U.S. NAVAL RESEARCH LABORATORY

Fermi Gamma-ray Space Telescope

Gamma-ray Novae

C. C. Teddy Cheung

Naval Research Laboratory

on behalf of the Fermi-LAT collaboration

Thanks: Pierre Jean, Steve Shore, Tyrel Johnson, Sara Buson

Research supported by NASA DPR S-15633-Y

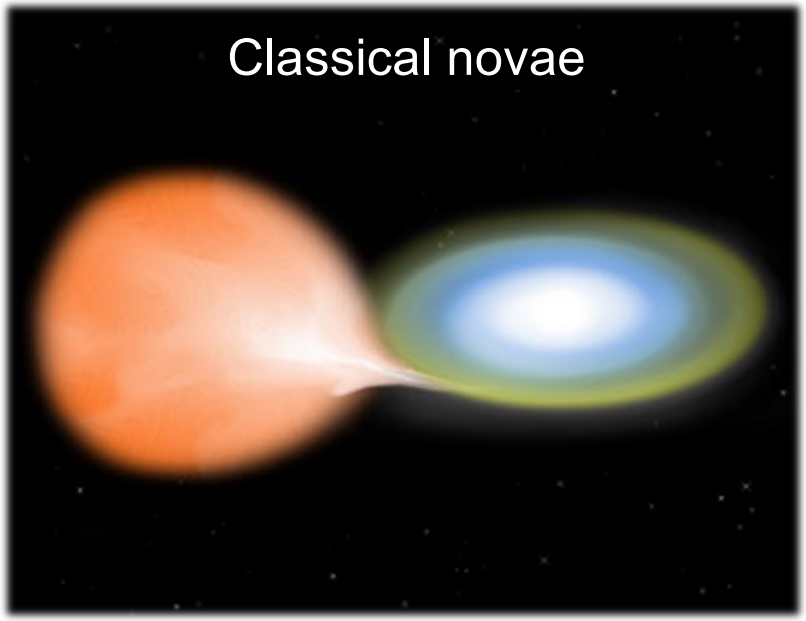
White Dwarfs in Close Binary Systems

Compact cataclysmic variable:

WD + Main Sequence

↓

Roche lobe overflow



- separations, a ~ 10^{11}cm ~ $R_\odot$
- P_{orb}~ hr-day
- P_{rec} >~ 10^4 yr
- rate ~ 30 – 50 / yr in Galaxy

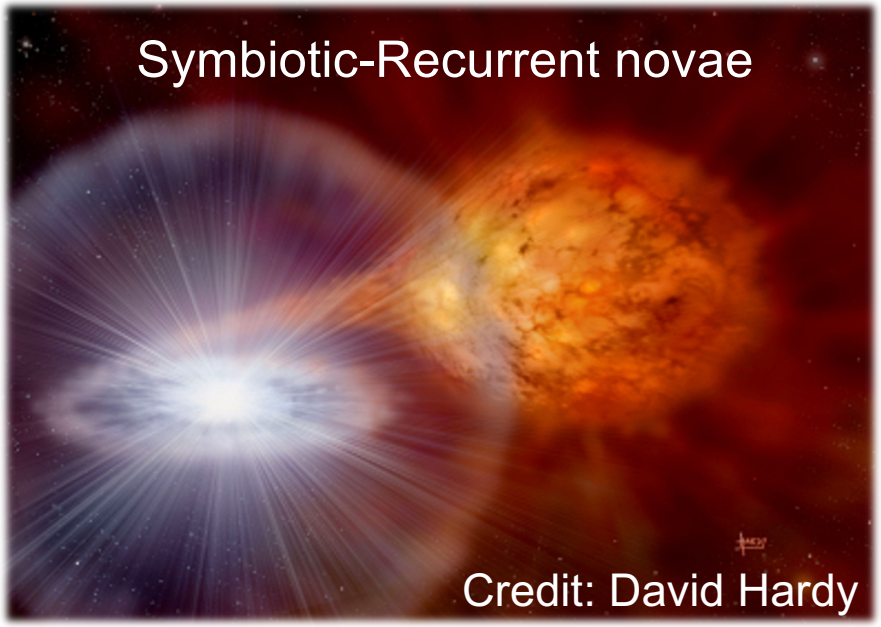
Hydrogen burning in degenerate conditions on top of the white dwarf

Symbiotic system:

Massive WD + Red Giant

↓

accretion from red giant wind



- a ~ 100's $R_\odot$
- P_{orb}~ years
- P_{rec} < 100 yrs
- ~10 known symbiotic-recurrents

Adapted from M. Hernanz, X-ray Universe 2011 talk

Fermi-LAT >0.1 GeV Novae: 2008 - 2015

Status ca. 2017, Variable Galactic Gamma-Ray Sources (IV), Tokyo

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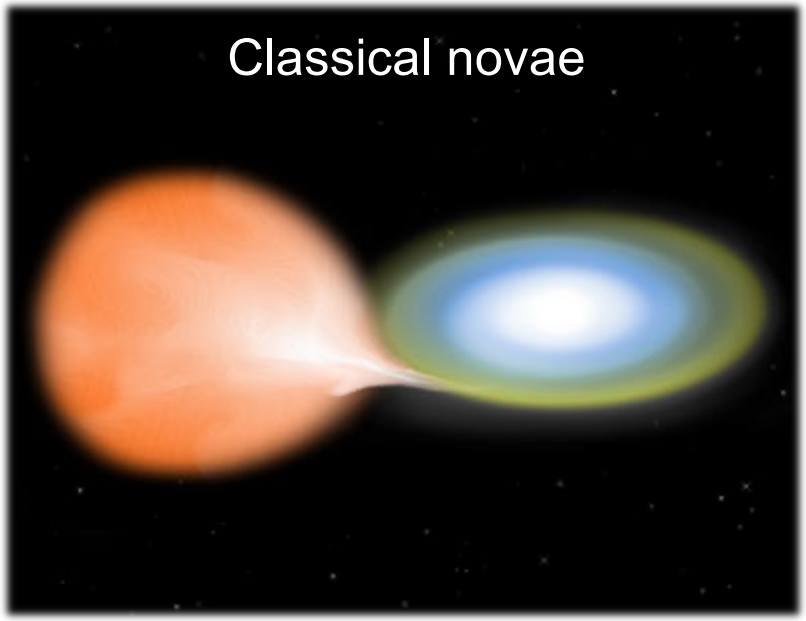

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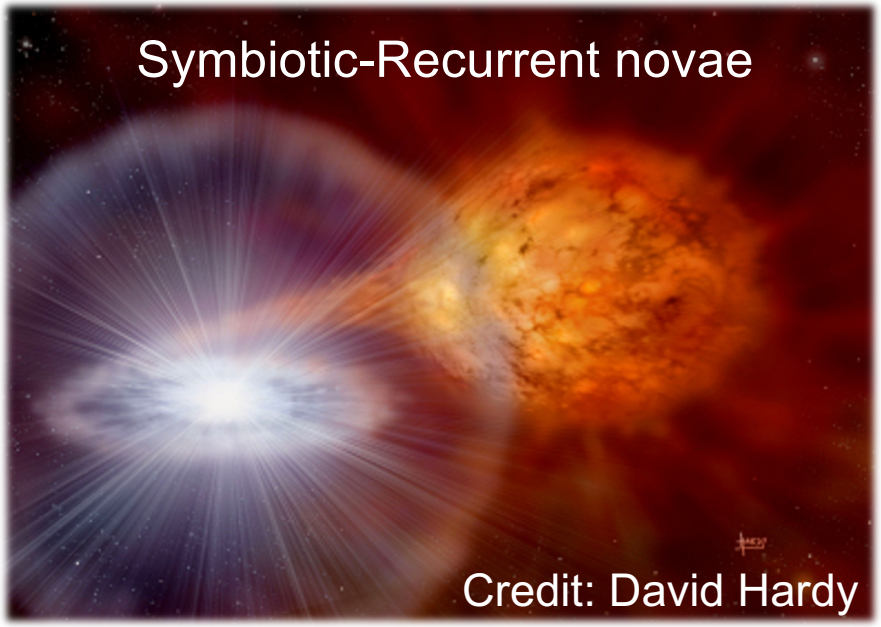


- V1324 Sco 2012, V959 Mon 2012, V339 Del 2013 (Ackermann+14)
- V1369 Cen 2013, V5668 Sgr 2015 (Cheung+16)
- Three additional novae in 2016 (in Atels)

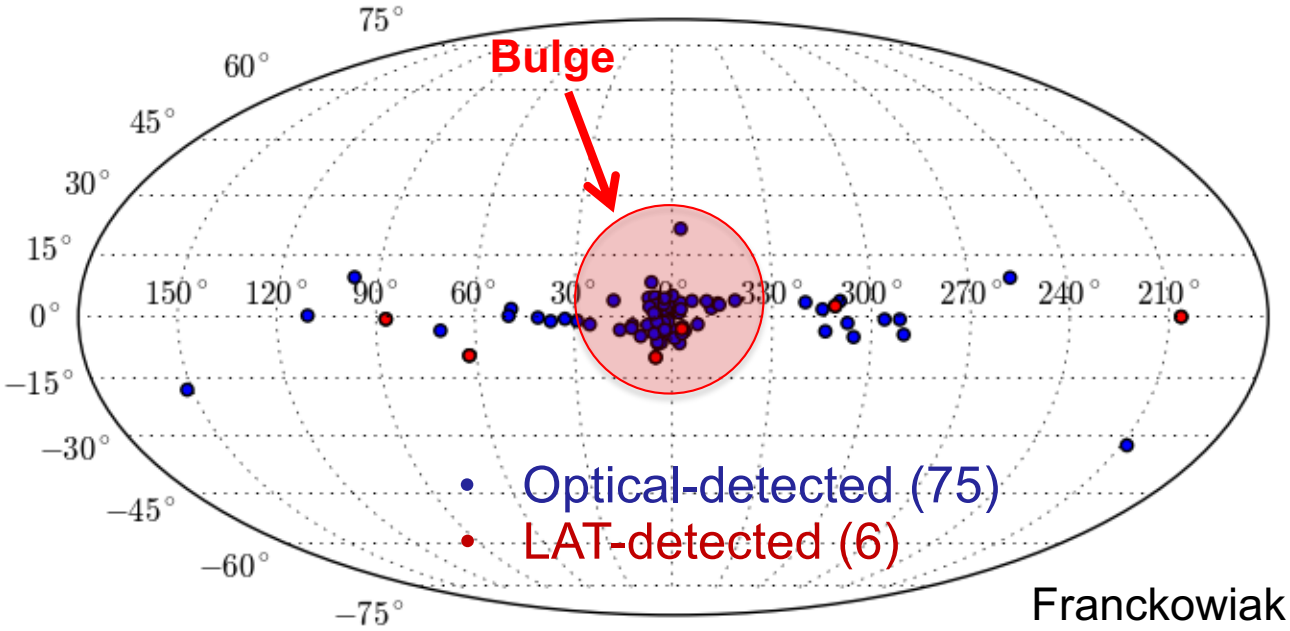
- Symbiotic V407 Cyg 2010 (Abdo+10)
- Symb.-rec. V745 Sco 2014 - 2σ (Cheung+14 Atel)
- Symbiotic V1535 Sco 2015 - 2σ (Franckowiak+18)

