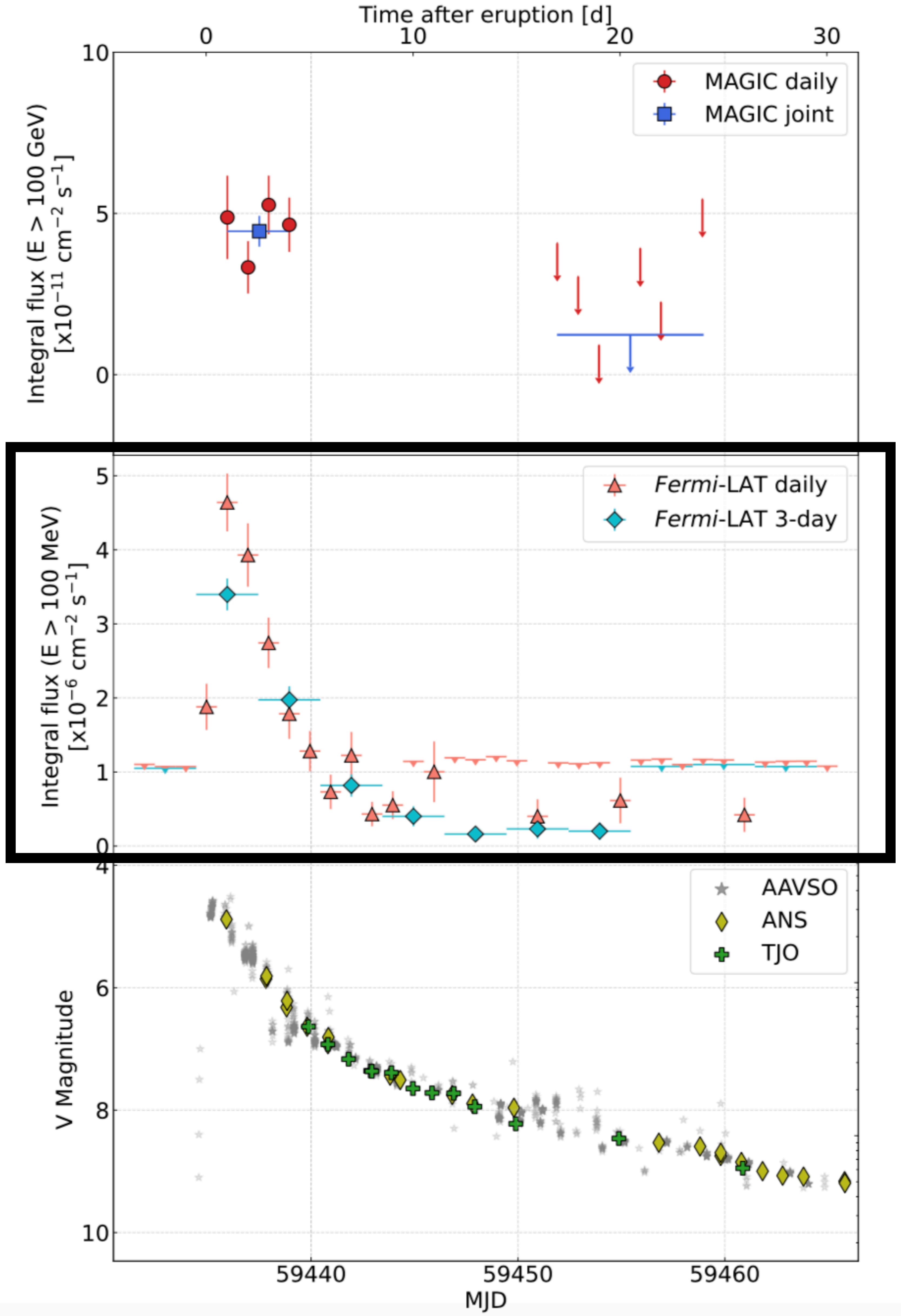
- The MAGIC observations reveal **VHE emission contemporaneous to the *Fermi*-LAT and optical maxima**
- Emission peaked at optical and MeV, but **VHE emission is** consistent with being **constant over the first 4 days**
- **First nova detected in the VHE regime**

Novae established as a new type of source of VHE gamma rays

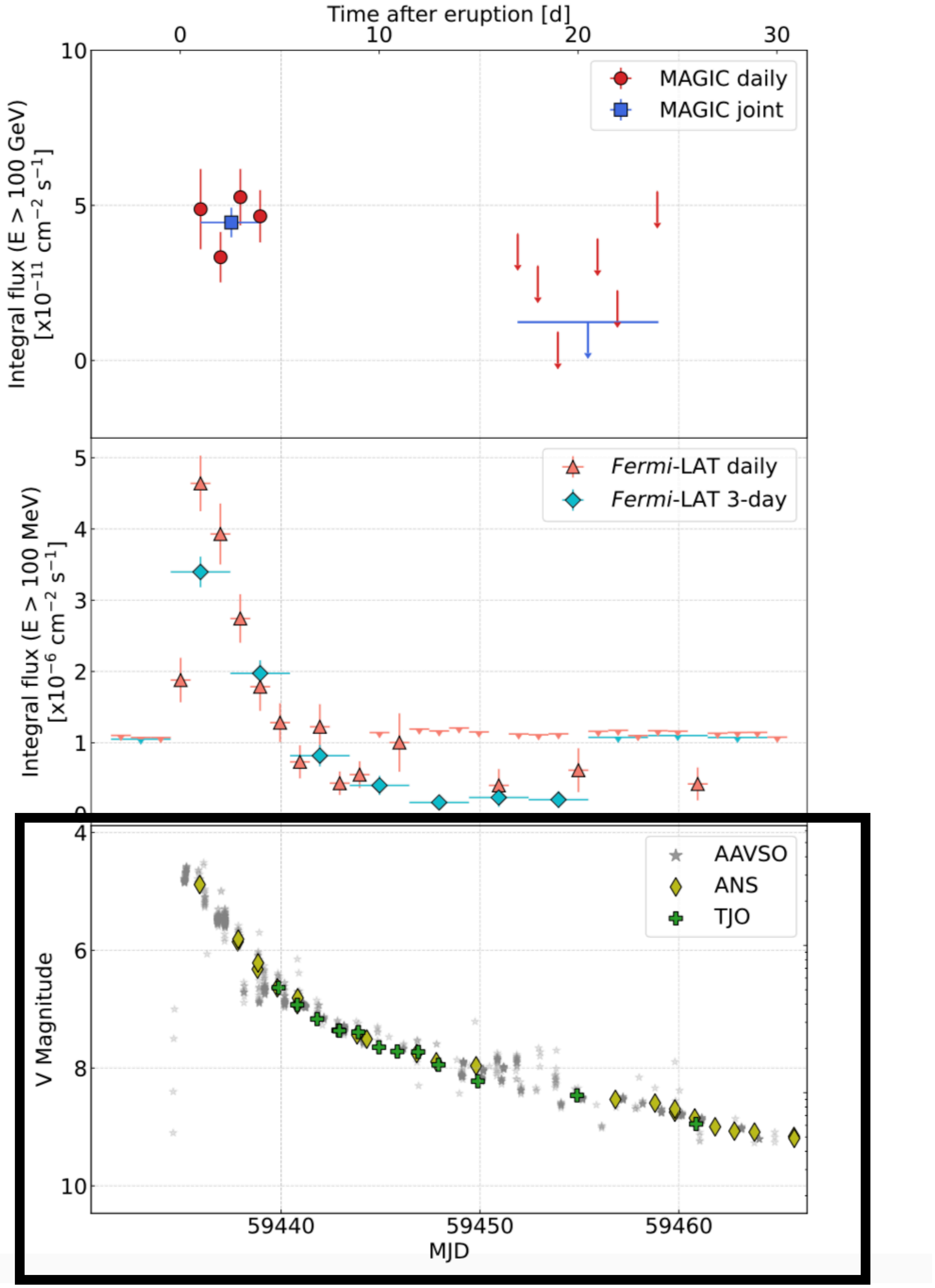


Fermi-LAT ligthcurve

- *Fermi*-LAT: 1-day and 3-day LC (E: 0.1-1000 GeV)
    - 1-day LC: **exponential decay with halving time of (2.20 ± 0.18) days**



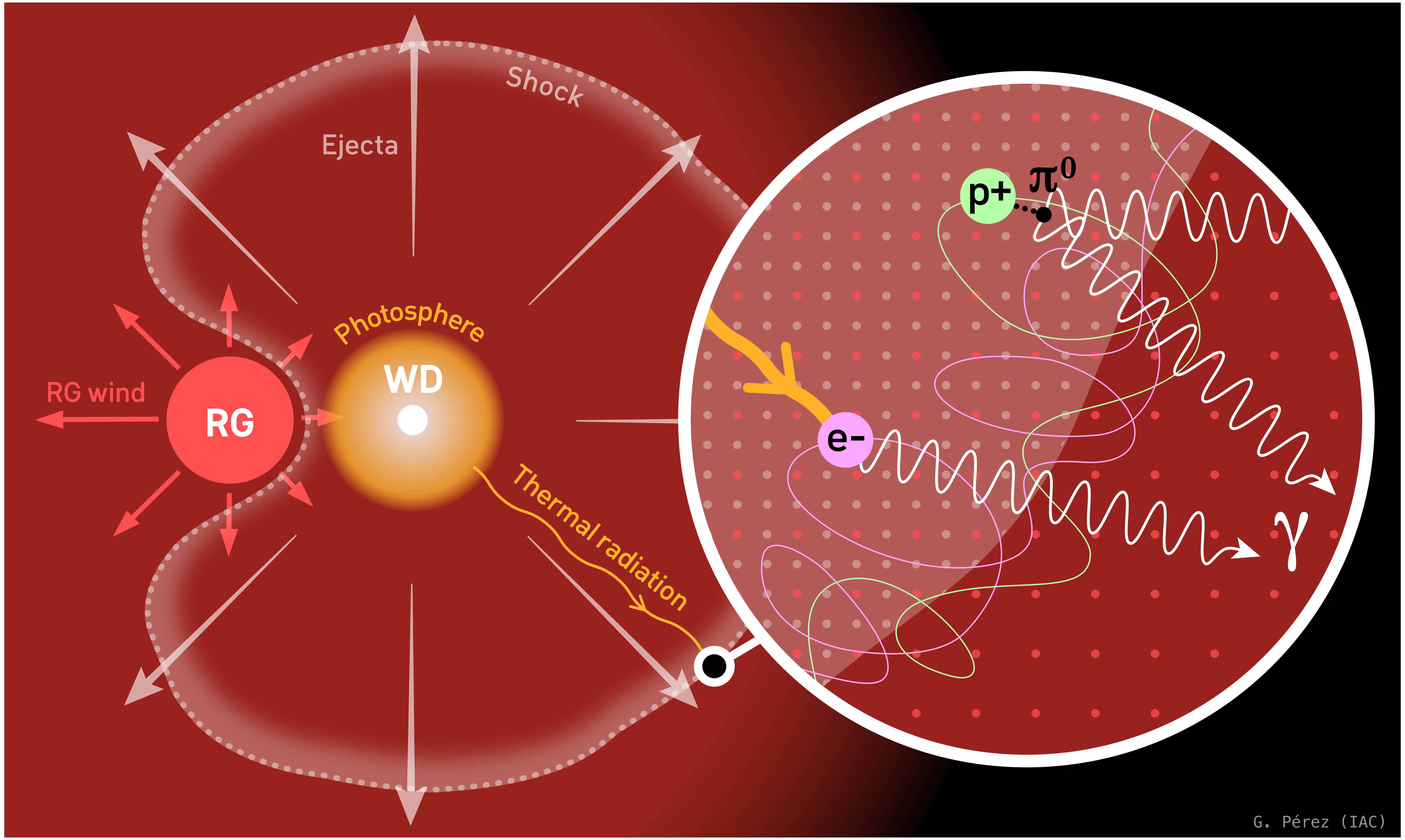
Optical ligthcurve



- **During the nova outburst the photospheric emission creates the dominant radiation field**
- Photometry
  - **TJO and ANS**
  - The emission*can be described by the **photosphere temperature dropping from** **T_{ph} = 10800 K to 7680 K and radius R_{ph} = 200 $R_\odot$**
    - Similar to those from 2006 outburst
- Spectroscopy:
  - **Varese 0.84 m and Catania 0.91 m telescopes**
  - **4500 ± 250 km s^{-1}** for the ejecta expansion at the earliest stage*

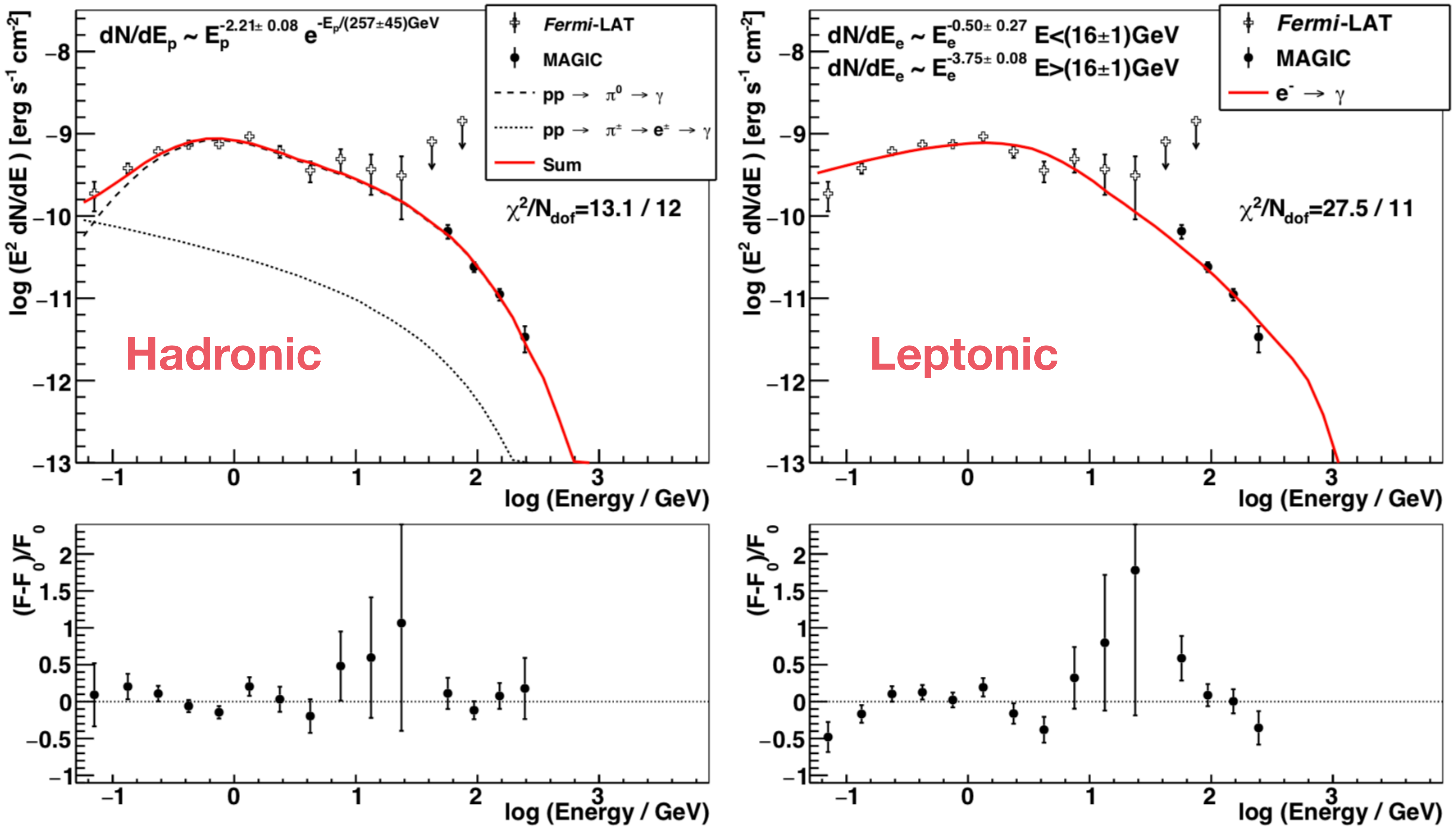
* during first
4 days

The physics



- **Protons**: pp interaction on **nova ejecta** (with some contribution from RG wind)
- **Electrons**: IC on thermal radiation of the **WD photosphere**
- Modeling: particles are injected and either **cool down completely (electrons)** or we gather their emission during the **acceleration time (protons)**

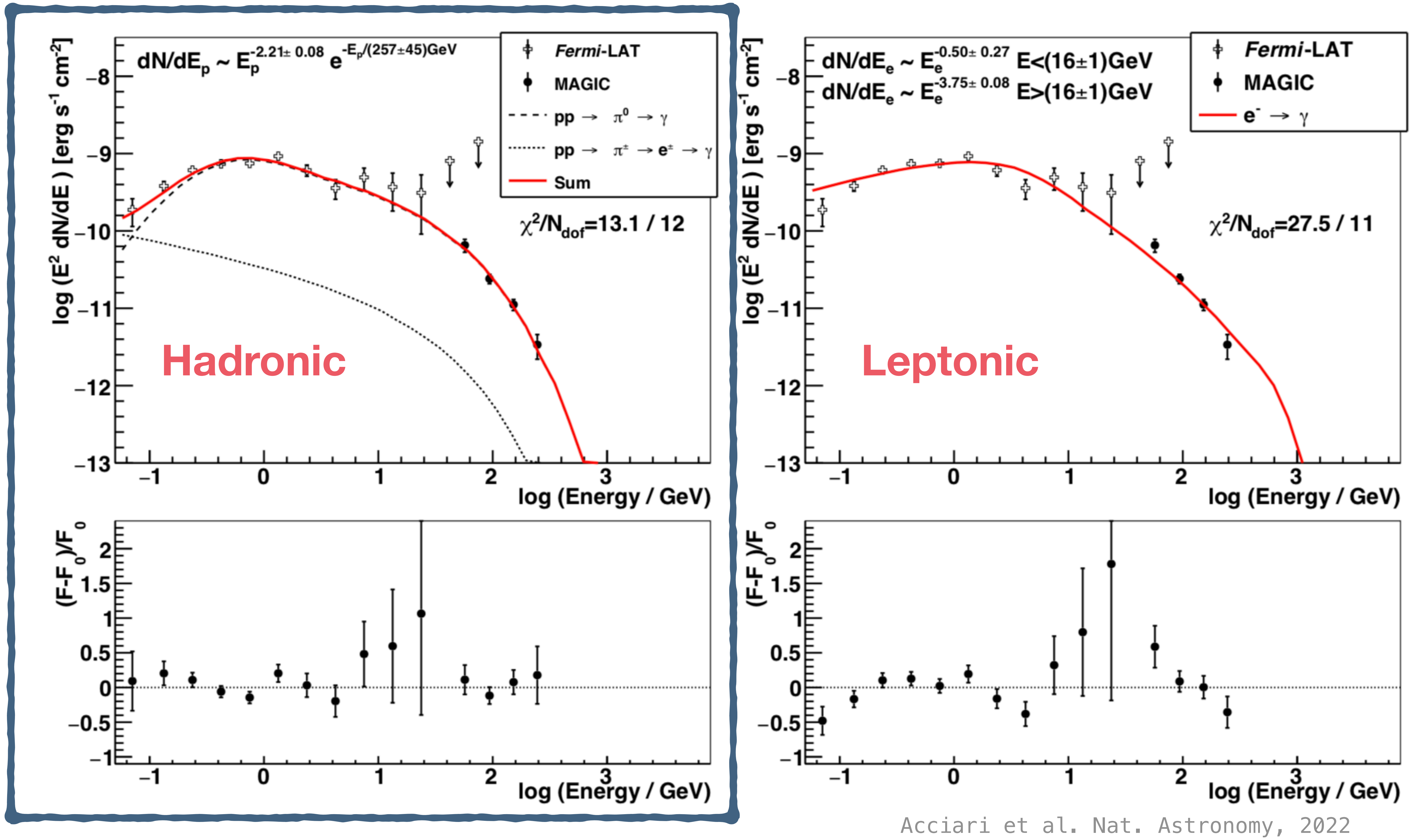
Gamma-ray modelling



Acciari et al. Nat. Astronomy, 2022

- **Joint Fermi-LAT +MAGIC** spectrum can be described as a **single**, smooth **component** spanning **from 50 MeV to 250 GeV**

Gamma-ray modelling



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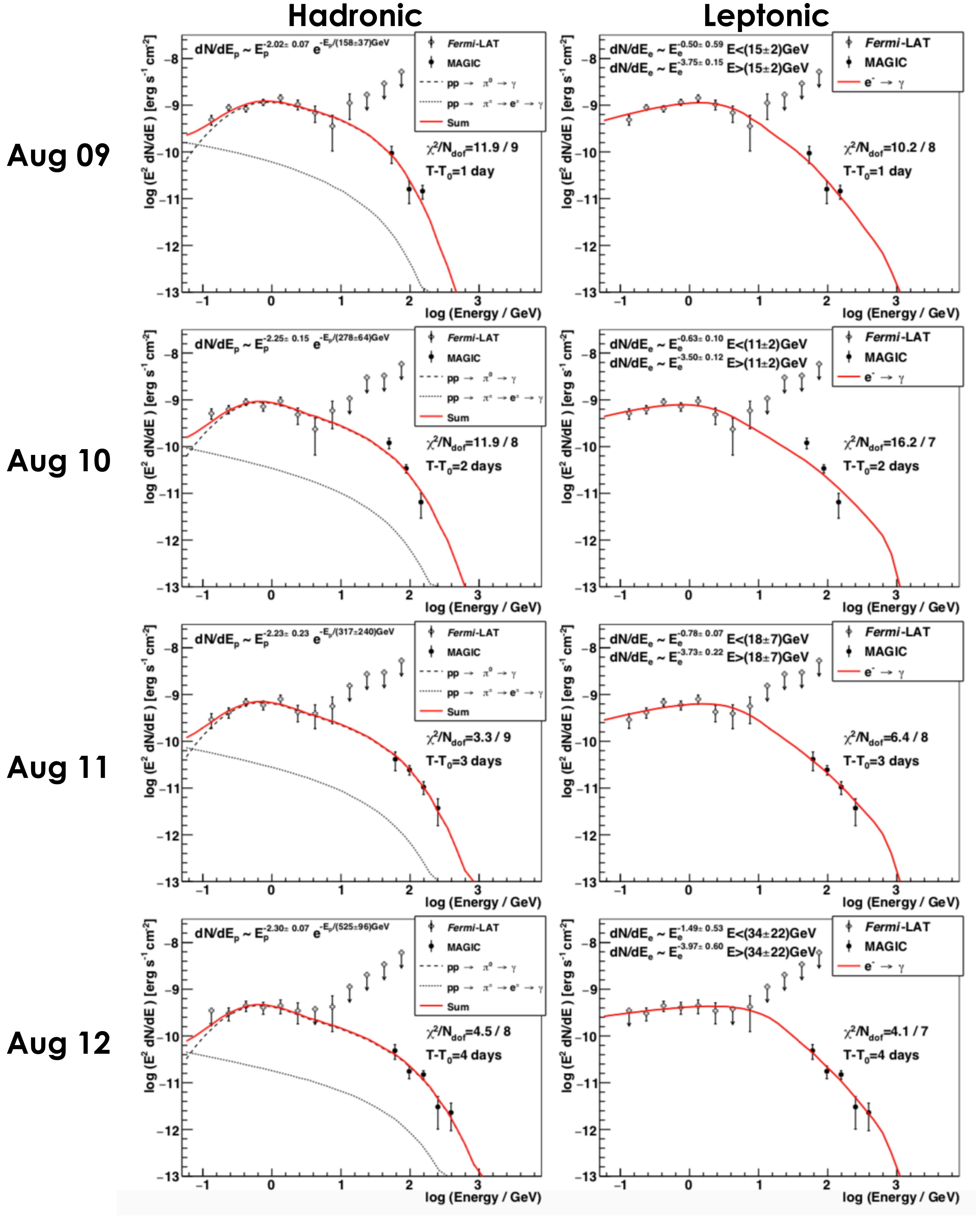
- **Joint Fermi-LAT +MAGIC** spectrum can be described as a **single**, smooth **component** spanning **from 50 MeV to 250 GeV**
- **Hadronic scenario is favored**