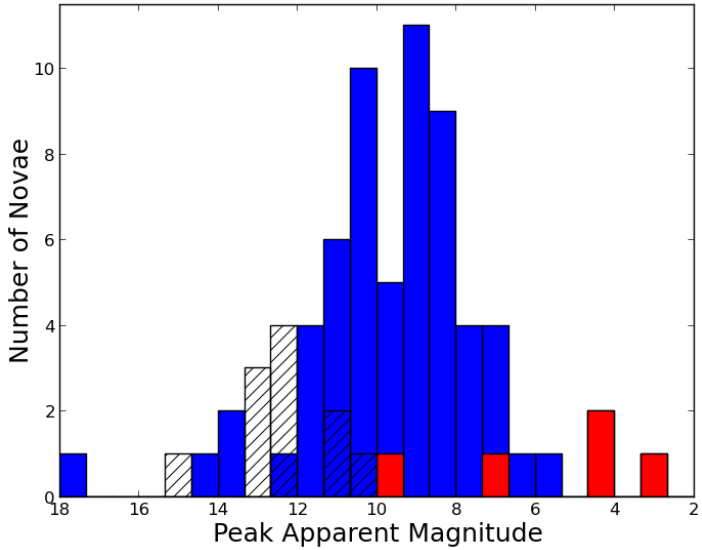
Note later: Recurrent, non-symbiotic KT Eri 2009, T Pyx 2011, U Sco 2010 (2022) were not detected (Franckowiak+18)

Fermi-LAT >0.1 GeV Novae: 2008 - 2015

Status ca. 2017, Variable Galactic Gamma-Ray Sources (IV), Tokyo

- Fermi-LAT search of 75 Galactic novae from Aug 2008-Dec 2015
- **LAT** detected 0-2 each year, 6 total (**average ~1 per year**)





Franckowiak et al. 2018

- Modern **optical/IR surveys** continue to detect 7-17 novae per year (**average ~10 per year**)
- Overall Galactic nova rate ~30-50 per year based on recent optical, near-IR, and mid-IR transient surveys (ASAS-SN, OGLE-IV, Palomar-IR, NEOWISE; Mroz et al. 2015, De et al. 2020, Kawash et al. 2021, 2022); narrower range than early estimates (Shafter 1997, 2017)

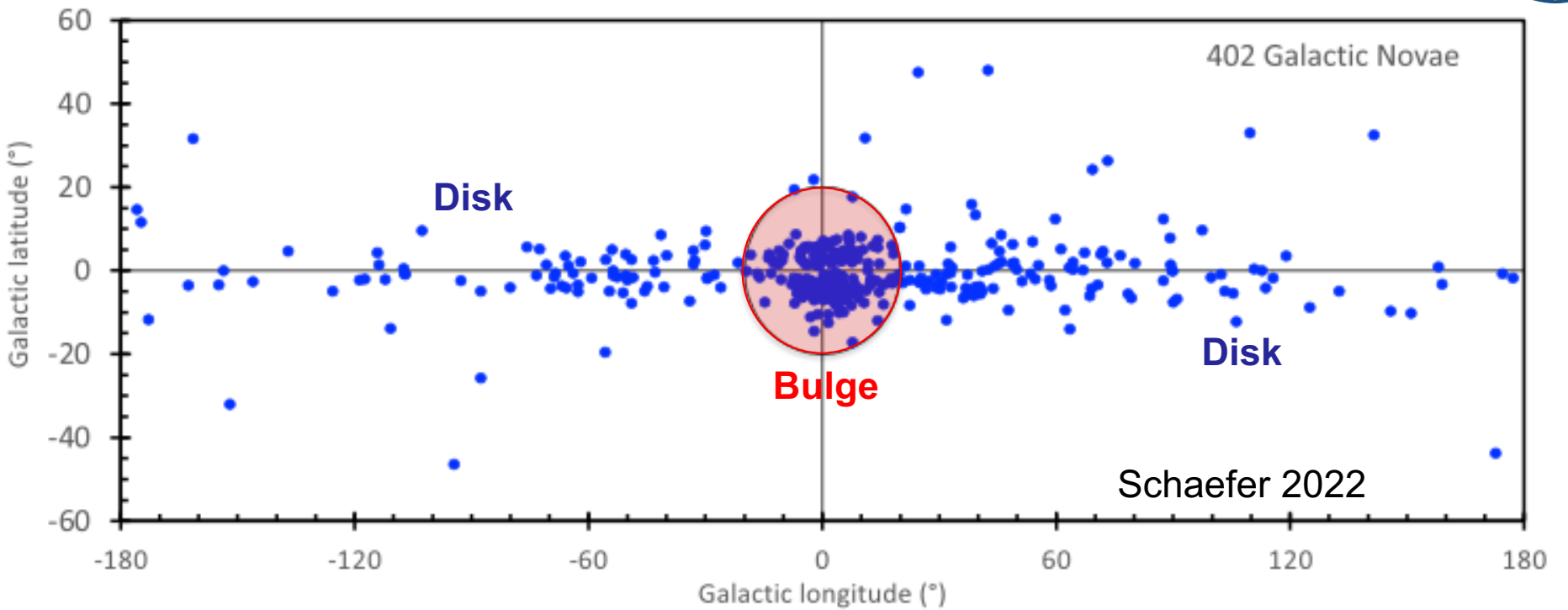
Gamma-ray Novae: Questions

- **Are all novae GeV gamma-ray sources ?**

- **Symbiotics (and recurrents) as keystone systems ?**

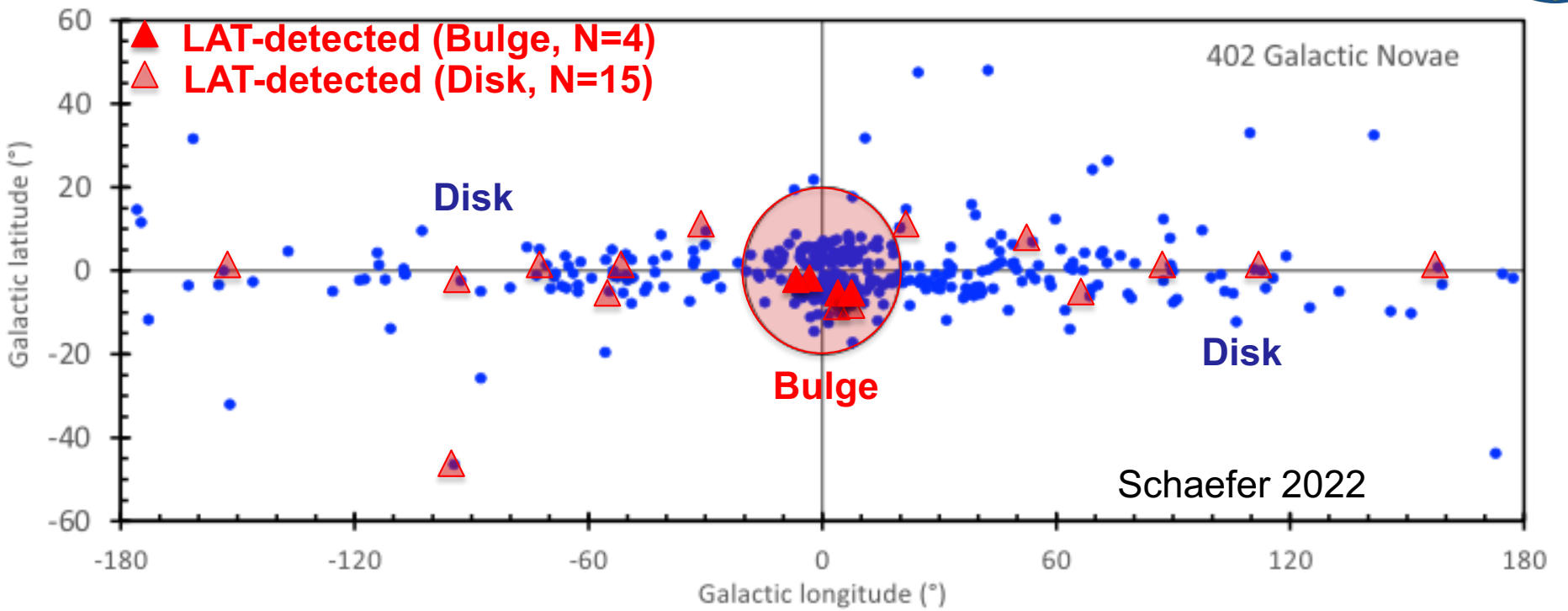
- **Are the γ-ray shock acceleration sites identifiable at lower-energies ?**
  - e.g., Aydi+20, Chomiuk+22; B. Reville (this meeting)
- **Role of future VHE observations, particularly with CTA ?**
  - A. Aguasca-Cabot, VHE talks (this meeting)

New: Distances to Galactic Novae



- Bayesian distances to 402 Galactic novae using Gaia DR3 parallax (74 “good”, i.e., with <30% uncertainty) and non-parallax distance measures (Schaefer 2022)
  - 124 novae occurred in Fermi-era (2008 – 2021.6)
  - Derived 220 distances with <30% uncertainty
- Two *observed* populations:
  - ~40% in Galactic Bulge (D ~ 8.0 +/ 0.8 kpc); rest in Galactic Disk (scale height 140 +/- 10 pc), i.e., the local population to Earth
  - Symbiotic (red giant) systems are relatively rare in the disc population (5 +/- 2 %) vs. the bulge population (35 +/- 8%) – no simple explanation
  - Otherwise, populations indistinguishable (e.g., absolute optical mag, lightcurve decline times, optical spectral types)

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

Fermi-LAT GeV Novae: 2008 - 2023

N=19 LAT detections, 0-3 novae each year, average ~1.3 per year

Nova	D (kpc)	t_γ^a (days)	Γ^b	E_c^c (GeV)	F_γ^d (10^{-7} cm^{-2} s^{-1})	Refs	
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	7.1 – 8.6	17	1.9 ± 0.2	7.7 ± 4.7	4.4 ± 0.9	2,14,21	
V959 Mon 2012	2.5 – 4.1	22	1.5 ± 0.3	1.3 ± 0.5	2.6 ± 0.5	2,14,22	2008 - 2015
V339 Del 2013	1.3 – 2.9	27	1.7 ± 0.2	3.0 ± 1.8	1.5 ± 0.2	2,14,23	
V1369 Cen 2013	0.53 – 1.0	39	2.0 ± 0.3	2.0 ± 1.0	2.5 ± 0.5	3,14,24	
V5668 Sgr 2015	1.0 – 1.9	55	2.1 ± 0.1	-	0.6 ± 0.1	3,14,5	"First" six
V407 Lup 2016[e]	2.3 – 4.7	3	2.2 ± 0.3	-	1.6 ± 0.7	4,5	
V5855 Sgr 2016	7.3 – 8.8	26	2.3 ± 0.1	-	3.0 ± 0.8	6	
V5856 Sgr 2016[f]	2.3 – 6.0	15	1.9 ± 0.1	5.9 ± 2.6	5.4 ± 0.5	7,5	
V549 Vel 2017[g]	1.8 – 5.1	33	1.8 ± 0.2	-	0.4 ± 0.2	8,5	2016 - 2020
V357 Mus 2018	2.5 – 5.1	27	2.2 ± 0.1	-	1.3 ± 0.2	5	
V906 Car 2018[h]	2.9 – 7.6	> 20[i]	1.8 ± 0.1	5.9 ± 1.1	12.2 ± 0.4	9	
V392 Per 2018	3.1 – 4.2	$\gtrsim 8$[j]	2.0 ± 0.1	-	2.2 ± 0.4	10,25	From Chomiuk+21, ARAA
V1707 Sco 2019	7.3 – 8.8	5	2.1 ± 0.2	-	2.9 ± 1.0	11,12	
YZ Ret 2020	2.2 – 2.6	18	2.2 ± 0.1	-	2.6 ± 0.2	12,13,26	