Modelling: daily proton acceleration



- **Daily SED**
  - **Hadronic scenario favored**

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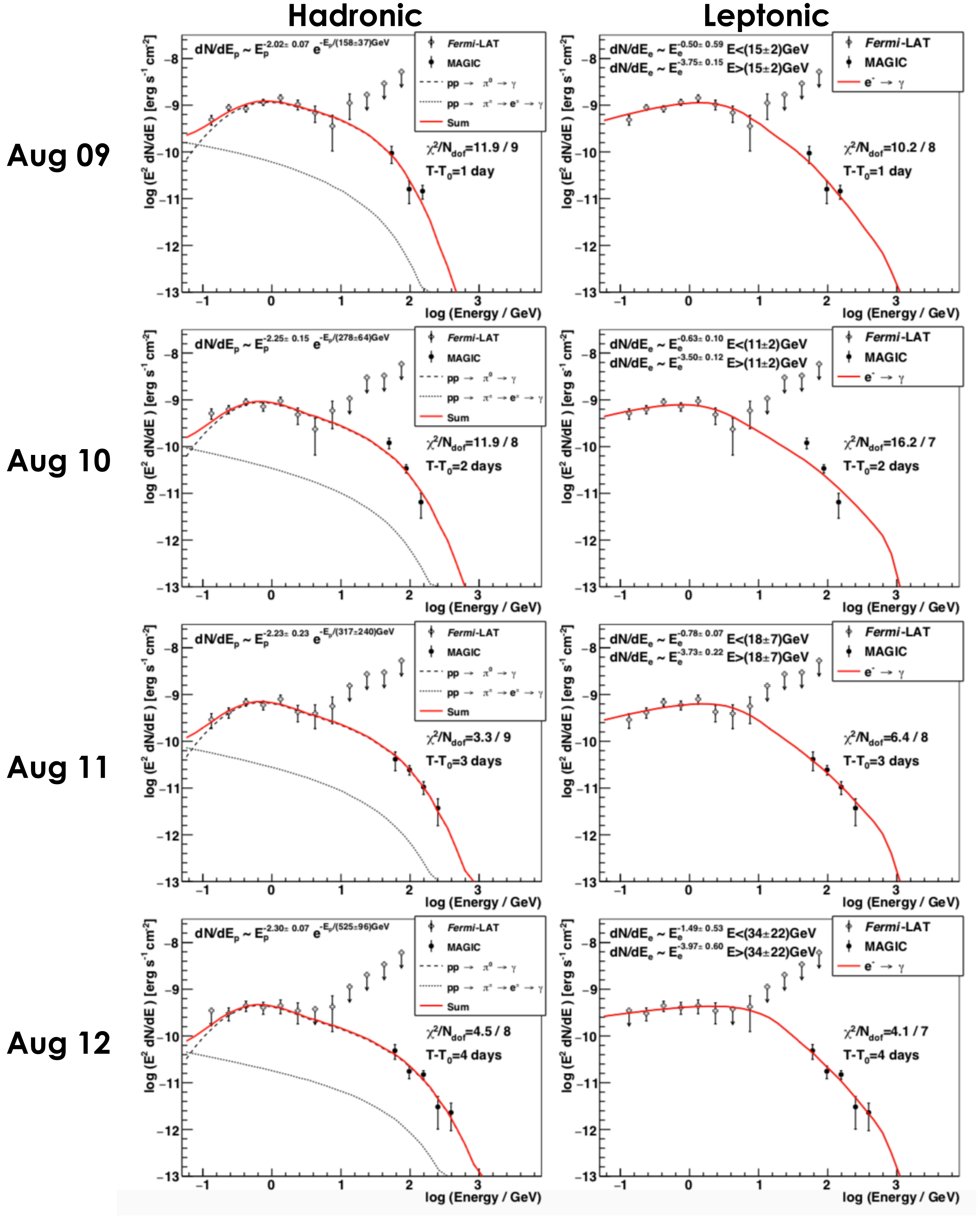
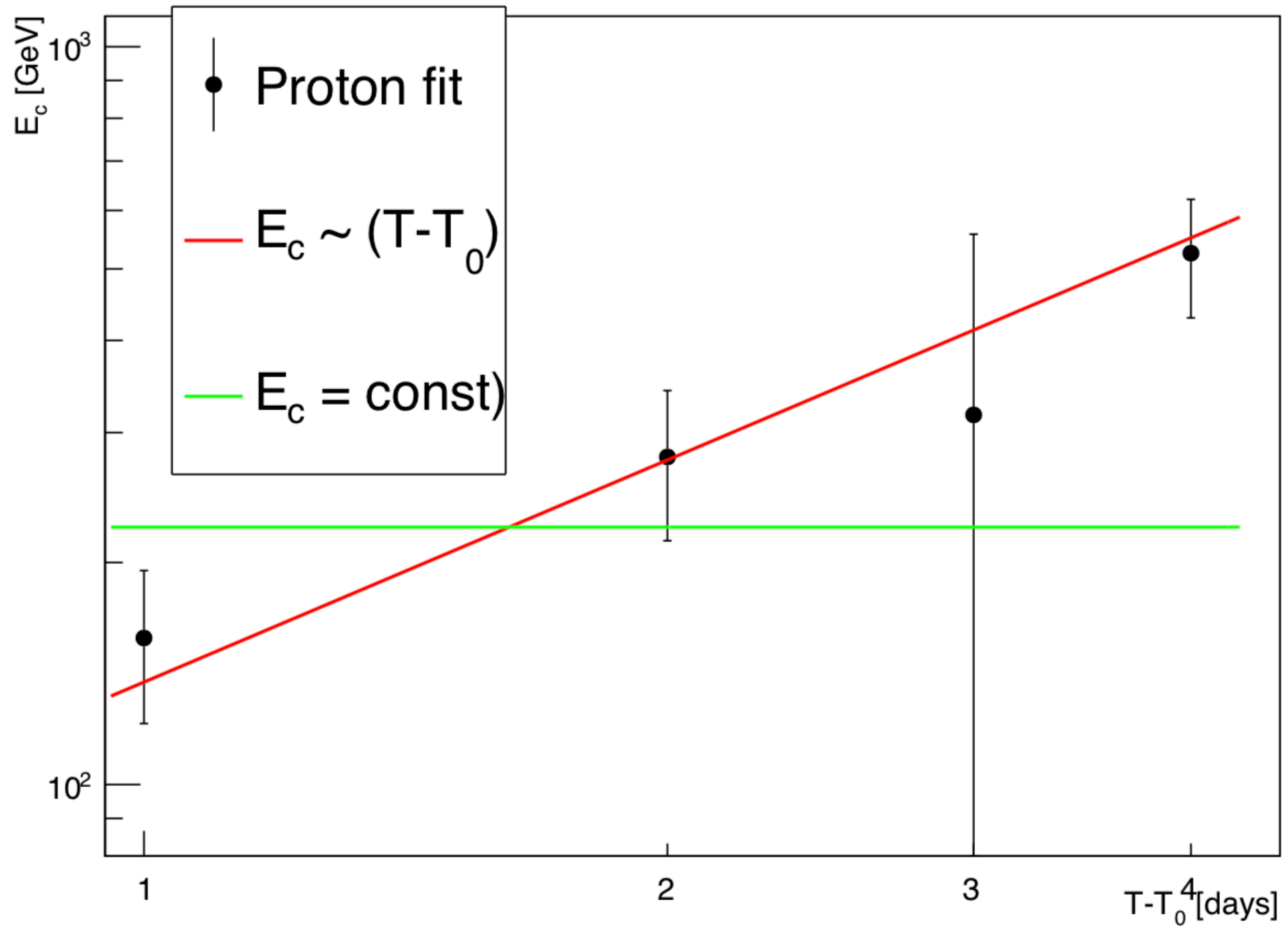
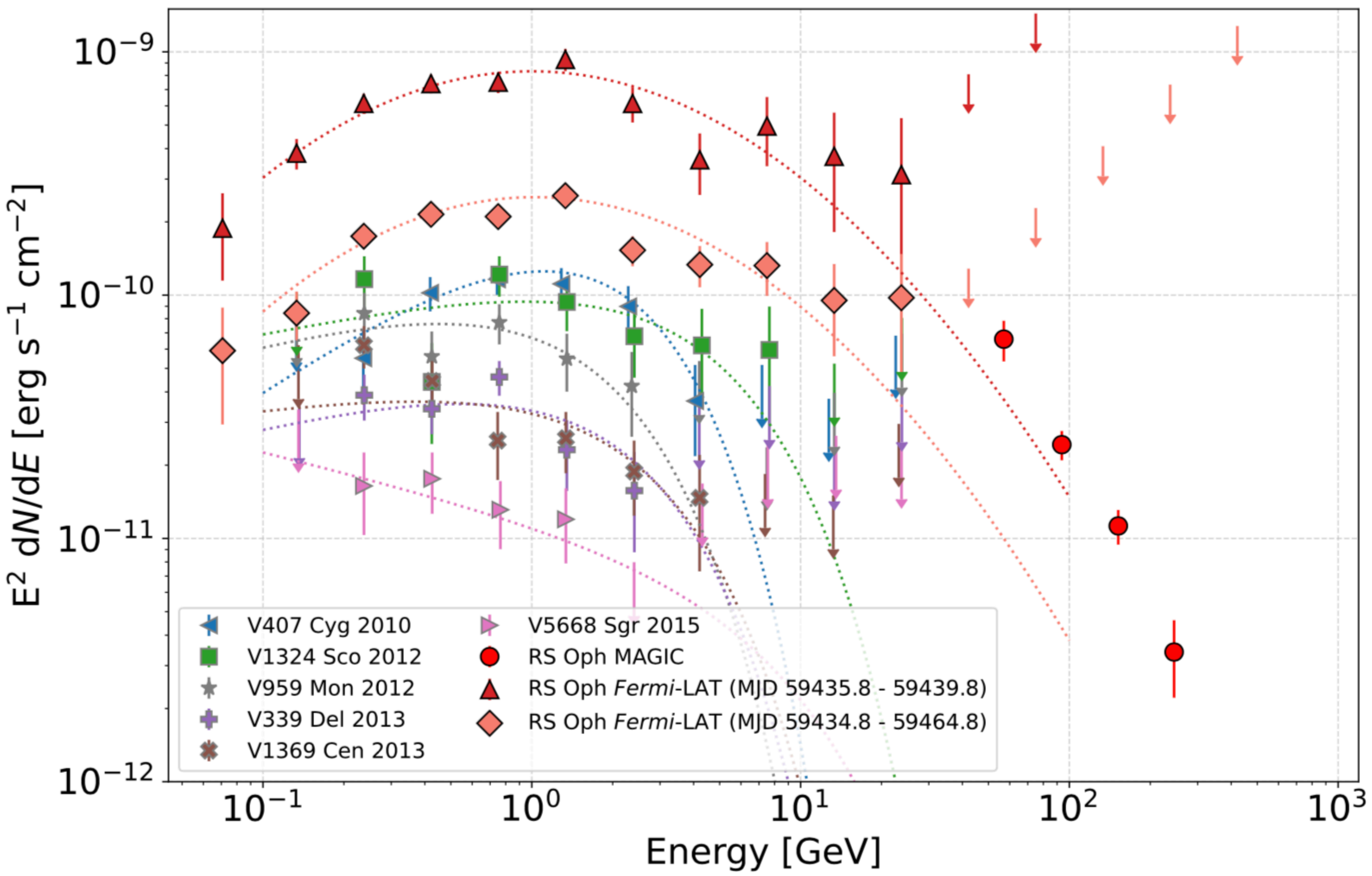


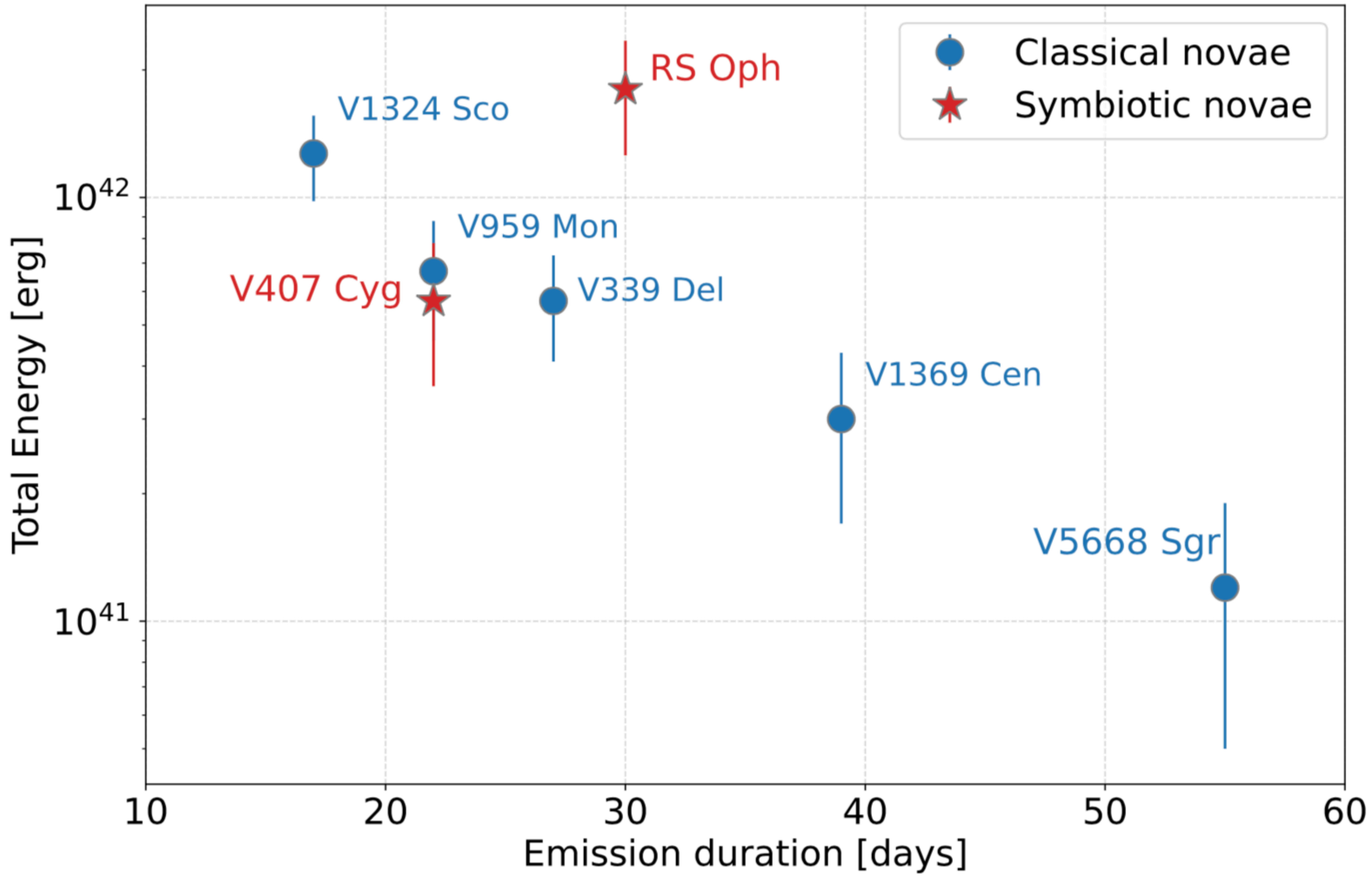
- **Daily SED**
  - **Hadronic scenario favored**

- **Increase of the cut-off energy with time:** hint of spectral hardening
  - In line with the expectations from the cooling and acceleration timescales
  - **Hadronic scenario favored**



RSOph vs other novae





- RS Oph is the nova with the **highest flux** and **brightest nova**
  - Almost two orders of magnitude larger than previously-detected eruptions
- **Comparison does not reveal any peculiarity** in the emission of RS Oph, except for its brightness

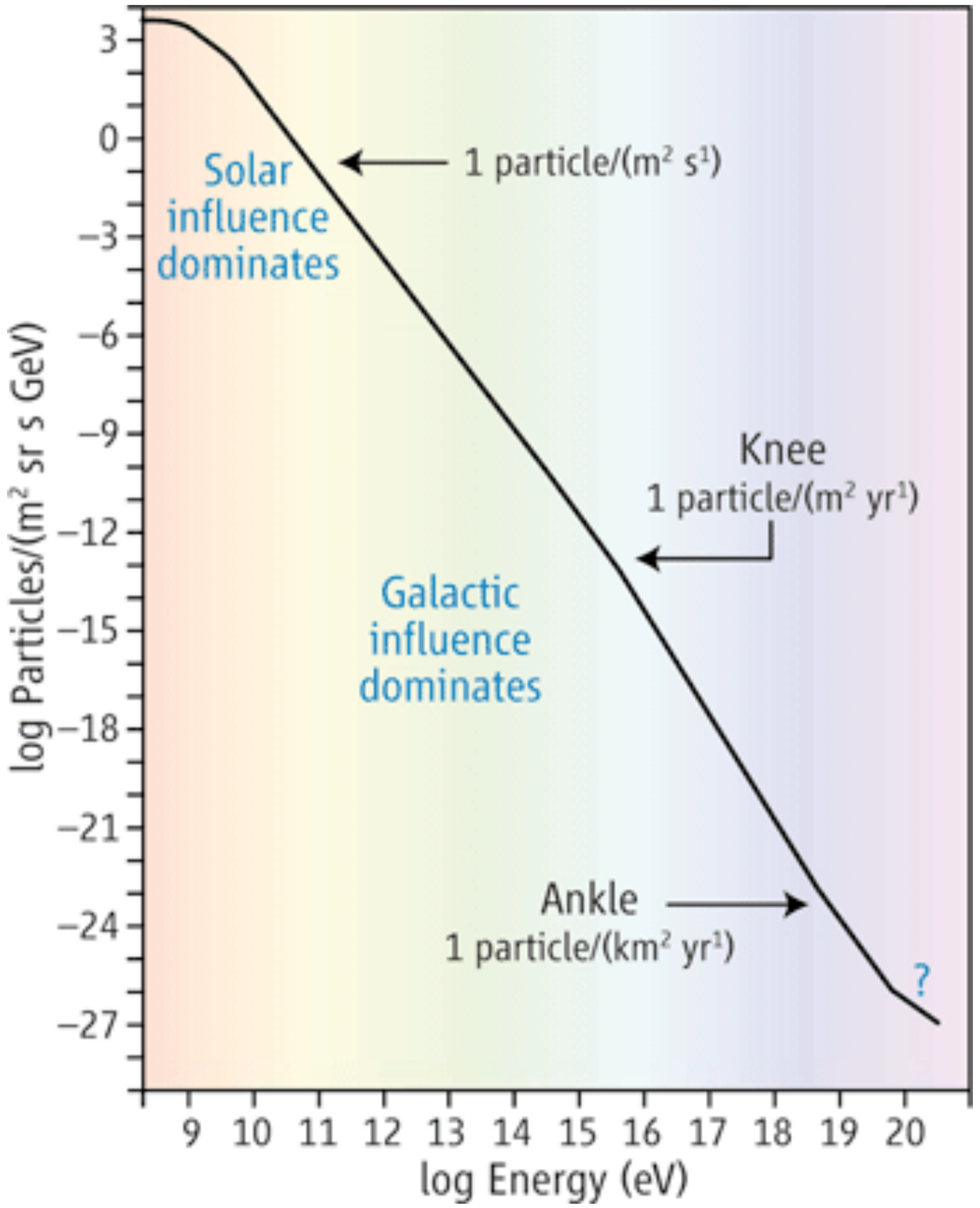
Galactic novae and Cosmic Rays

- **Accelerated protons will eventually escape the nova shock** carrying away most of their obtained energy. Such protons could **contribute to the Galactic Cosmic Ray sea**

- Using the CR energetic derived for RS Oph (~ 4.4 × 10^{43} erg): <**0.2% of the contribution from supernovae**

- Despite the small contribution to the overall CR sea, **novae would significantly increase the CR density in its close environment**: E_density(nova)>E_density(CR)

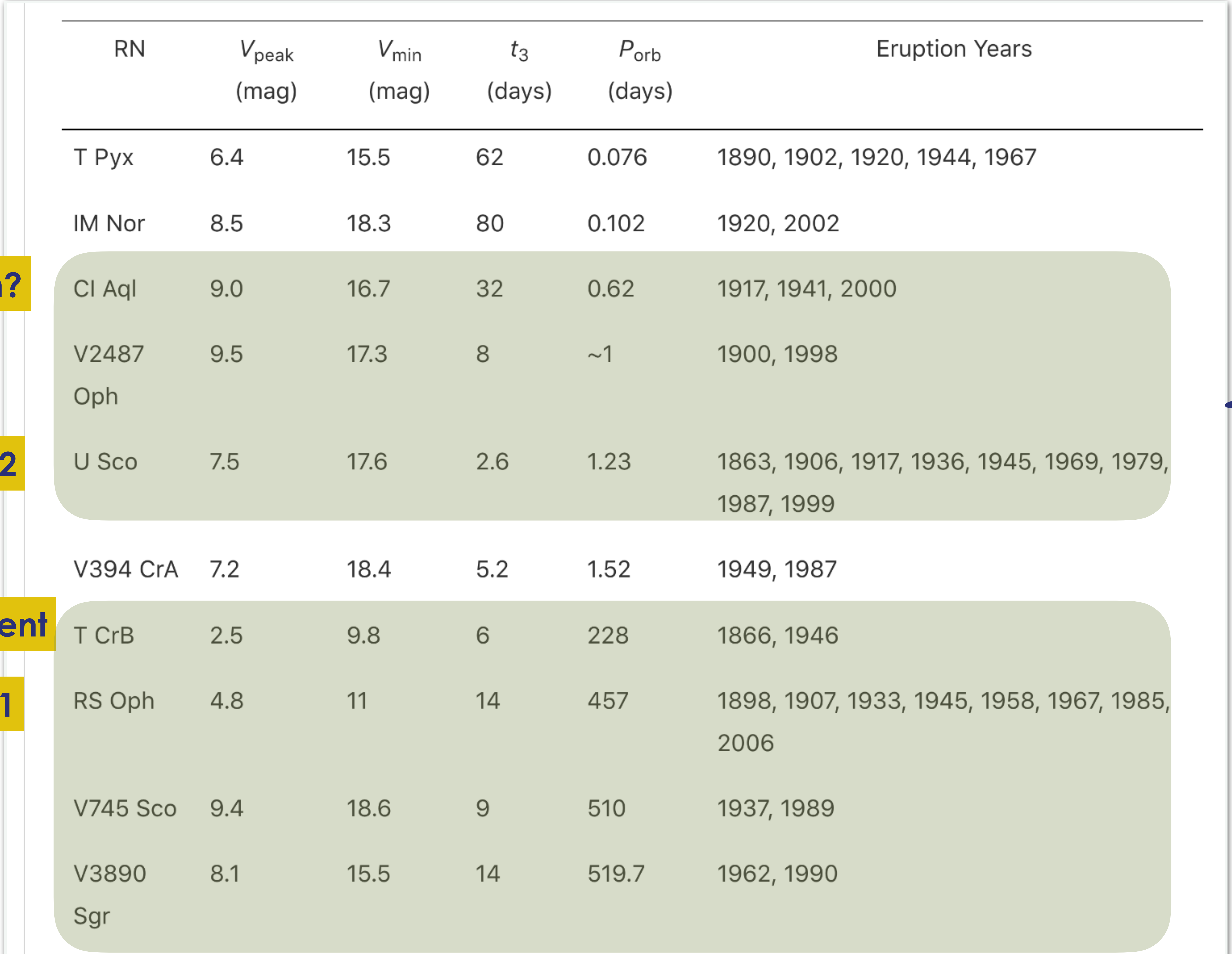
- In the case of **recurrent novae, protons will accumulate in a ~10 pc bubble** with enhanced CR density



Extracted from Dulgig, Science 2020

Future prospects

Recurrent novae in the Galaxy



RN	V_{peak} (mag)	V_{min} (mag)	t_3 (days)	P_{orb} (days)	Eruption Years
T Pyx	6.4	15.5	62	0.076	1890, 1902, 1920, 1944, 1967
IM Nor	8.5	18.3	80	0.102	1920, 2002
CI Aql	9.0	16.7	32	0.62	1917, 1941, 2000
V2487 Oph	9.5	17.3	8	~1	1900, 1998
U Sco	7.5	17.6	2.6	1.23	1863, 1906, 1917, 1936, 1945, 1969, 1979, 1987, 1999
V394 CrA	7.2	18.4	5.2	1.52	1949, 1987
T CrB	2.5	9.8	6	228	1866, 1946
RS Oph	4.8	11	14	457	1898, 1907, 1933, 1945, 1958, 1967, 1985, 2006
V745 Sco	9.4	18.6	9	510	1937, 1989
V3890 Sgr	8.1	15.5	14	519.7	1962, 1990

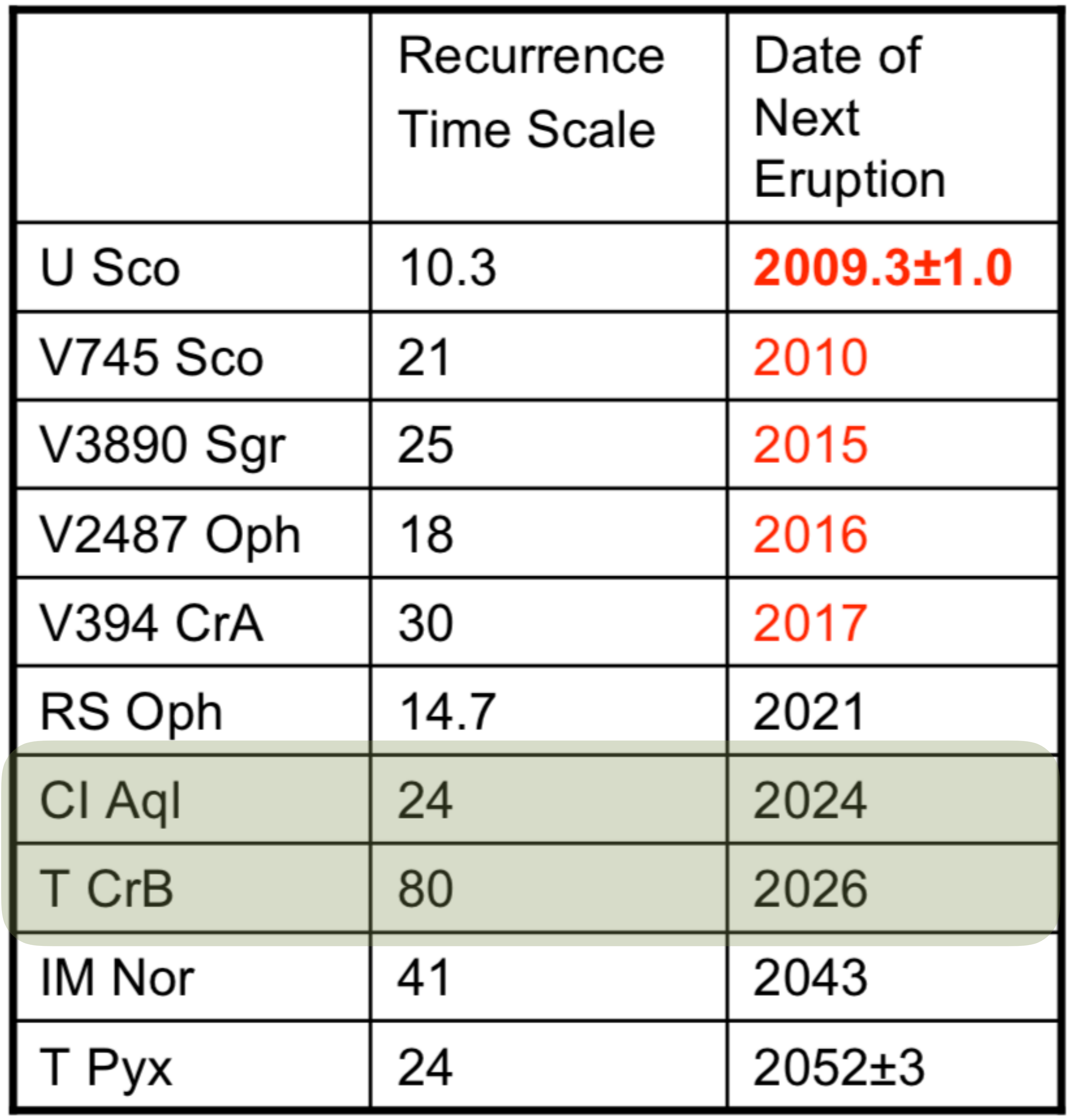
soon?

2022

inminent

2021

Schaefer 2010



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V2487 Oph	18	2016
V394 CrA	30	2017
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CI Aql	24	2024
T CrB	80	2026
IM Nor	41	2043
T Pyx	24	2052±3