V1405 Cas 2021 1.6 – 1.8
V1674 Her 2021 2.5 – 5.4
RS Oph 2021 2.6 – 2.9
2022 and 2023 - none

2021 - onward

V3890 Sgr 2019 8.1 – 9.1

See Koji Mukai's updated list: https://asd.gsfc.nasa.gov/Koji.Mukai/novae/novae.html

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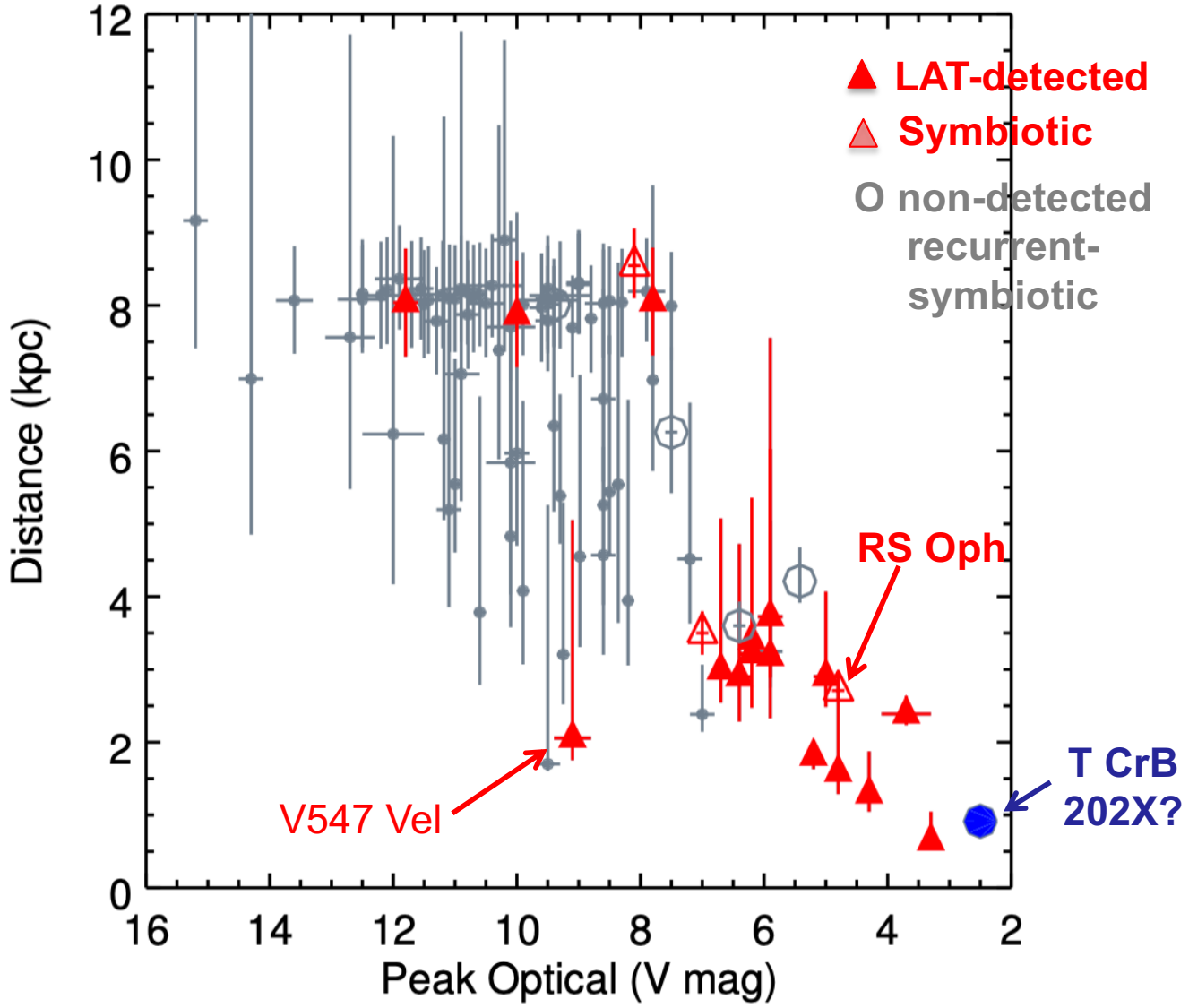

Data from Schaefer (2022), except V~5 inferred in V959 Mon 2012; added V407 Cyg 2010

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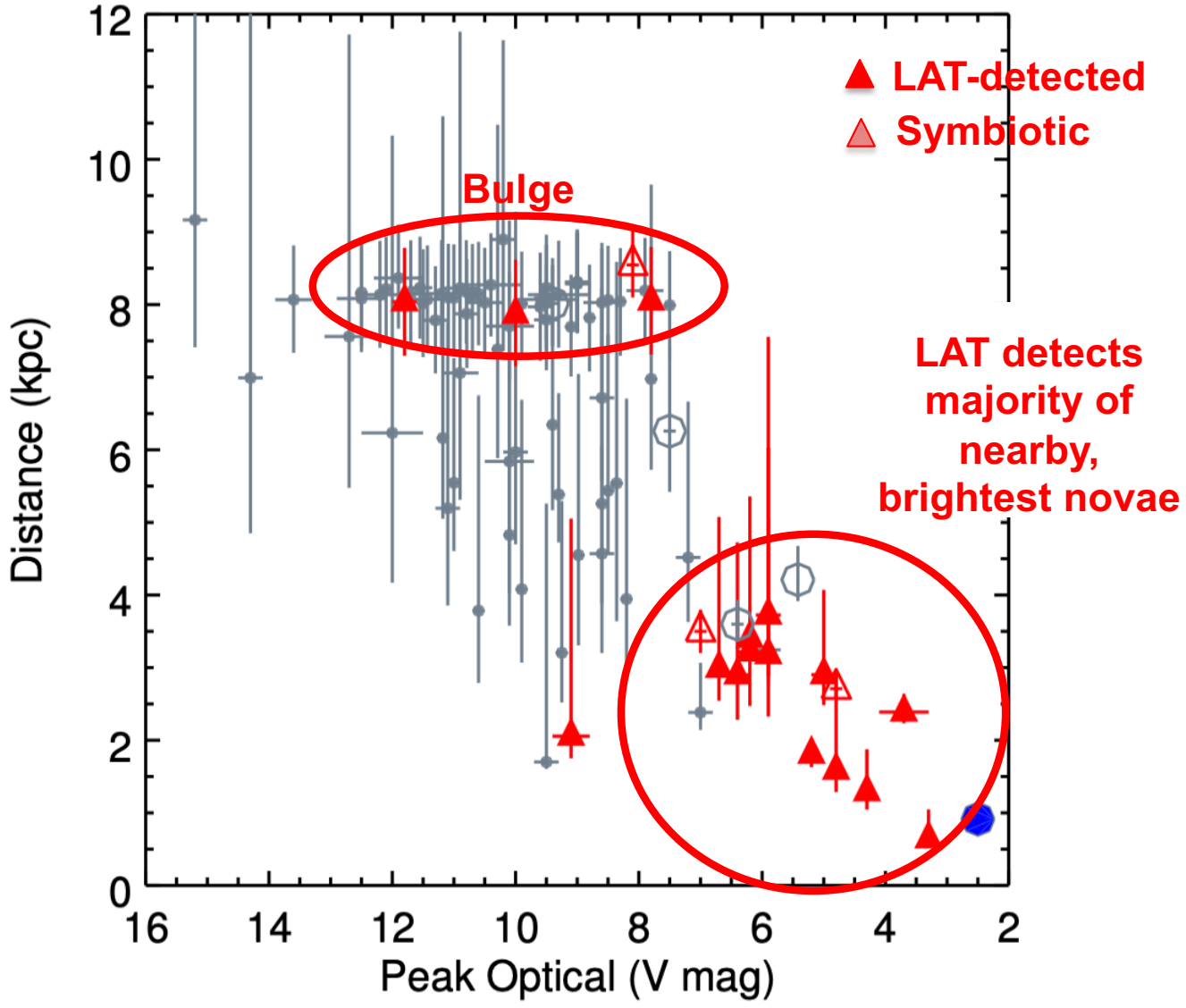

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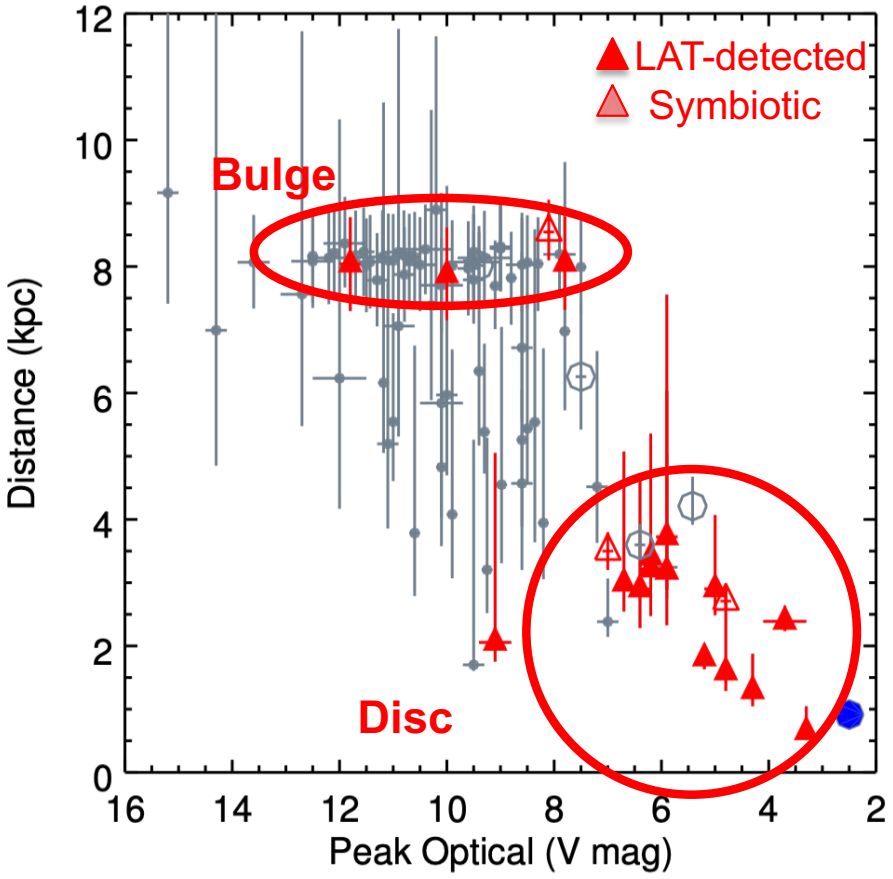
Fermi-LAT GeV Novae: 2008 - 2023