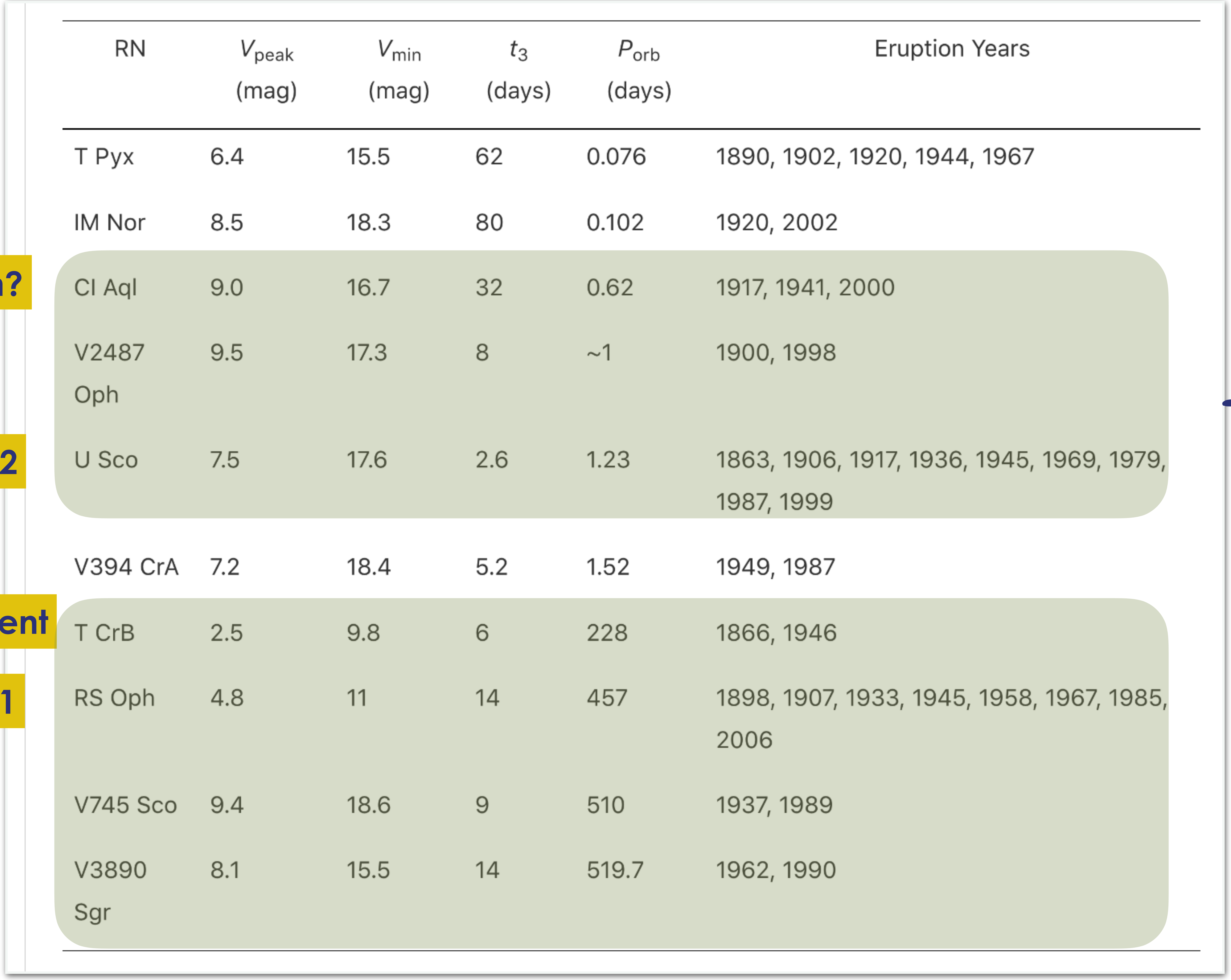
~3 kpc

~0.9 kpc

Schaefer 2010

10 known Galactic RNe

Recurrent novae in the Galaxy



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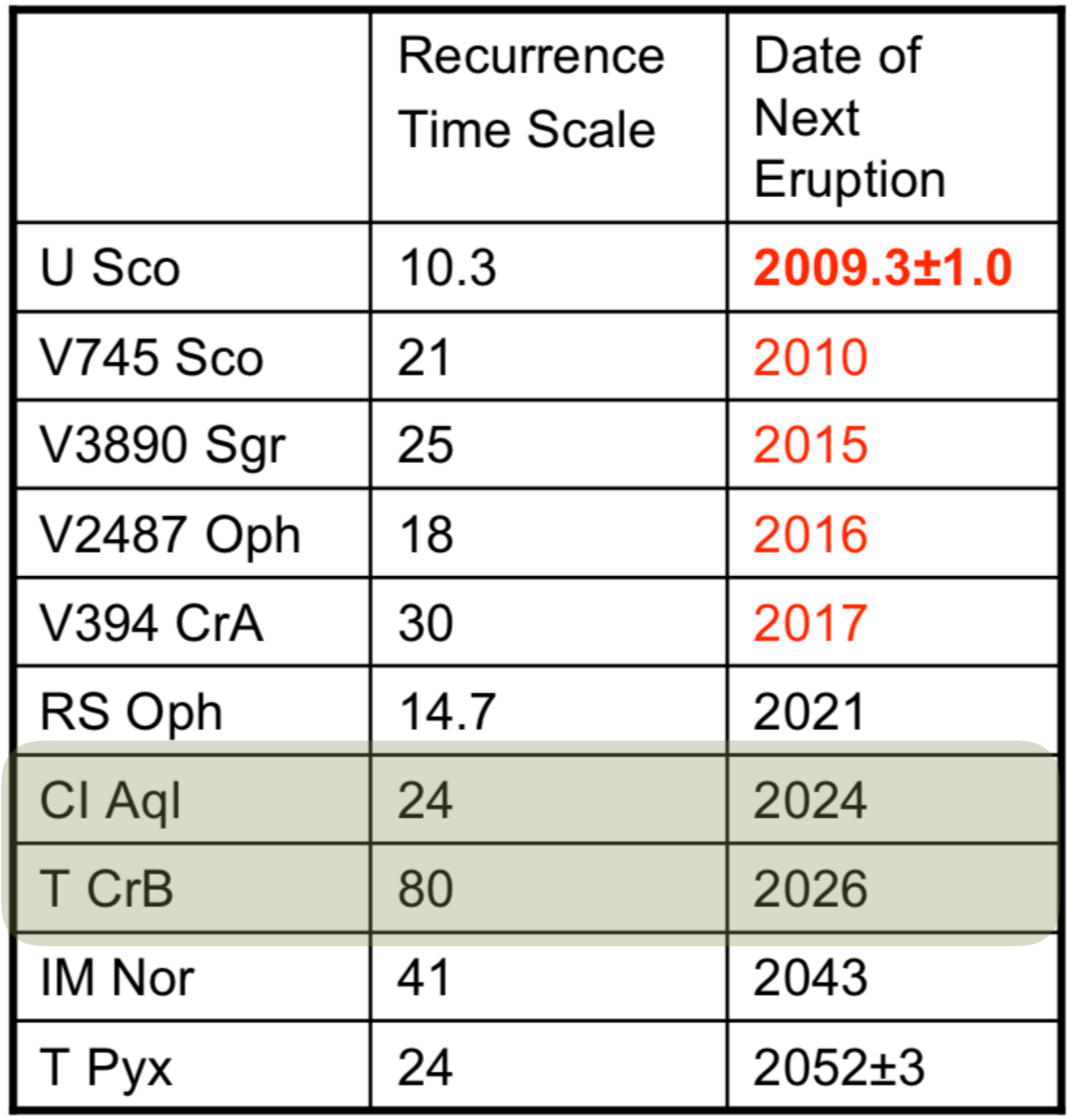

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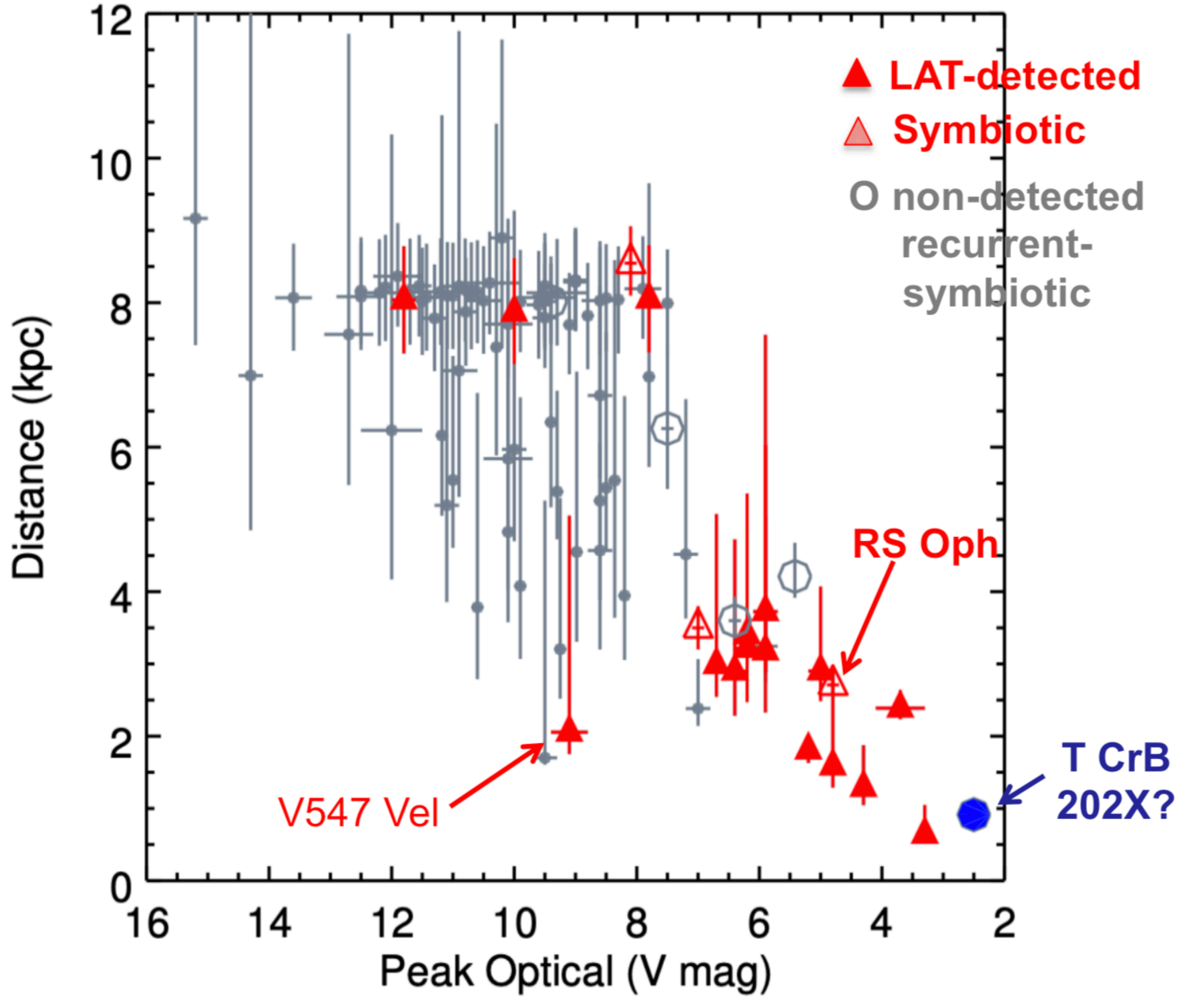
~3 kpc

~0.9 kpc

Schaefer 2010

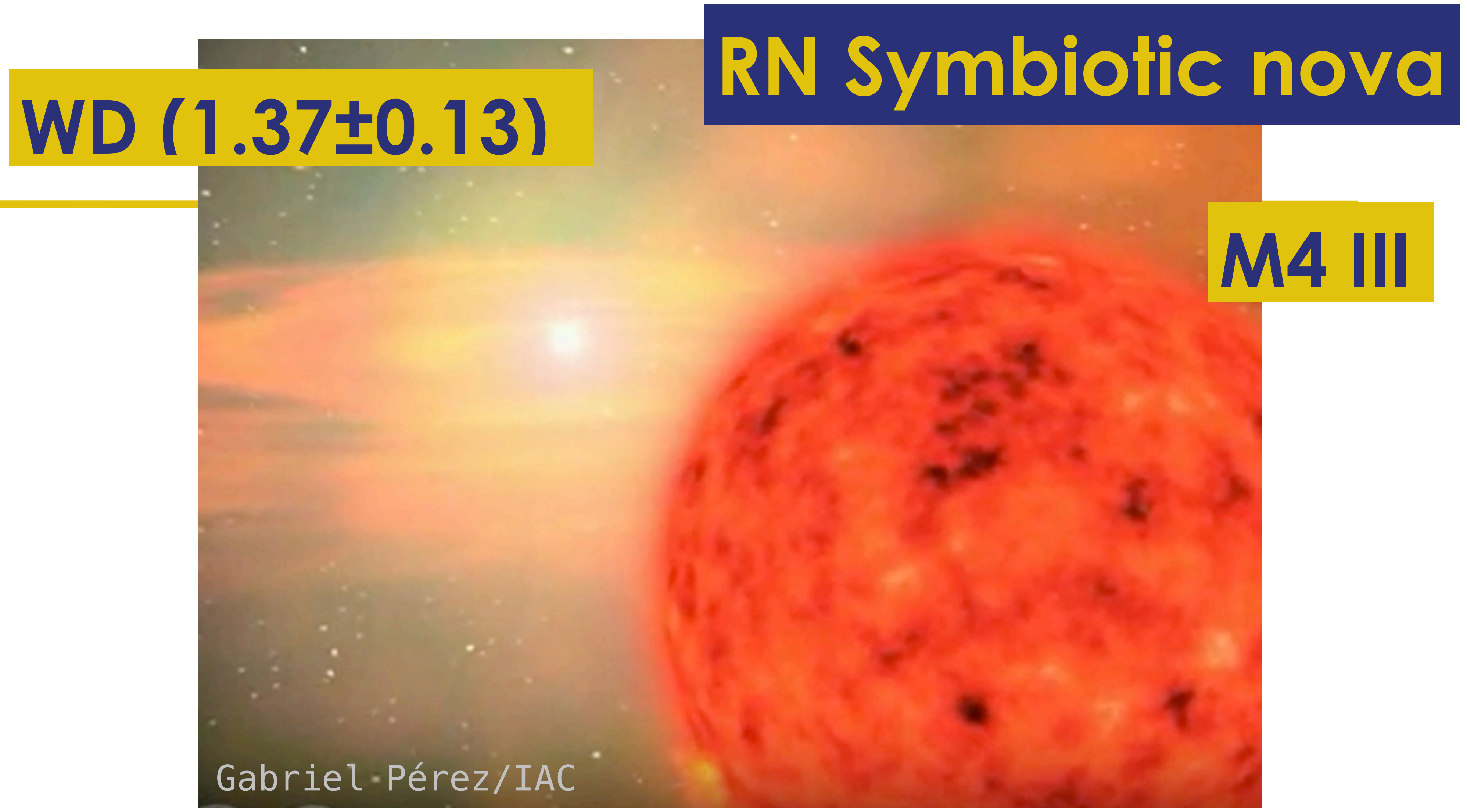
- **New RNe?**
  - `Schaefer` compiled a list of novae with **expected fast recurrence rate**:
    - `V4643 Sgr (3.1kpc), V5589 Sgr (4kpc), V1534 Sco (7.4kpc), V1187 Sco (3.2kpc), V2275 Cyg (3.6kpc)`

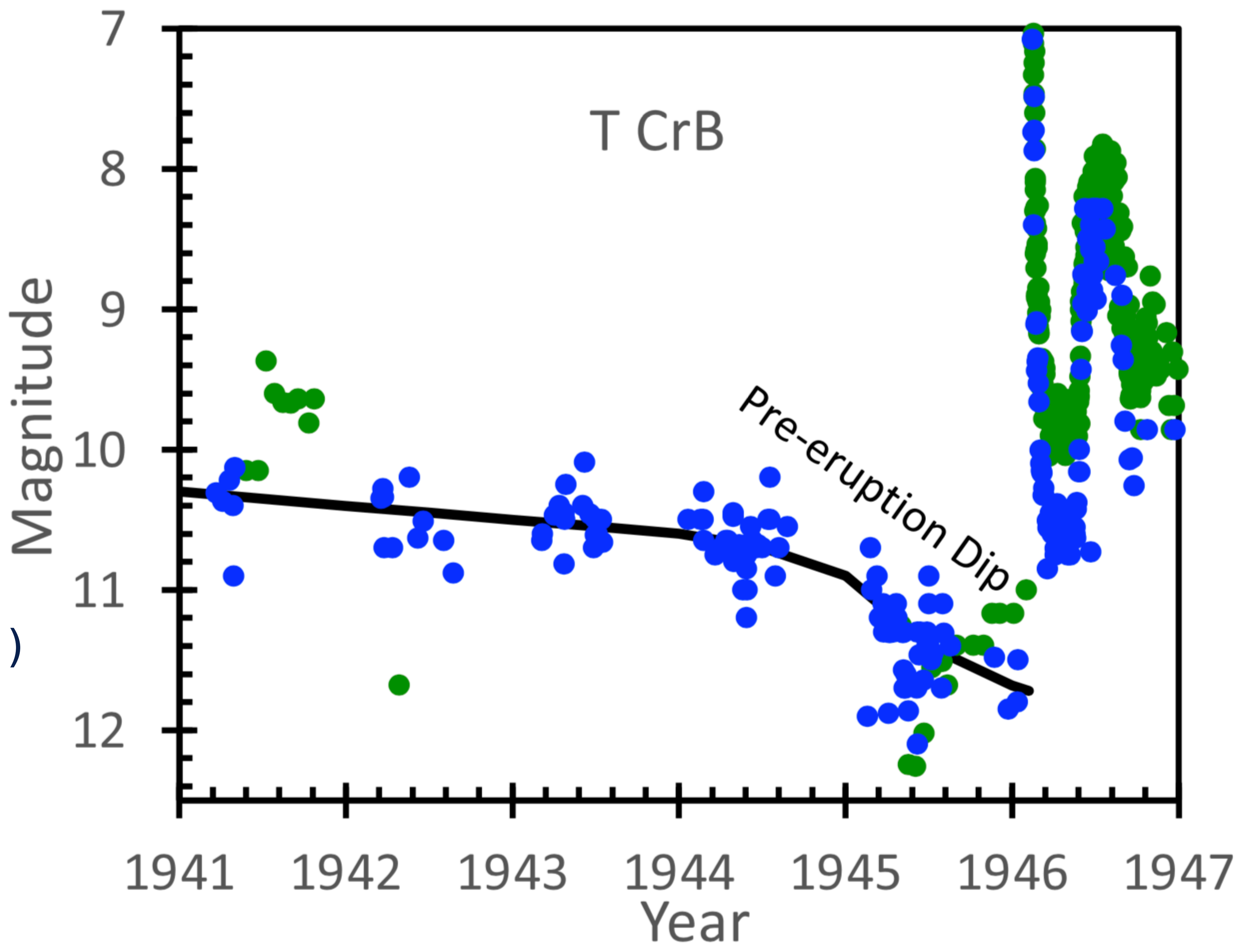
Inmediate future: T CrB



Data from Schaefer (2022), except V~5 inferred in V959 Mon 2012; added V407 Cyg 2010

From T. Cheung (VGGRS VI)



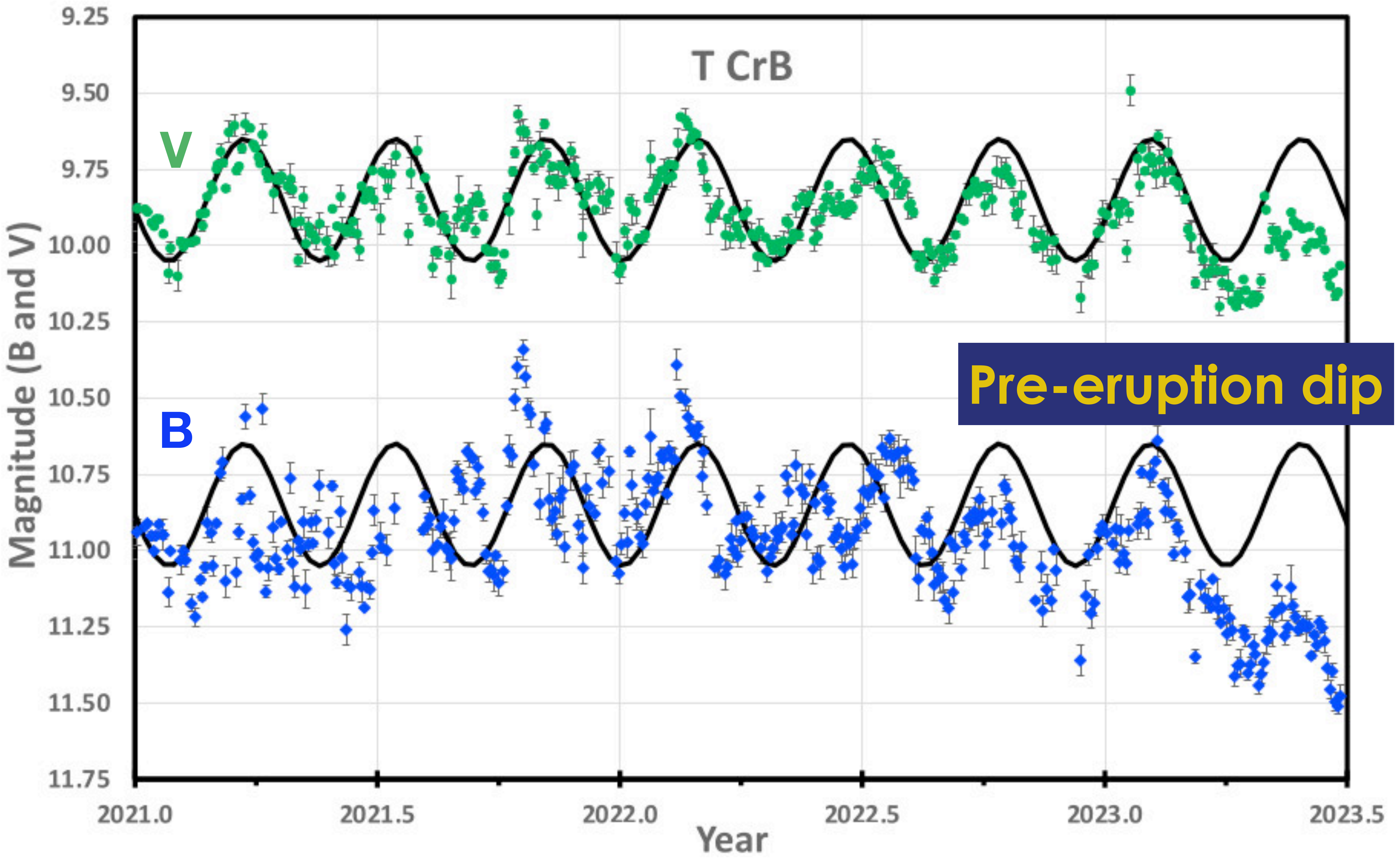


Schaefer 2022

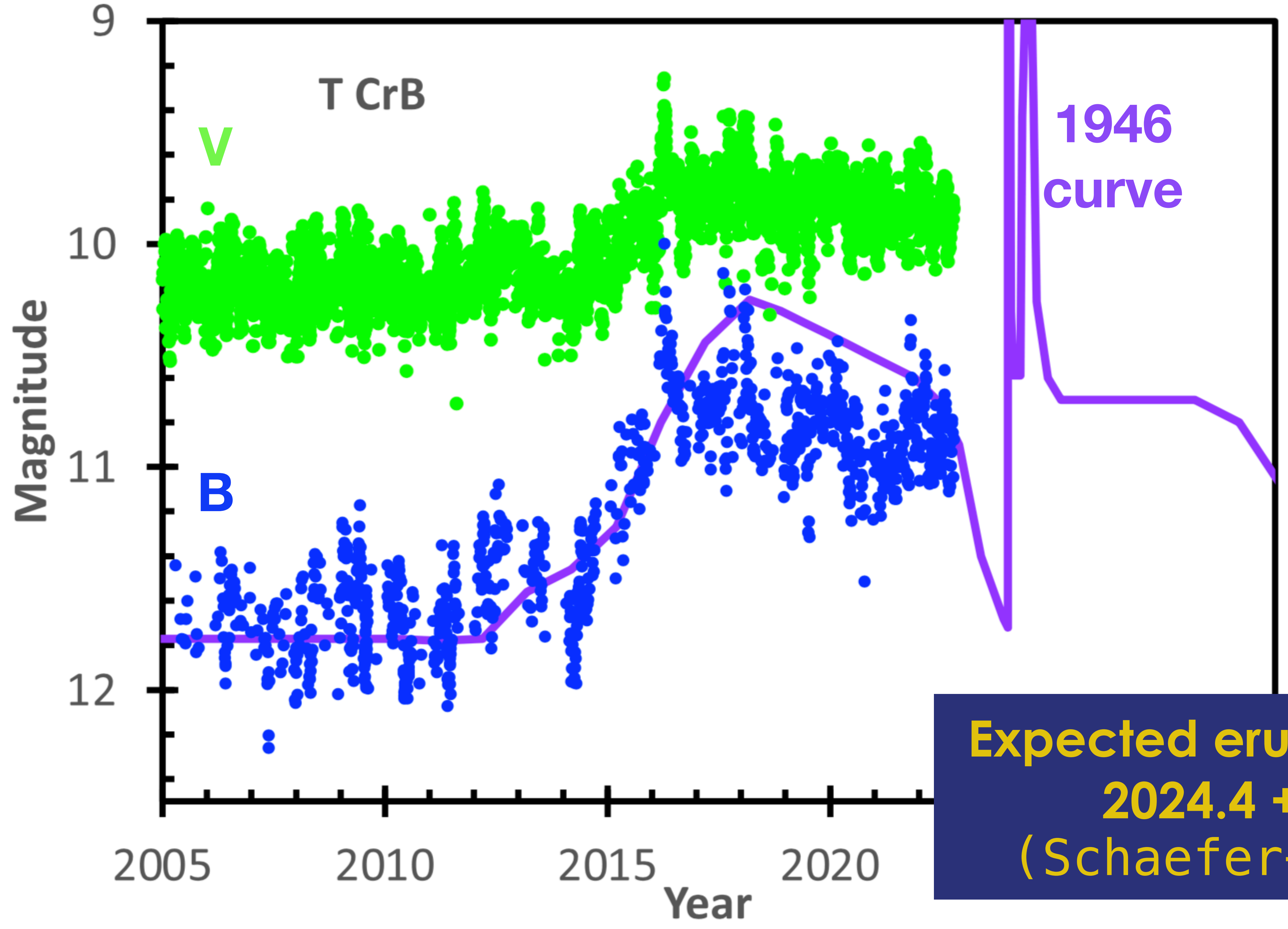
- **Closest known RN symbiotic nova**, D = 0.91 +/- 0.02 kpc (Schaefer 2022)
  - Recurrency period of about **~80 years**
  - Two peaks+dip
- Optical first **peak at mag~2**
- 3x closer than RS Oph; naively scale by distance => ~10x brighter?

Inmediate future: T CrB

- **Pre-eruption dip already started in March/April** `(Schaefer et al. 2023, ATel #16107)`
- **Expected eruption date: 2024.4 ± 0.3** `(Schaefer+ 2023)`