Observational Summary

- LAT-detected novae in Galactic disc tend to be closest and brightest !
- In fact, LAT detected 13/17 of the optically brightest novae during Fermi era; exceptions are:
  - two recurrent novae: KT Eri (V = 5.4), T Pyx (V = 6.4)
  - FM Cir 2018 (V = 5.9) – larger end of distance range?
  - V5583 Sgr 2009 (V = 7) viewed through the Galactic bulge
- Note, two nearby, D ~ 1 kpc systems (not shown in plots) have ill-defined explosion dates (HV Cet 2008, V1375 Cen 2010)
- V549 Vel 2017 is fainter both optically (V = 9.1, D ~ 2-5 kpc) and in gamma rays, and is one of the least luminous gamma-ray novae (Li et al. 2020)

- 4 LAT detections (including symbiotic-recurrent V3890 Sgr) are in the Galactic bulge with range of V peaks consistent with general population



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2021 - onward

RS Oph – recall talks by Aguasca-Cabot (Wednesday), Reville (Thursday)

2022 and 2023 - none

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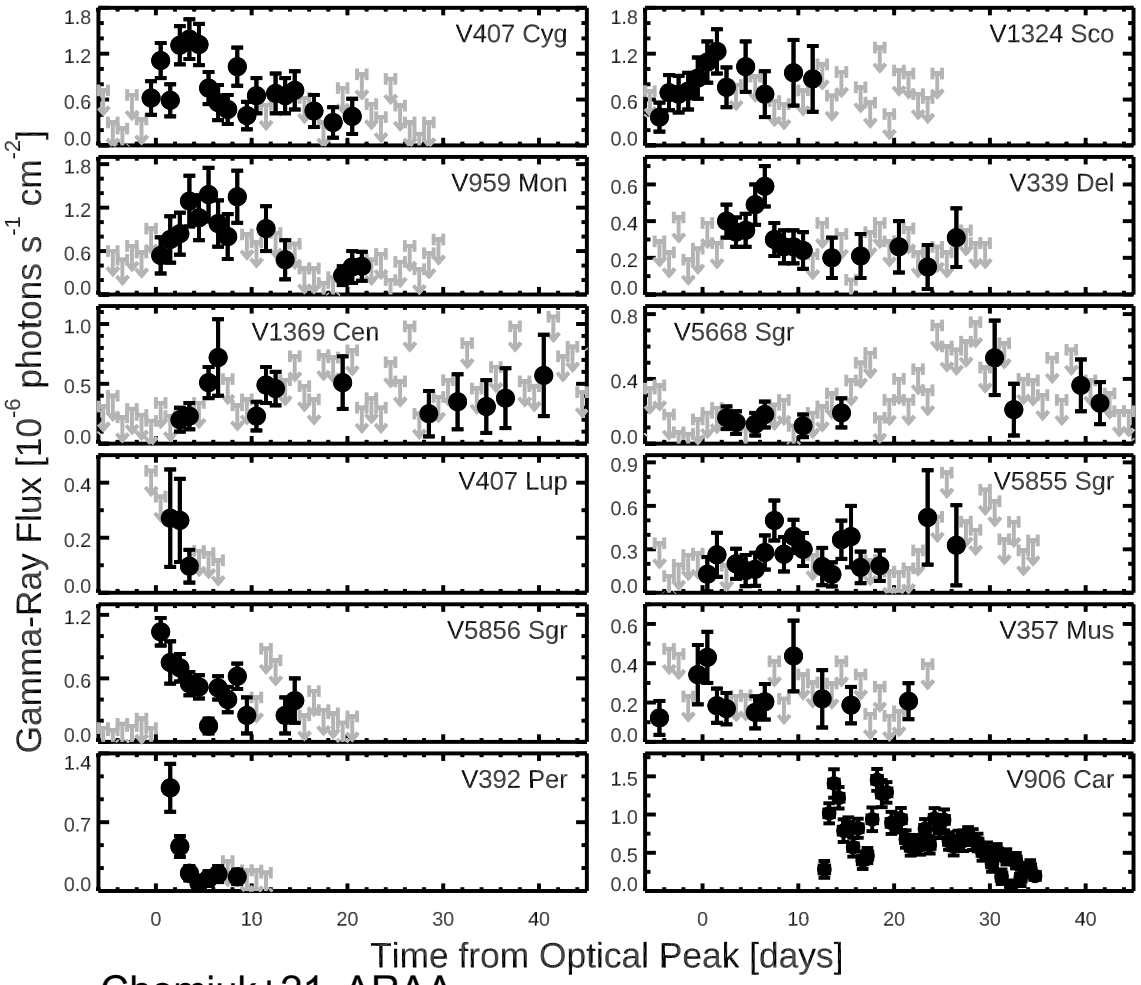
Gamma-ray Properties



Chomiuk+21, ARAA

- Durations ~ 5-55 days
- t_{rise} ~ t_{fall} ~ 2-7 days

(shortest duration = 0.75 day in fastest nova Her 2021; Sokolovsky+23)

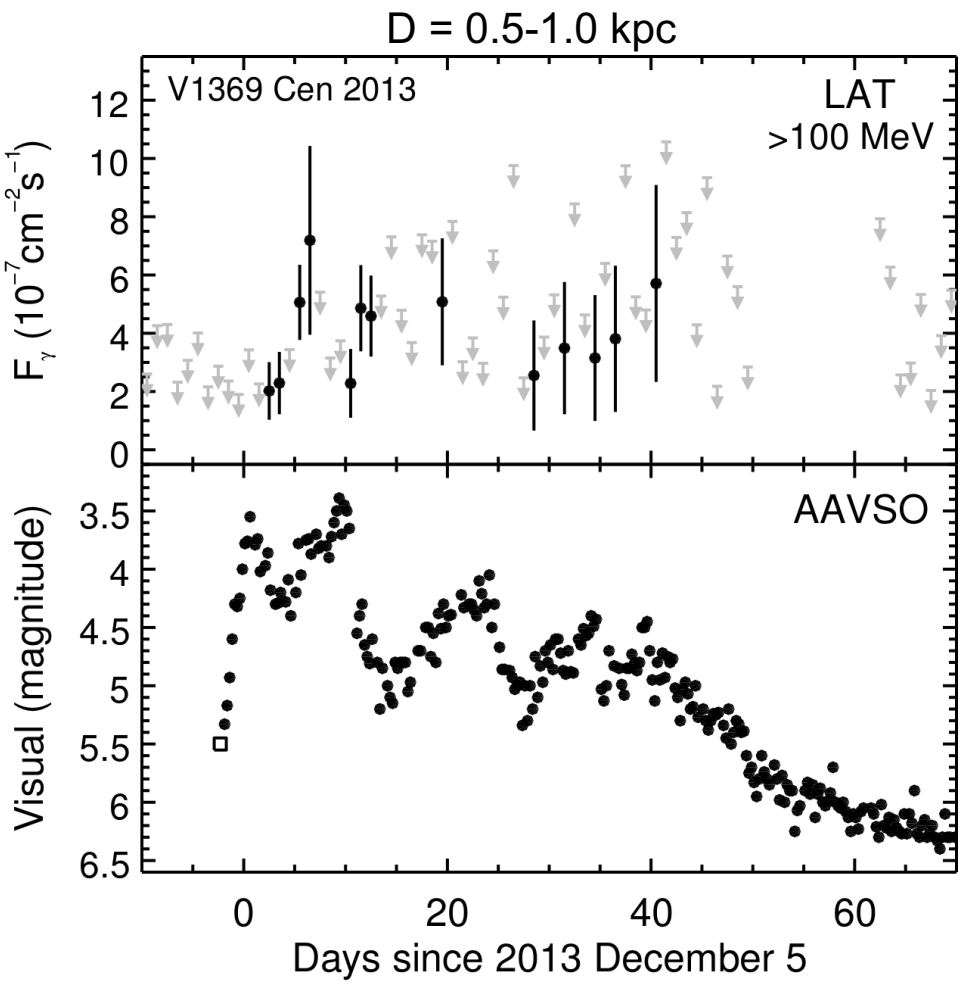
- flux peaks (>0.1 GeV) ~ 0.1-5 x 10^{-6} ph cm^{-2} s^{-1}
- Power law (Γ = 1.8-2.3); many with cutoffs (E_c ~ GeV)

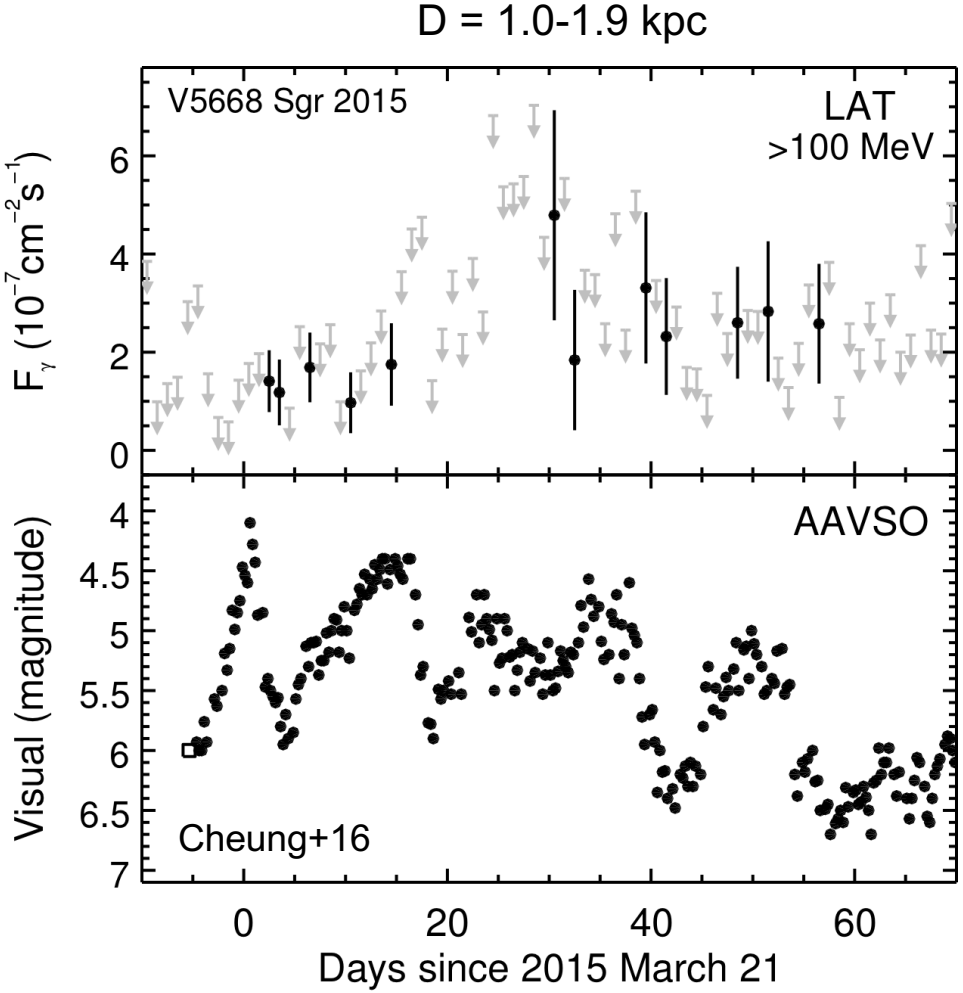
(slightly harder in symbiotics)

- Average luminosities (>0.1 GeV) ~ 10^{34} - 4 x 10^{36} erg s^{-1}

(highest in the bulge)

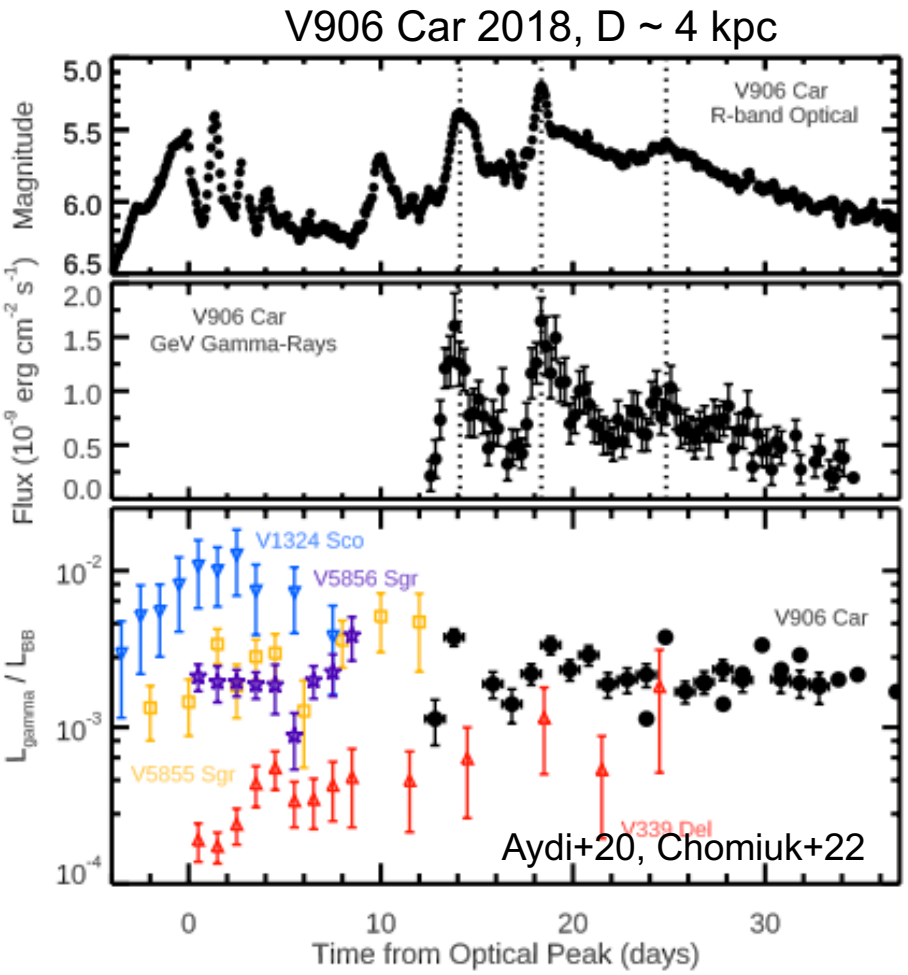
Late-time LAT emission in nearby novae

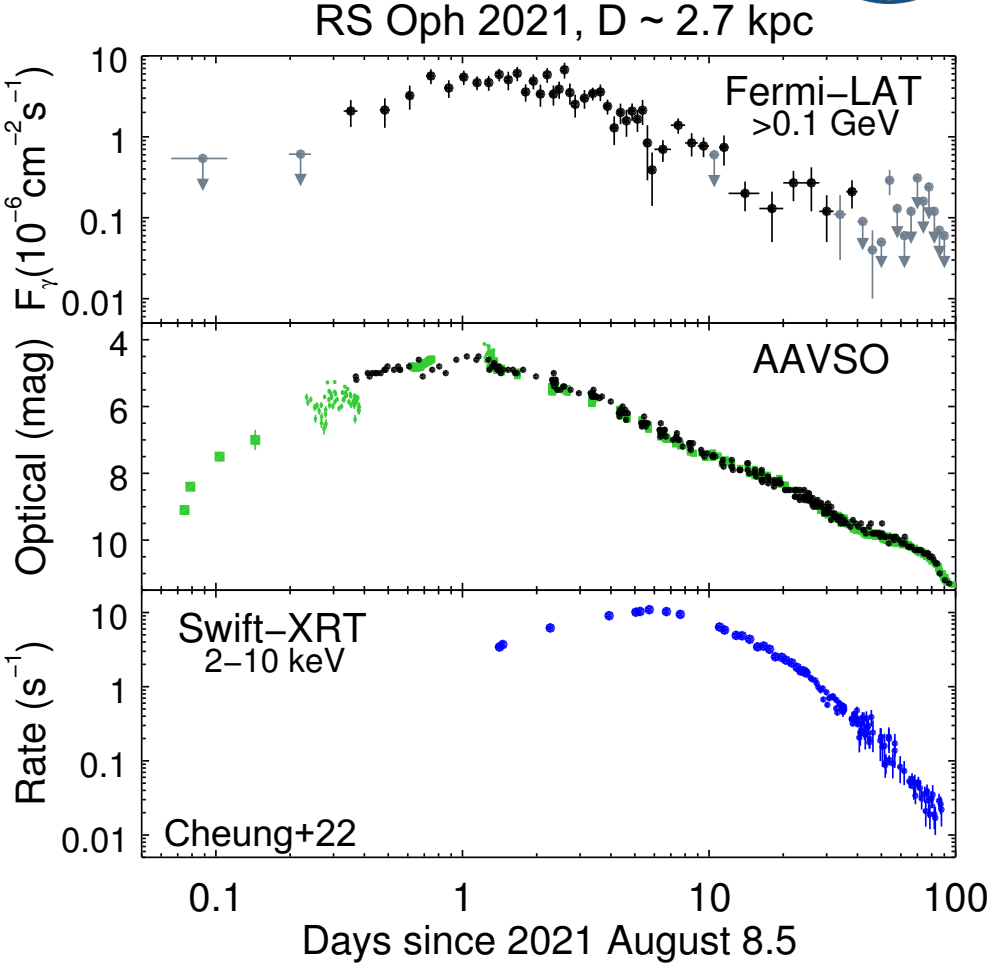




- Late-time emission (39-55 days) observed for classical novae within ~2 kpc (above, and V1405 Cas 2021, Buson+21)
- Late-time emission (55 days) in symbiotic recurrent RS Oph 2021 (D~2.7 kpc); future explosion from T CrB (closer system; D ~ 0.9 kpc)?

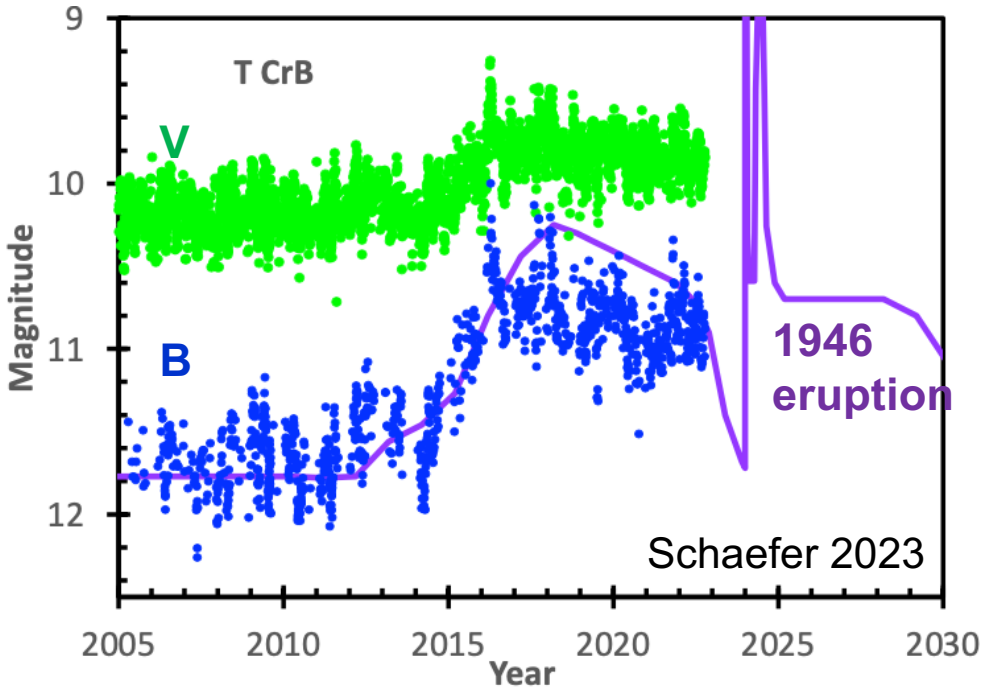
Correlated lightcurves in brightest LAT novae





- Range of optical vs. gamma-ray lightcurve behaviors in classical novae, with a subset strongly correlated (e.g., V906 Car; Aydi+20)
- Late-time emission (55 days) in symbiotic recurrent RS Oph 2021; future explosion from T CrB (closer system; D ~ 0.9 kpc)?

T CrB Watch – keystone system

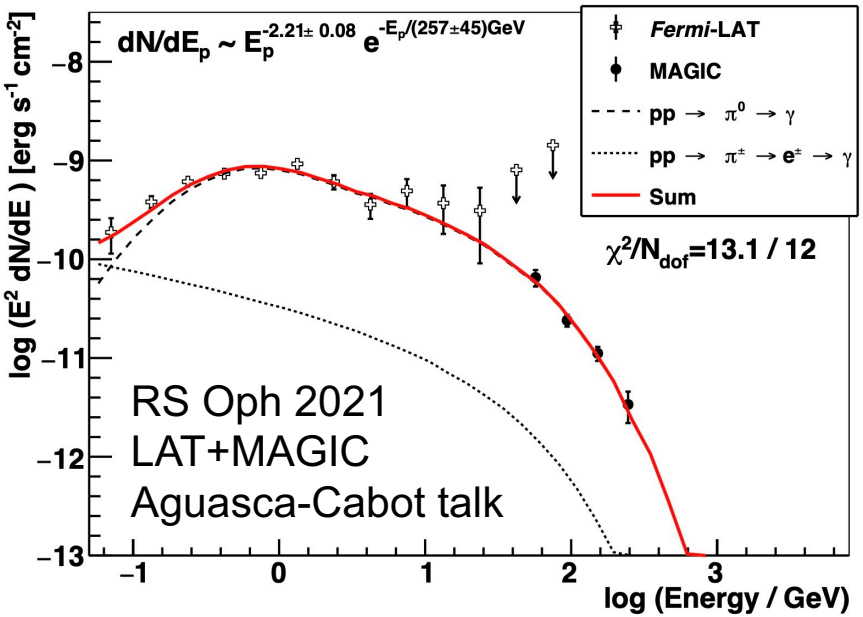


- T CrB (T Coronae Borealis)
  - M4.5 III red giant companion, Porb = 227.57 day (Fekel et al. 2000)
  - M_WD = 1.37 (0.13) Msun (Stanishev et al. 2004)
- Eruptions in 1866, 1946, P rec ~80 year
  - Optically very bright -- peaks of 2 mag and 3 mag, respectively
- RA, Dec (J2000) = 15 59, +25 55 (north)
- Closest known recurrent-symbiotic nova, D = 0.91 +/- 0.02 kpc (Schaefer 2022)
- Earlier predictions by Luna+20, others