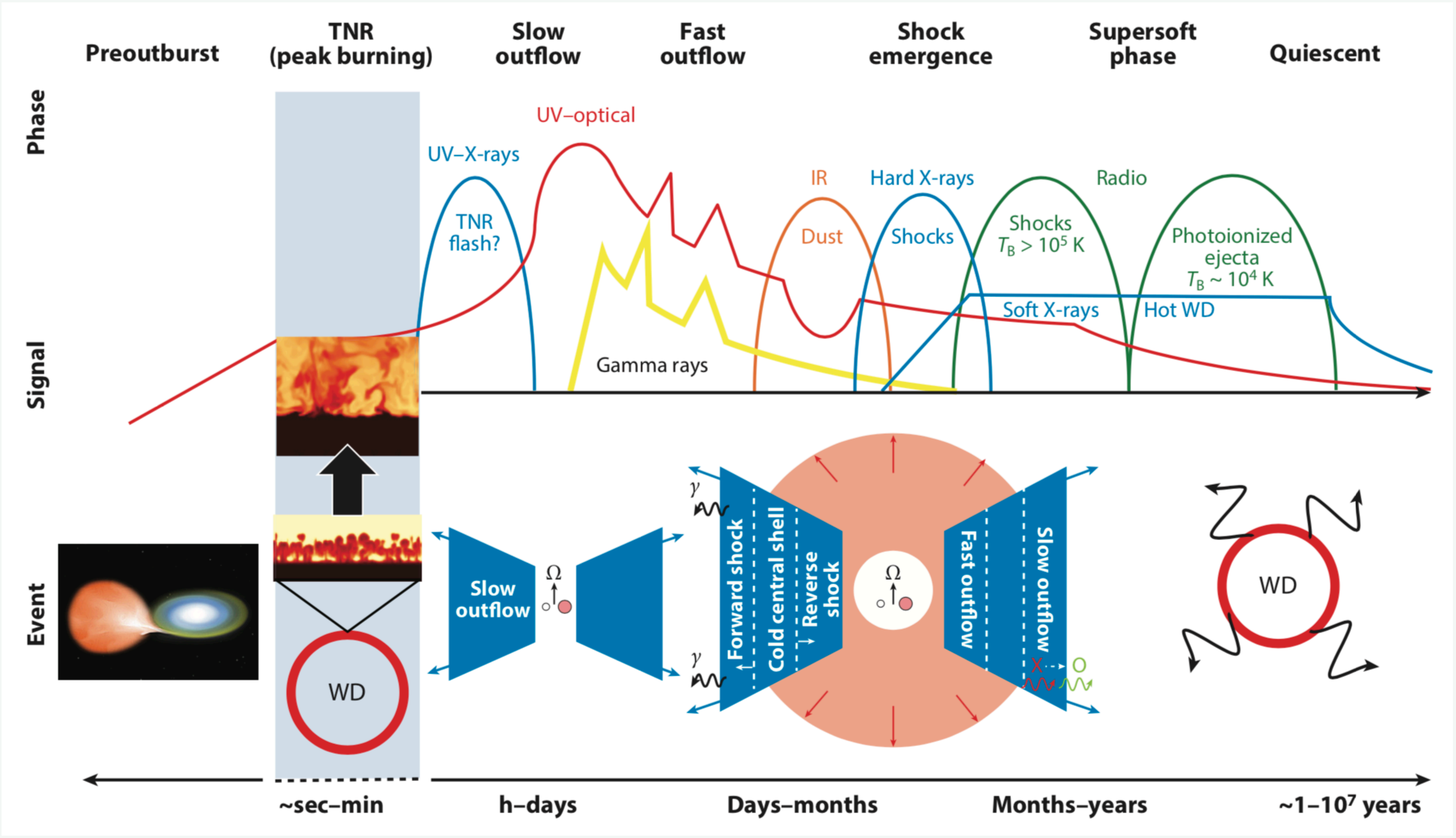
Pre-eruption dip



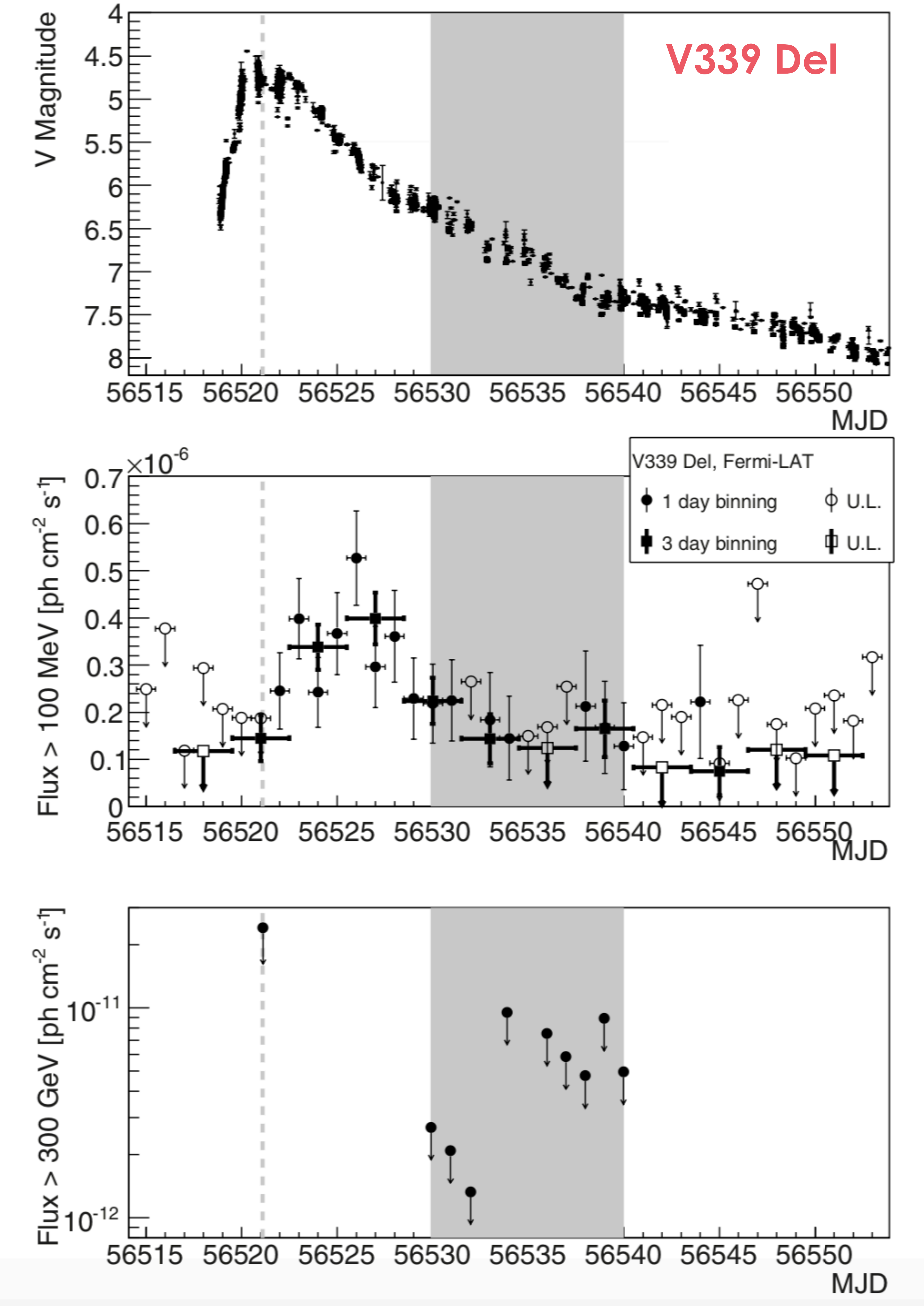
Expected eruption date:
2024.4 +- 0.3
`(Schaefer+ 2023)`

Classical novae

- Classical novae are **HE emitters** `(Ackermann et al. 2014)`
- **No classical nova yet detected at VHE** `(Ahnen et al. 2015, Albert et al. 2022)`
  - What is the maximum particle energy?
  - Emax ~ 10 GeV–10 TeV can lead to emission extending > 100 GeV `(Metzger et al. 2016)`
- **Shocks were unexpected in classical novae,** shocks are radiative: kinetic to radiative luminosity
  - **Slow+fast wind**
  - the ejecta properties of embedded/symbiotic novae **may be similar** to classical novae `(Diesing et al. 2023)`



Chomiuk et al. 2021



Ahnen et al. 2015

Nebulae around recurrent novae?

- Particles accelerated to ~GeV in several novae, TeV emission in RS Oph
- (HE) gamma-ray emission observed up to ~month after explosion

- `Bednarek & Sitarek 2023`: considered hypothesis:
  - **acceleration of electrons at nova shells long after explosion**
    - the acceleration could continue during the time scale corresponding to the recurrence period
  - Escape of electrons into the nebula surrounding RNe
    - **gamma-ray nebulae around RNe: nova super-remnant (NSR)**
  - NSR from RS Oph out of the sensitivity limit of current IACTs
    - other possible target (closer, shorter recurrency period)?

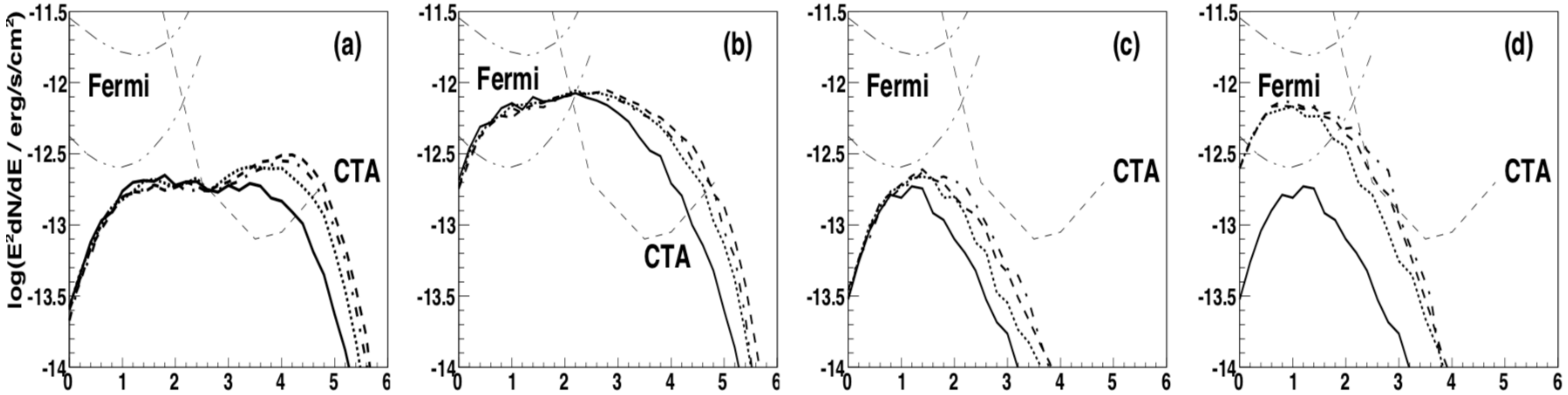
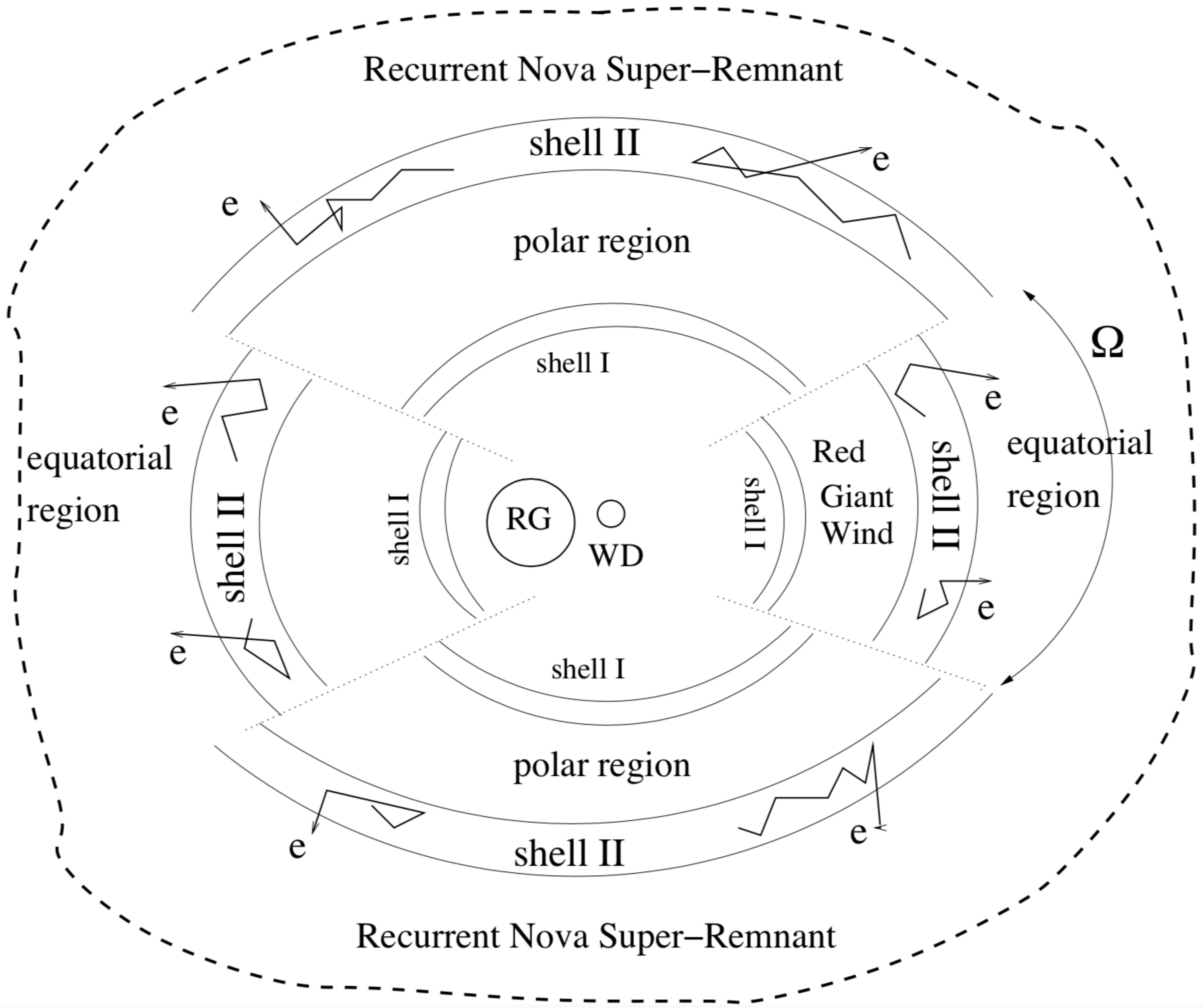


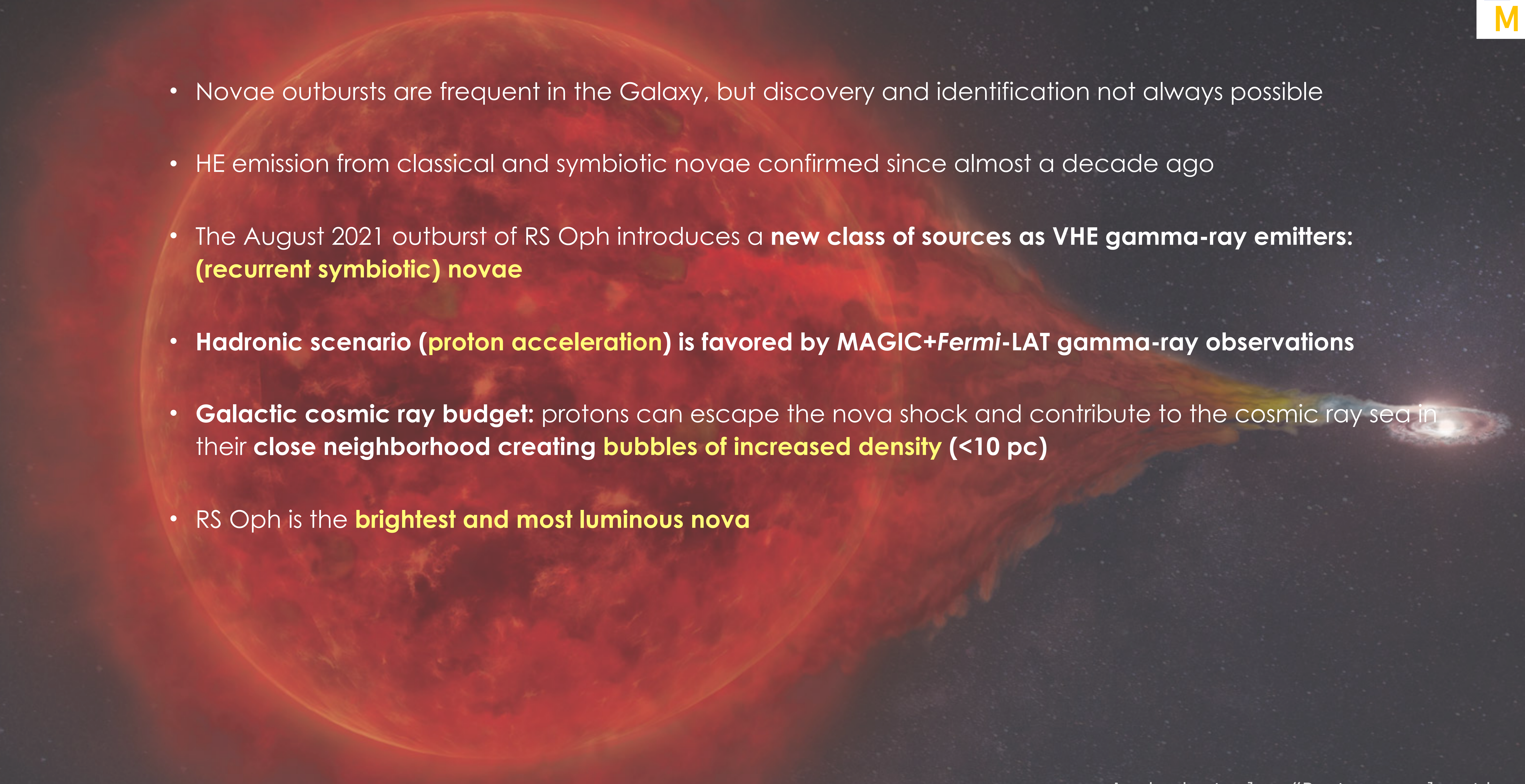
Figure 6: γ-ray emission from nova nebula expected in terms of different acceleration models of electrons within the nova shell, electrons accelerated in the polar regions of the shell, during the recurrence period of RS Oph ($t_{\rm max} = 15$ years);
Different magnetic field in the shell: $\alpha = 10^{-5}$ (solid), 10^{-4} (dotted), 10^{-3} (dashed), 120^{-2} (dot-dashed);
Fast acceleration (figures (a) and (b) and slow acceleration (c) and (d);
Activity period of recurrent nova $T_{\rm active} = 10^4$ yrs ((a) and (c)) and 10^5 yrs ((b) and (d));