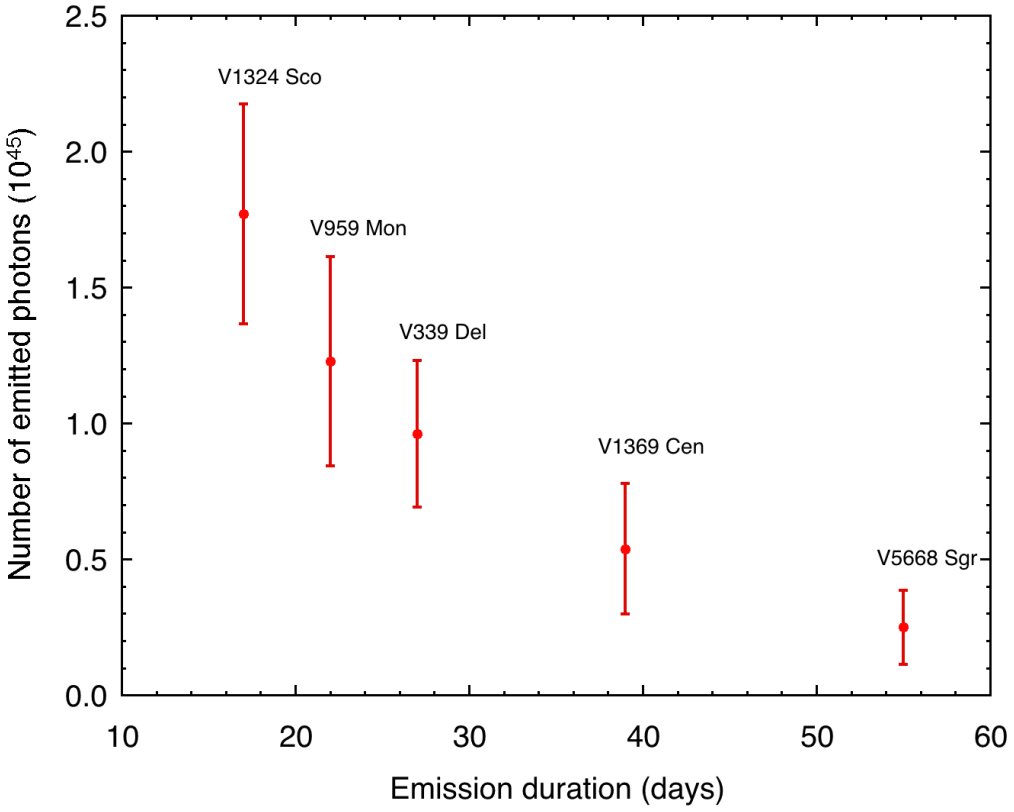
Predicted eruption date: ~2024.2 (as shown) to 2026.8. Data shown up to epoch 2022.8.

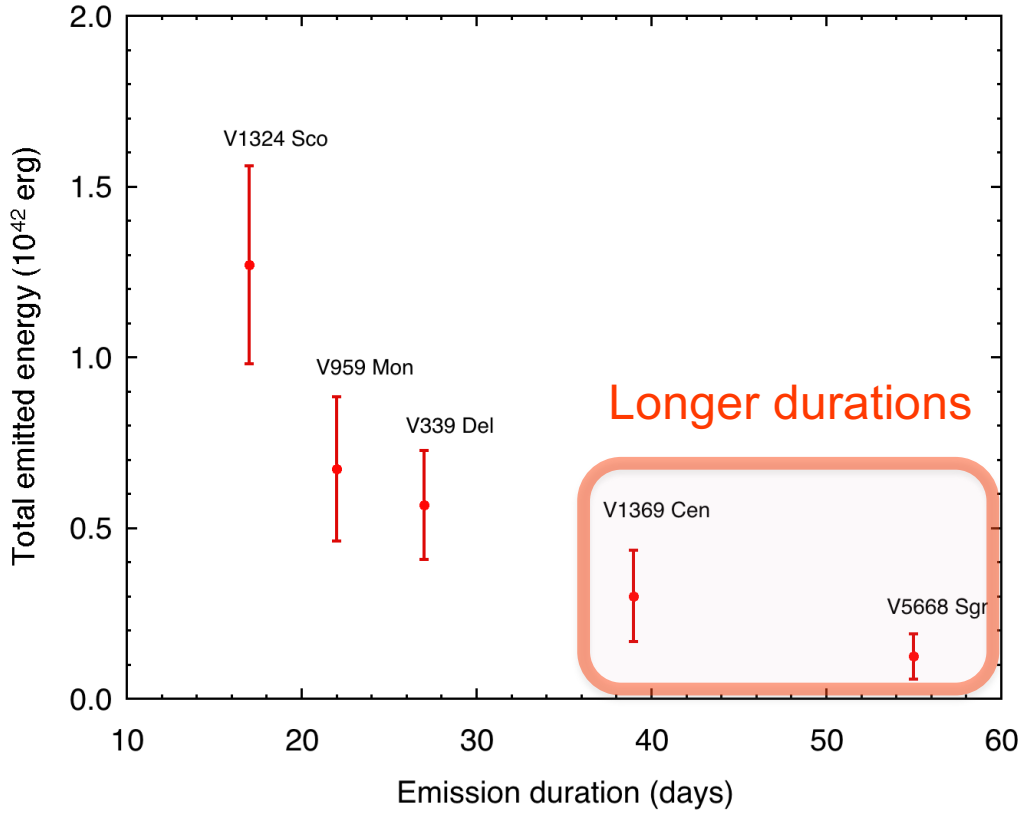
- All other known recurrent-symbiotic novae have exploded during Fermi-era (V745 Sco 2014, V3890 Sgr 2019, RS Oph 2021; also symbiotic V407 Cyg 2010)
- 3x closer than RS Oph; naively scale by distance => ~10x brighter?

Other symbiotic binary systems:
Neutron star GX 1+4/V2116 Oph; Black hole V404 Cyg



Widening Range of LAT Properties





Cheung et al. (2016)

- Observed apparent inverse relationship between >0.1 GeV LAT emission durations and total emitted energies (as well as total number of photons)
- Perhaps indicates more compact ejecta with higher density, producing more accelerated particles leading to:
(a) shorter emission duration and (b) stronger [or more intense] emission

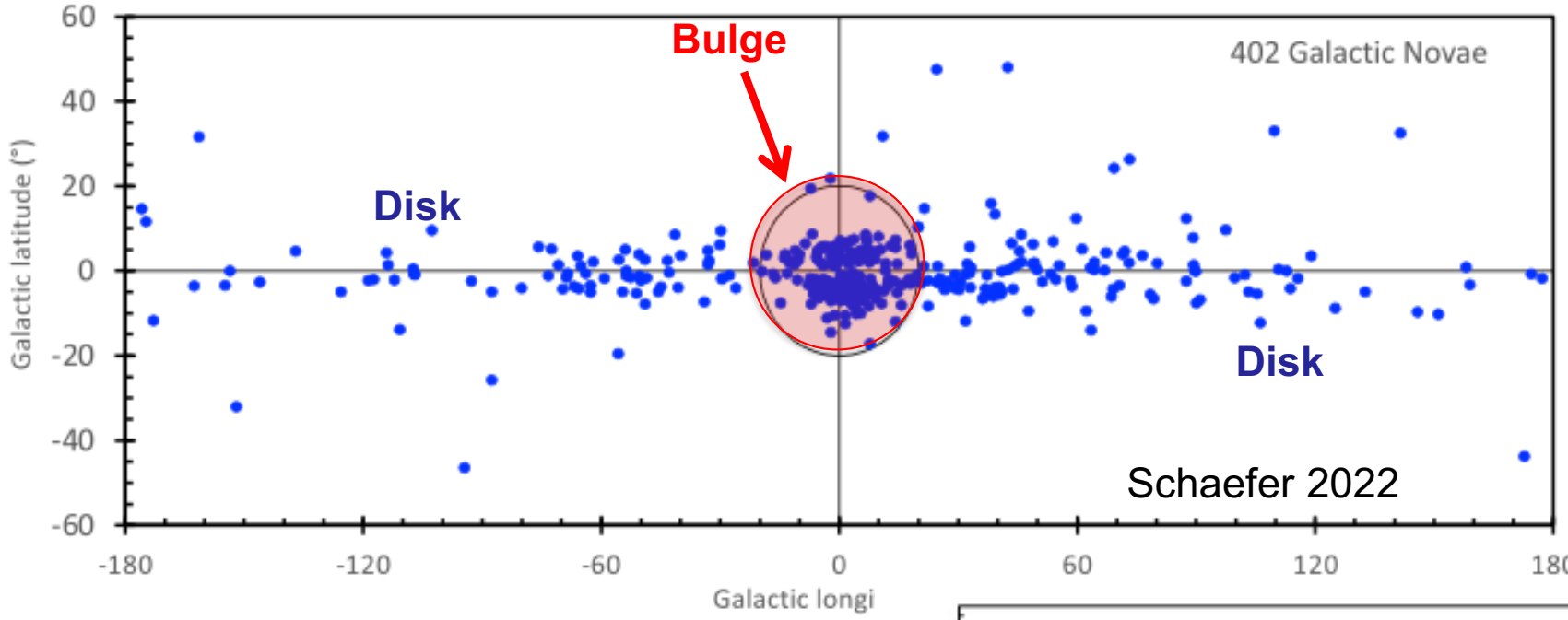
Cheung et al. (2016)

Questions and Prospects

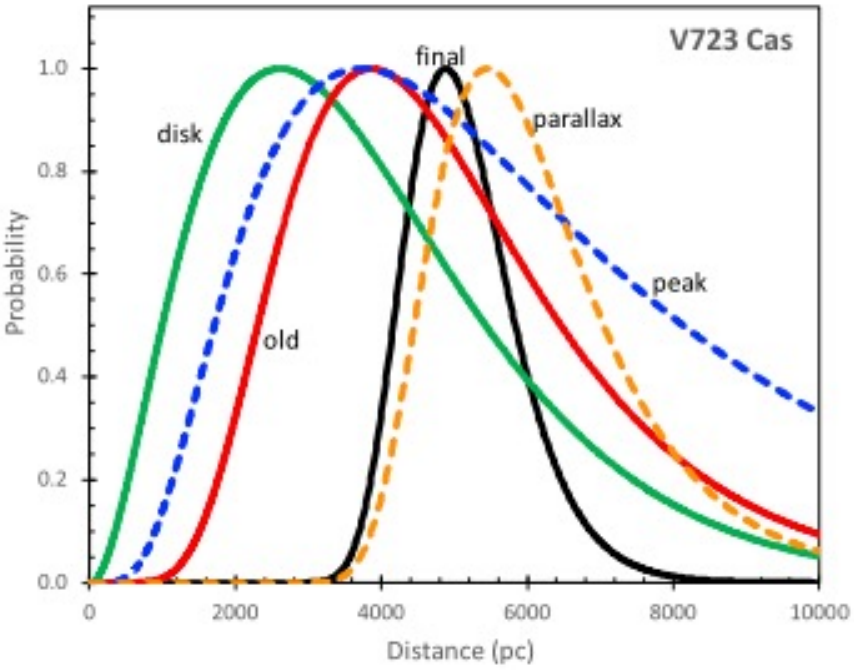
- **Are all novae GeV gamma-ray sources ?**
  - Yes, with reliable distances, majority of novae within ~4 kpc detected; subset of Bulge novae (D ~ 8 kpc)
- **Symbiotics (and recurrents) as keystone systems ?**
  - Hadronic emission has outsized role in RS Oph, and likely other symbiotics.
  - Expect outburst of T CrB (D~0.9 kpc), in 2020's, with prompt ~MeV (<1 day) coverage by COSI-SMEX. Additional outbursts from other known systems (RS Oph 203X?)
- **Are the γ-ray shock acceleration sites identifiable at lower-energies ?**
  - Consider the multi-wavelength observations necessary to correlated changes in gamma-ray emission with changes=s in radio morphology or optical spectral-line velocities ?
- **Role of future VHE observations, particularly with CTA ?**
  - Provide useful constraints on the maximum energy of accelerate particles
- **Bonus: Role of high-energy neutrino observations ?**
  - Expected neutrino signature of hadronic emission likely beyond present capabilities (Razzaque et al. 2010; Metzger et al. 2016; Guetta et al. 2023)

Backup slides

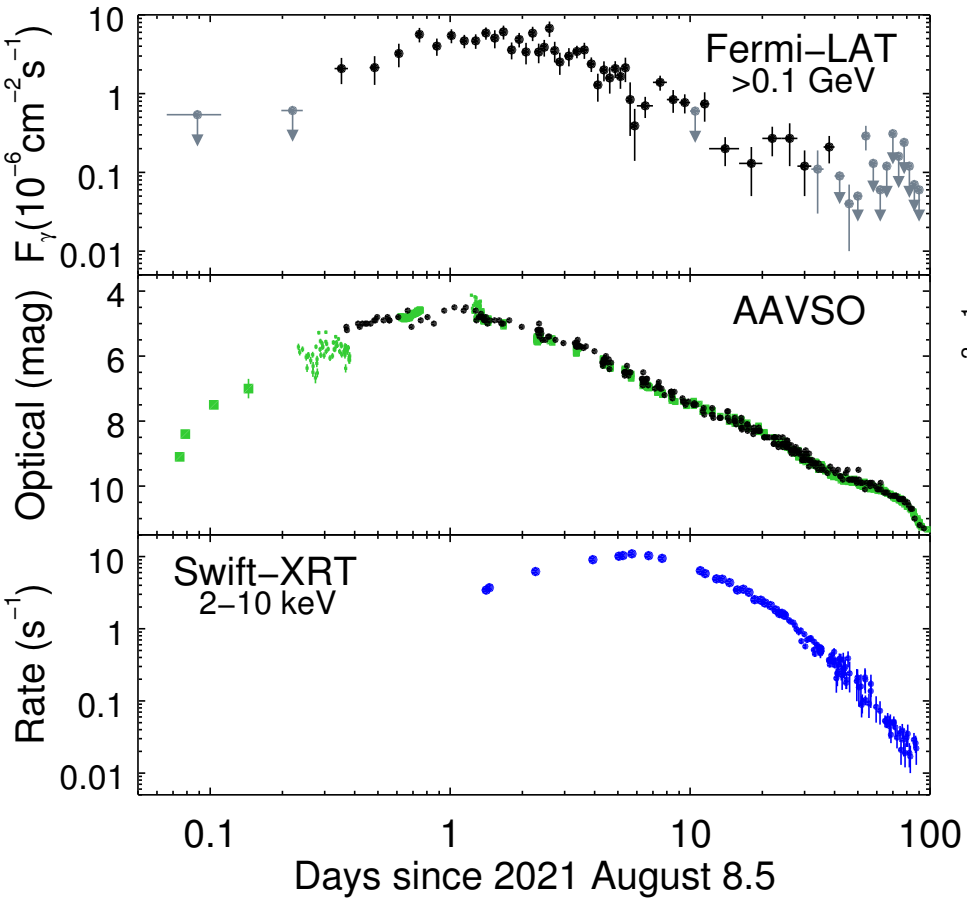
Backup: Historical Galactic Novae: up to 2021.6 (124 in Fermi-era)

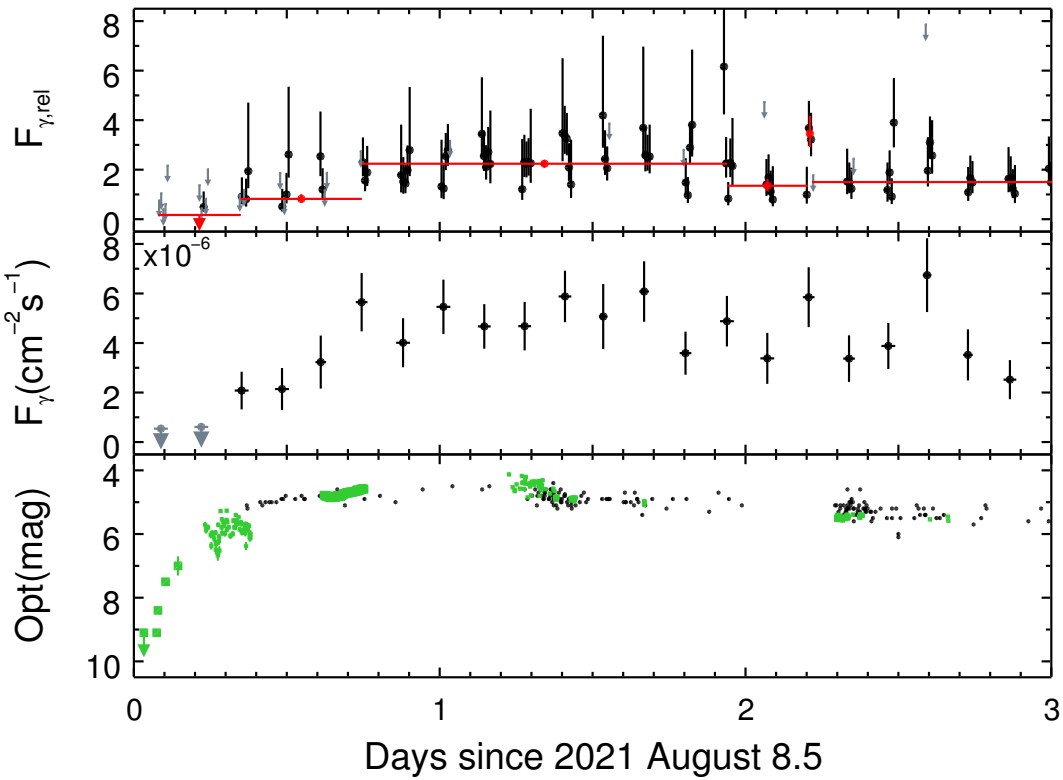


- 74 ”good” (<30% uncertainty) Gaia DR3 parallax distances 215 total Gaia DR3 counterparts
- 41 Gaia DR2 parallax distances (Schaefer 2018)
- 29 expansion parallax distances (Downes & Duerbeck 2000); also Schaefer (2018)
- 81 ISM extinction-based distances (Ozdonmez et al. 2018)
- 68 lightcurve shape (peak mag) distances (Hachisu & Katc 2021)
- Handful of blackbody distances for companions
- Few from other methods



Fermi-LAT Detects RS Oph 2021



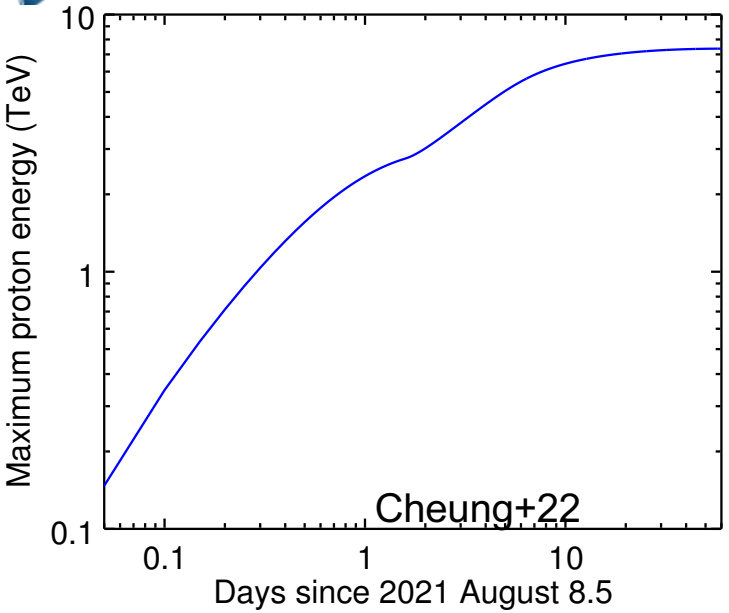


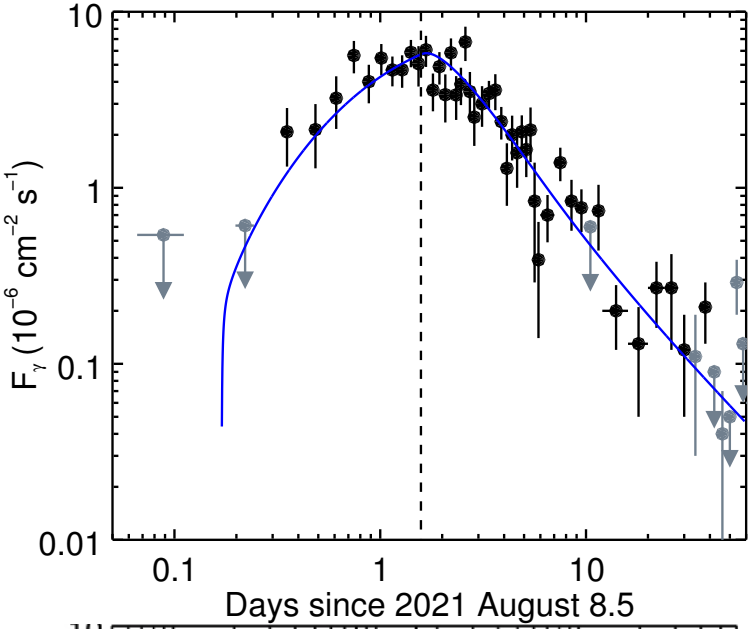
Left: LAT data with error bars (black) are >3σ detections, while 2–3σ data and upper limits are shown in gray. The optical data are V -band (green) and Visual observations (black) from the AAVSO; additional V -band measurements from days 0.233–0.381 and 1.227–1.375 are from our observations.

Right: LAT >0.1 GeV light-curve in 10-minute bins in units of relative flux and Bayesian Block partitions indicated in red, LAT >0.1GeV orbit-bin light-curve, and optical light-curve, but for the first three days of activity. This version of the figure helps show more detail in the optical observations obtained from the Global Meteor Network camera IL0003 on the nights of August 8 and 9.