`from Bednarek TeVPa 2023`



`Bednarek & Sitarek 2023`

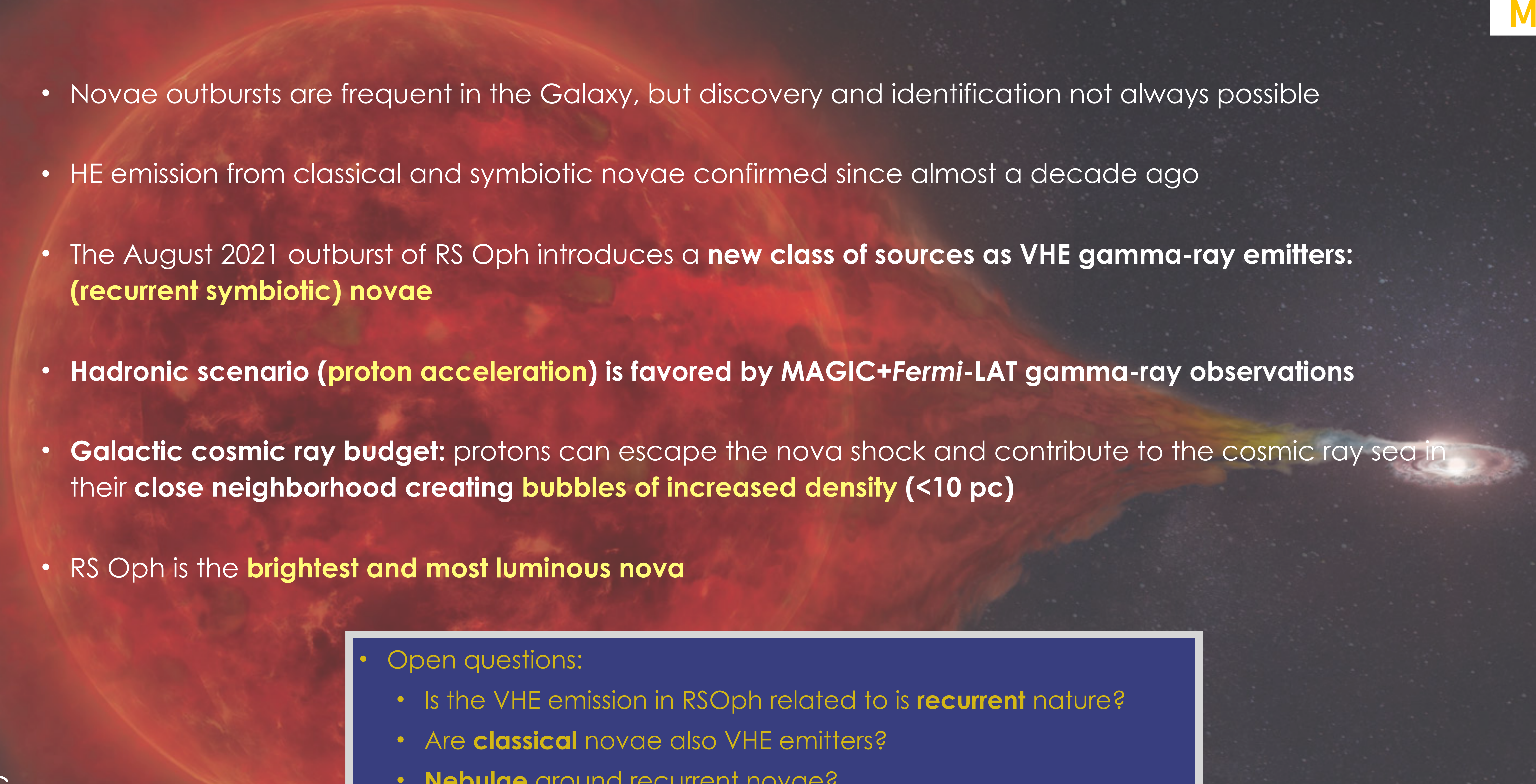
Summary



- Novae outbursts are frequent in the Galaxy, but discovery and identification not always possible
- HE emission from classical and symbiotic novae confirmed since almost a decade ago
- The August 2021 outburst of RS Oph introduces a **new class of sources as VHE gamma-ray emitters: (recurrent symbiotic) novae**
- **Hadronic scenario (proton acceleration) is favored by MAGIC+*Fermi*-LAT gamma-ray observations**
- **Galactic cosmic ray budget:** protons can escape the nova shock and contribute to the cosmic ray sea in their **close neighborhood creating bubbles of increased density (<10 pc)**
- RS Oph is the **brightest and most luminous nova**

Acciari et al., “Proton acceleration in thermonuclear nova explosions revealedby gamma rays”, Nature Astronomy, 2022
https://doi.org/10.1038/s41550-022-01640-z

Summary



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- Open questions:
  - Is the VHE emission in RSOph related to is **recurrent** nature?
  - Are **classical** novae also VHE emitters?
  - **Nebulae** around recurrent novae?

Thanks

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Acciari et al., “Proton acceleration in thermonuclear nova explosions revealedby gamma rays”, Nature Astronomy, 2022
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Plan de Recuperación,
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Novae with MAGIC

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Thanks

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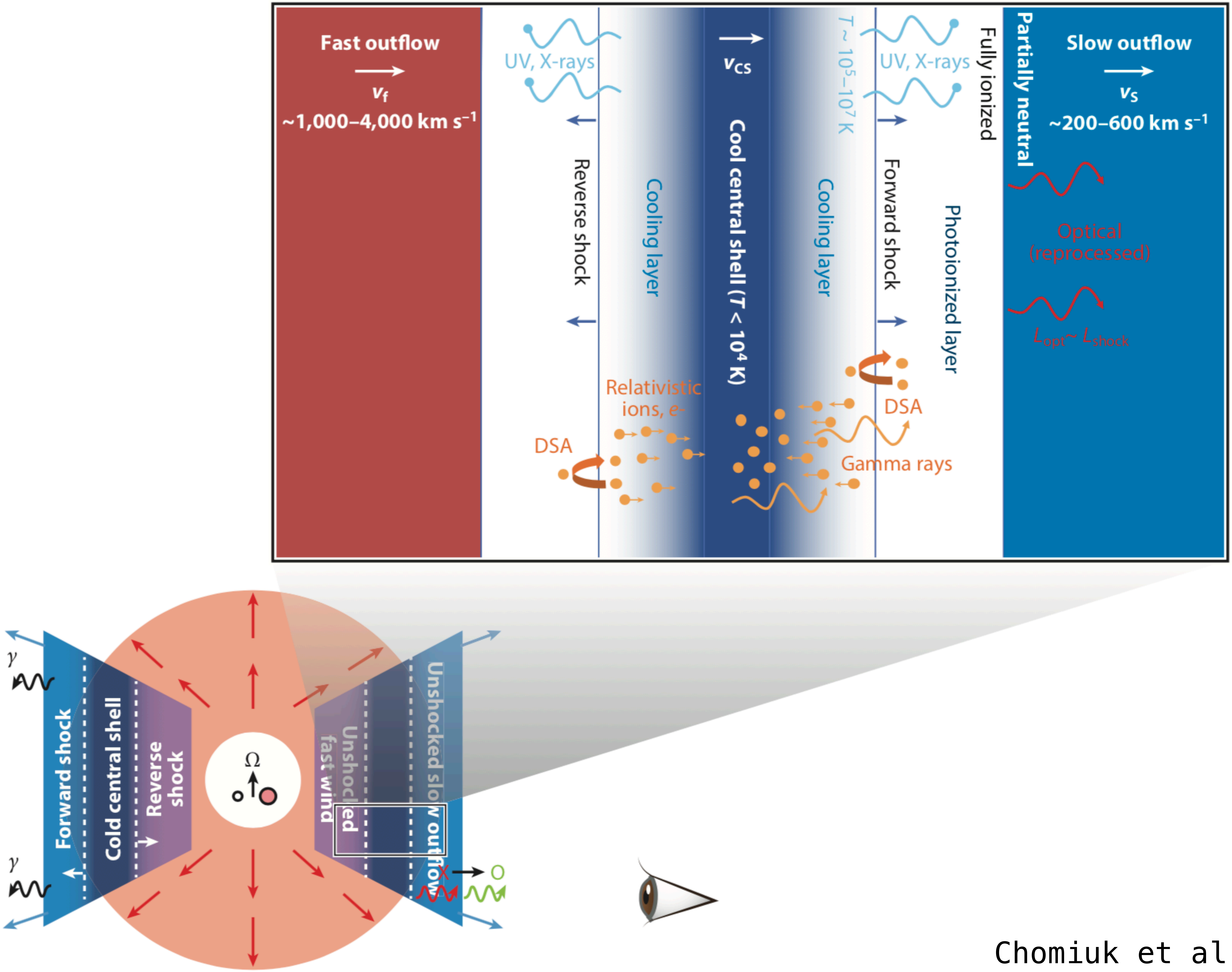
20 MAGIC Years Symposium, October 2023

Credit: Superbossa/MPP



Chomiuk et al. 2021

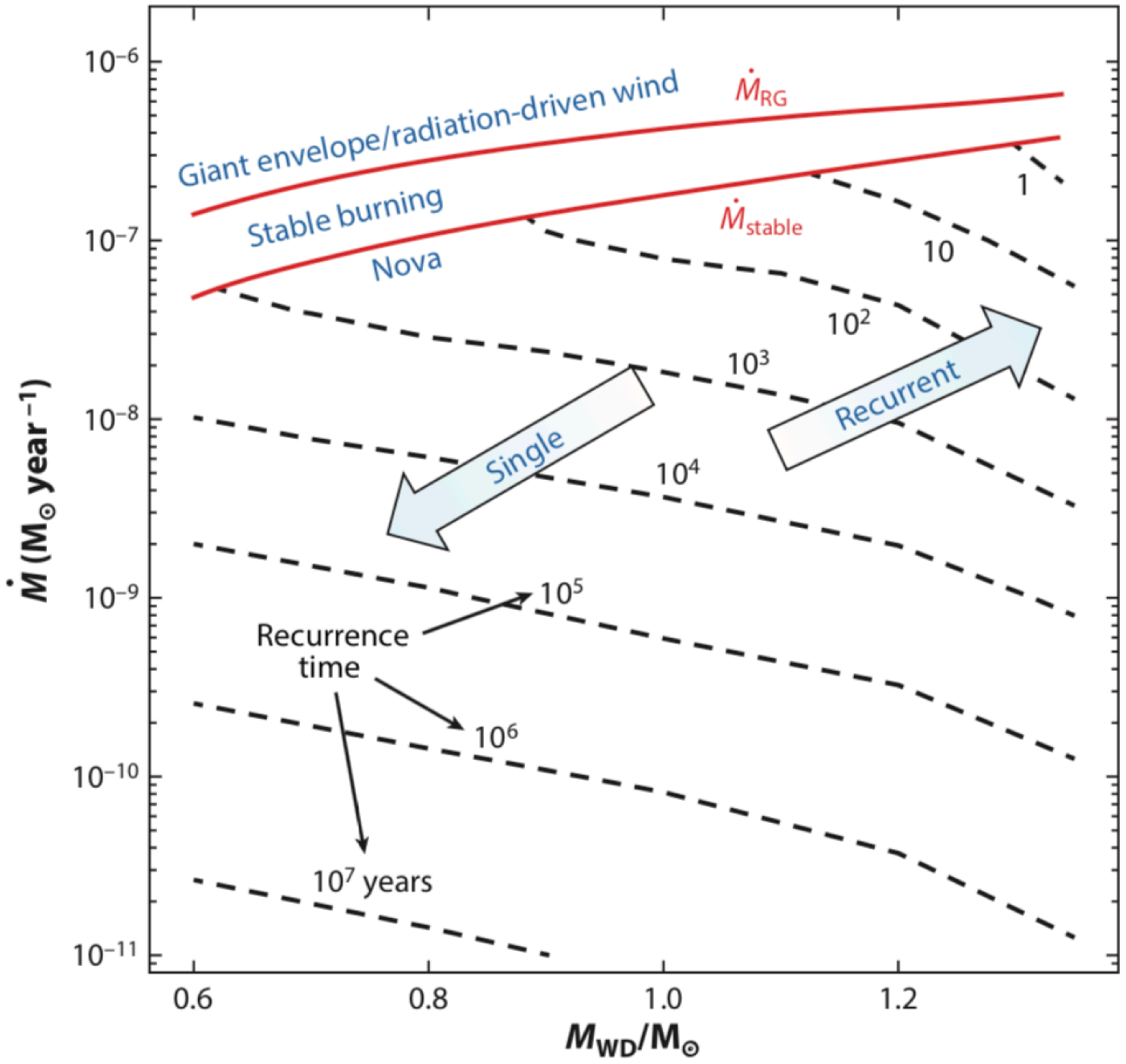


Figure 2

Depending on the WD mass and accretion rate ($\dot{M}$), a wide variety of phenomena are theoretically expected. The lower red line is $\dot{M}_{\text{stable}}$, the lowest accretion rate leading to stable burning for a given WD mass. At higher accretion rates, $\dot{M} > \dot{M}_{\text{RG}}$, hydrogen will still burn stably, but more slowly than the matter is accreted. The matter will pile up to form a red giant–like structure or it must be carried away in a wind. Below $\dot{M}_{\text{stable}}$, burning is unstable, resulting in nova eruptions. Dashed black lines are lines of constant nova recurrence time (labeled in units of years). Nova ejecta masses can be estimated as the product of recurrence time and $\dot{M}$. The stability lines are taken from Wolf et al. (2013). Recurrence timescales are calculated using the stellar evolution code `MESA` (v12115; Paxton et al. 2011) in a similar procedure as that described by Wolf et al. (2013), but with a central core temperature of 10^7 K and covering a larger range in accretion rates. Figure adapted with permission from Wolf et al. (2013); copyright AAS. Abbreviation: WD, white dwarf.

Chomiuk et al. 2021