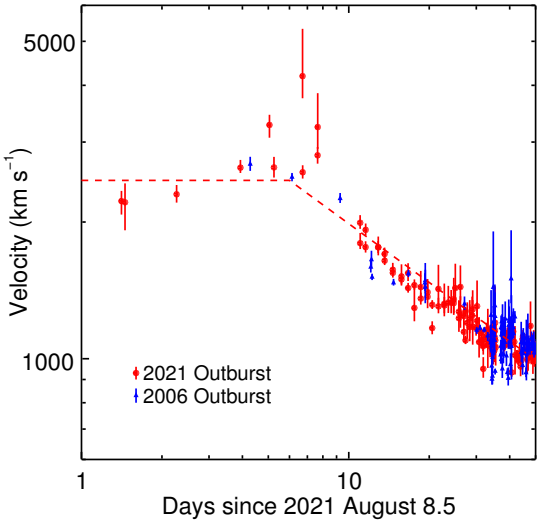
Cheung et al. (2022)

Fermi-LAT Detects RS Oph 2021

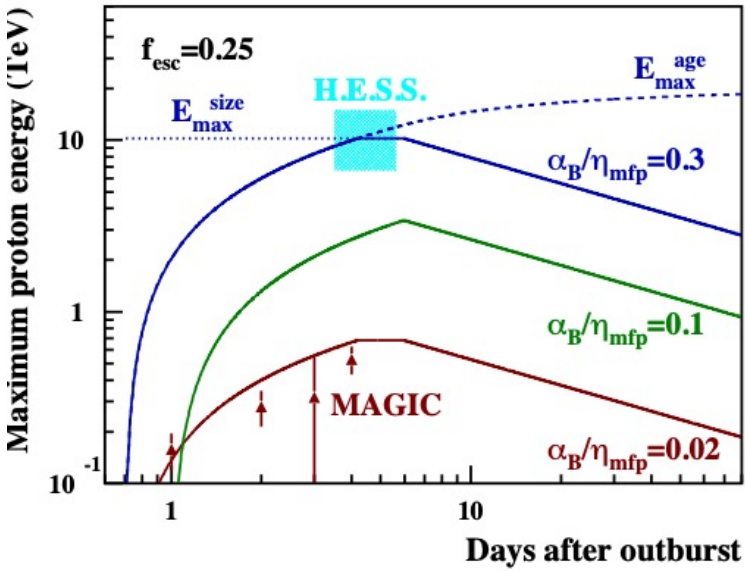


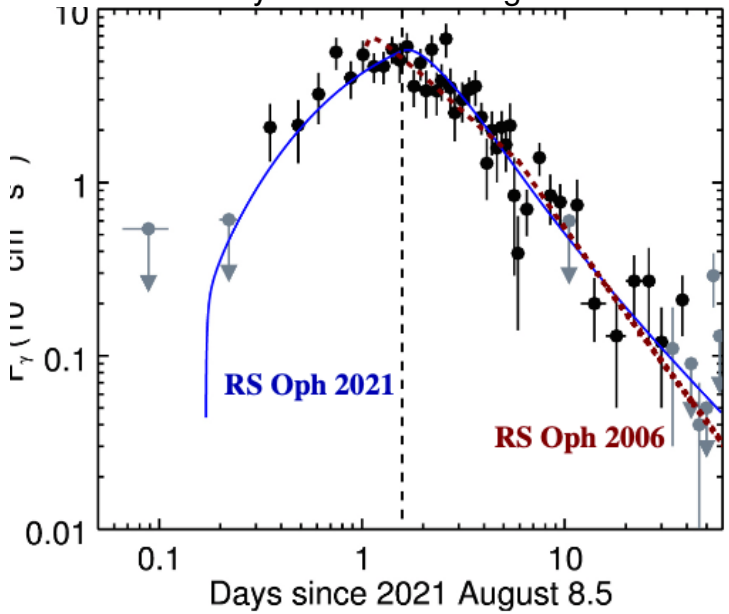


H.E.S.S. Collaboration (2022), MAGIC Collaboration detected variable VHE (>0.1 TeV) emission !



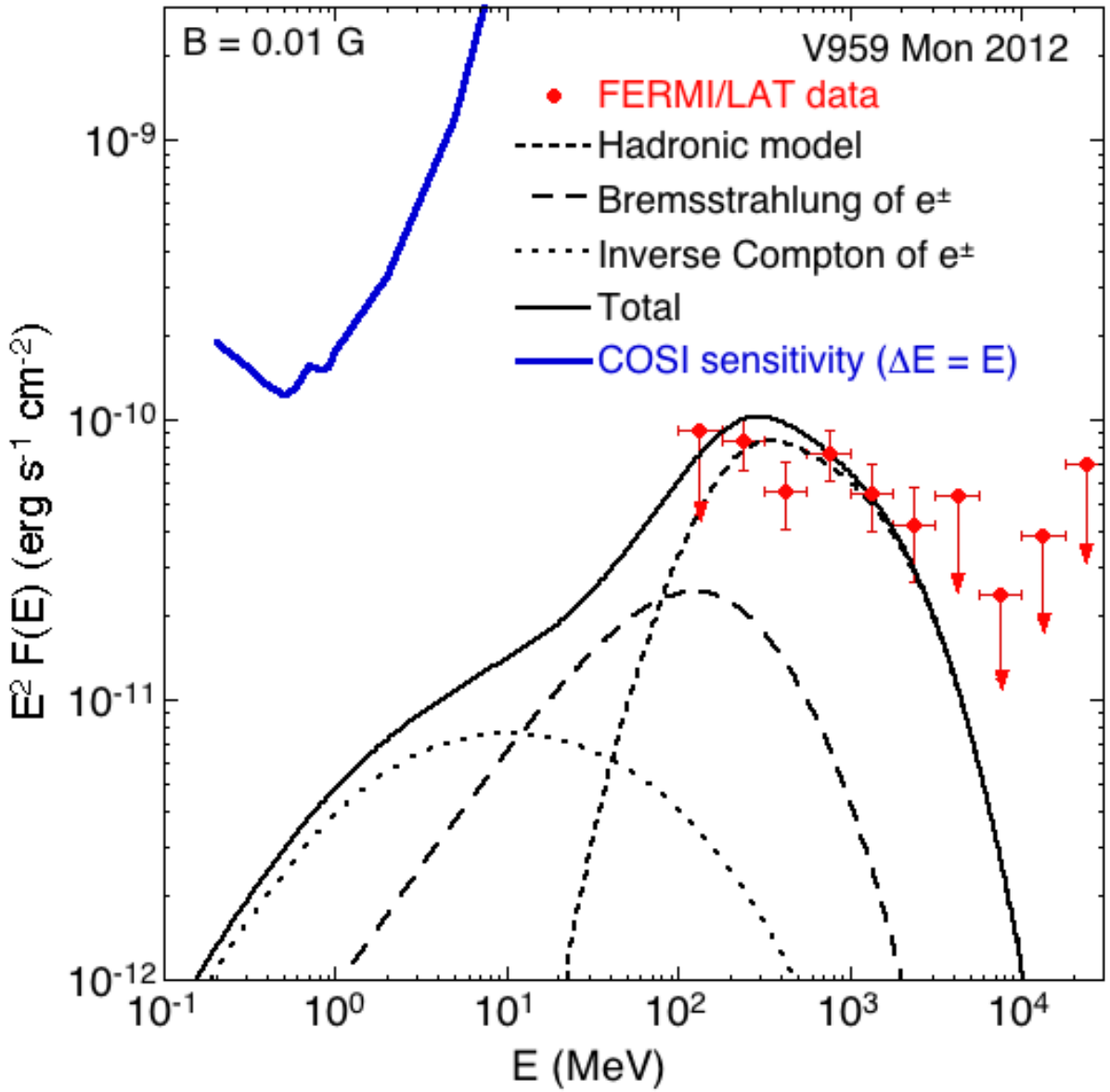
Shock velocities from Swift-XRT temperature measurements





Tatischeff & Hernanz (arXiv:2302.01276) considered their original 2007 model for the RS Oph 2006 explosion with the RS Oph 2021 high-energy (LAT) and VHE (HESS, MAGIC) gamma-ray observations.

Gamma-ray Spectra: COSI

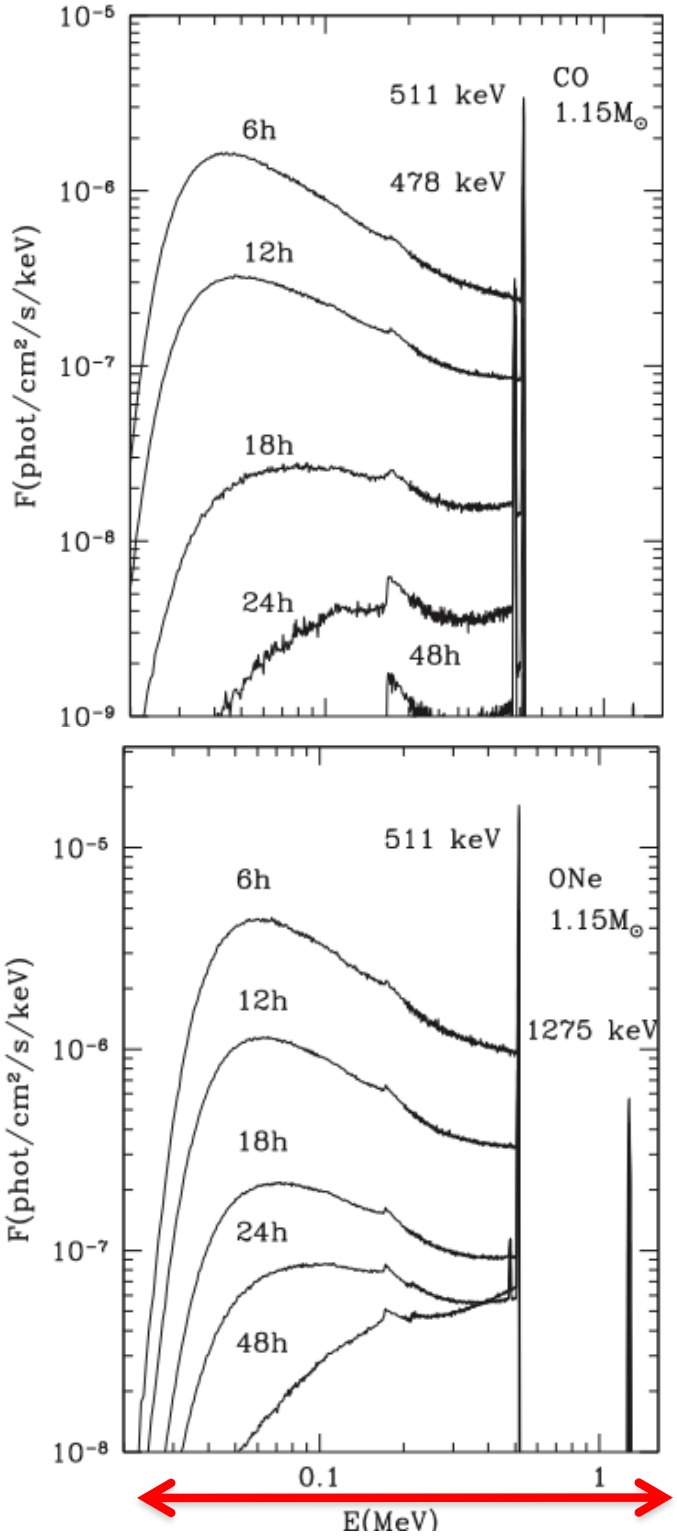


Courtesy: Pierre Jean

Why do novae emit gamma-rays with E~1 MeV?
Main radioactive isotopes synthesized in novae

Nucleus	τ	Type of emission	Nova type
^{13}N	862 s	511 keV line continuum (E<511 keV)	CO and ONe
^{18}F	158 min	511 keV line continuum (E<511 keV)	CO and ONe
^{7}Be	77 days	478 keV line	CO mainly
^{22}Na	3.75 yr	1275 keV line	ONe
^{26}Al	1.0X10^{6} yr	1809 keV line	ONe

Spectra MeV ➔➔ GeV



CO-type
478 keV

Hernanz 2014

ONe-type
1275 keV

~0.02-2 MeV

10 MeV-
10 GeV