Fermi Gamma-ray Space Telescope

Gamma-ray Novae

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on behalf of the *Fermi*-LAT collaboration

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Six *Fermi*-LAT >0.1 GeV Novae Detections

- **V407 Cyg 2010**: Abdo, A. A. et al. 2010, Science, 329, 817

- **V1324 Sco 2012**, **V959 Mon 2012**, **V339 Del 2013**: Ackermann, M. et al. 2014, Science, 345, 554

- **V1369 Cen 2013**, **V5668 Sgr 2015**: Cheung, C. C. et al. 2016, ApJ, 826, 142

Also: **Historical *Compton*/OSSE ~0.1 MeV continuum detection of V382 Vel 1999** -- Cheung, Jean, Shore, Grove, Leising 2015, PoS (ICRC2015), 34th ICRC; arXiv:1605.01375

Still preliminary LAT results:

-*V745 Sco 2014*: 2 and 3σ only on Feb 6th and 7th: Cheung, Jean, Shore 2014, ATel 5879

- Novae catalog with LAT Pass 8 (in preparation) with preliminary candidates -- Franckowiak, A., Buson, S., Jean, P., Cheung, T. 2015, 6th Fermi Symposium

- (Preliminary) upper limits for two selected examples: *KT Eri 2009* and *V1312 Sco 2011* – Cheung, C. C. 2012 Fermi Symposium; arXiv:1304.3475 – see bonus

Outline

- How *Fermi*-LAT works and how it detects novae
  - independent detections in normal sky-survey (Cyg ‘10, Sco ‘12)
  - γ-ray transient discovery before optical (Mon ’12 – see bonus)
  - target-of-opportunity on bright optical novae (Del ‘13, Cen ‘13, Sgr 15

- The six *Fermi*-LAT detections in >0.1 GeV continuum – chronological
  (not radioactive nuclear decay line emission around ~MeV energies – see bonus)
  - twists and turns

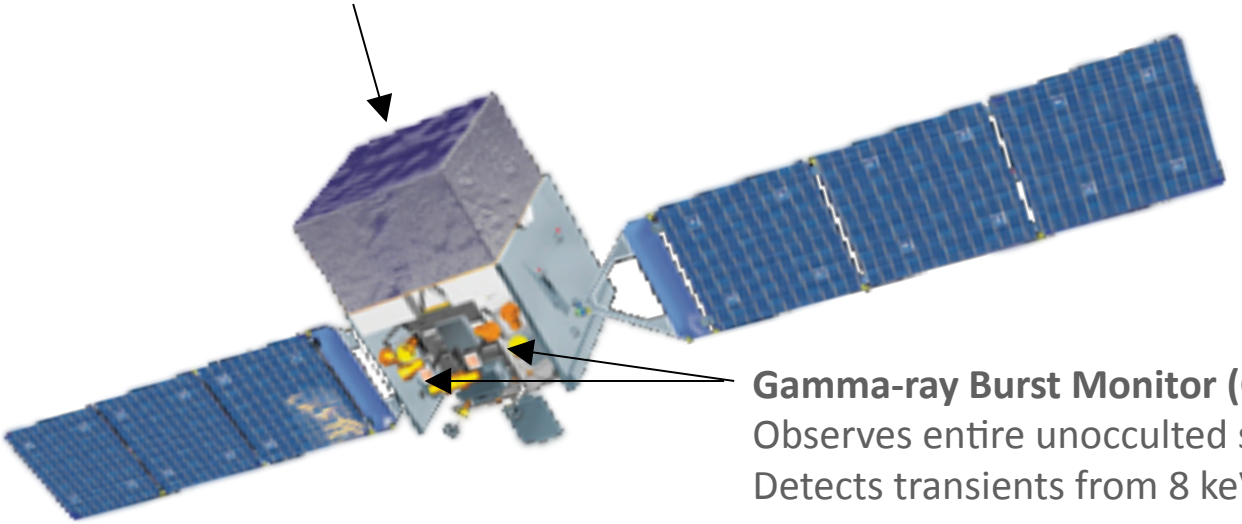
- *Fermi*-LAT >0.1 GeV light curves and spectra
  - onsets
  - durations
  - flares (flux doubling)
  - spectral shape (curvature)

Fermi Gamma-Ray Space Telescope

Large Area Telescope (LAT)

Observes 20% of the sky at any instant, views entire sky every 3 hrs

20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV



Gamma-ray Burst Monitor (GBM)

Observes entire unocculted sky

Detects transients from 8 keV - 40 MeV

- **Unique Capabilities for GeV astrophysics**
  - **Large effective area**
  - **Good angular resolution**
  - **Huge energy range**
  - **Wide field of view**

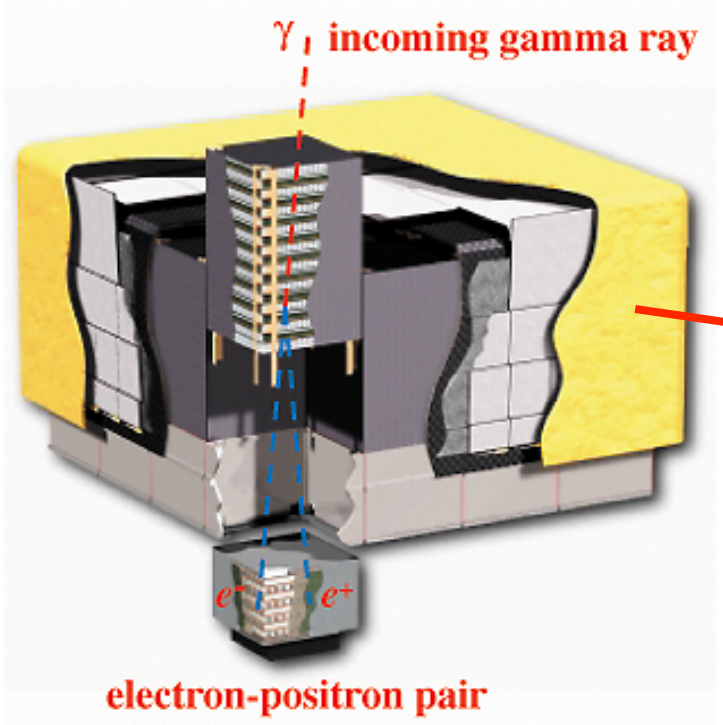
Launched June 2008

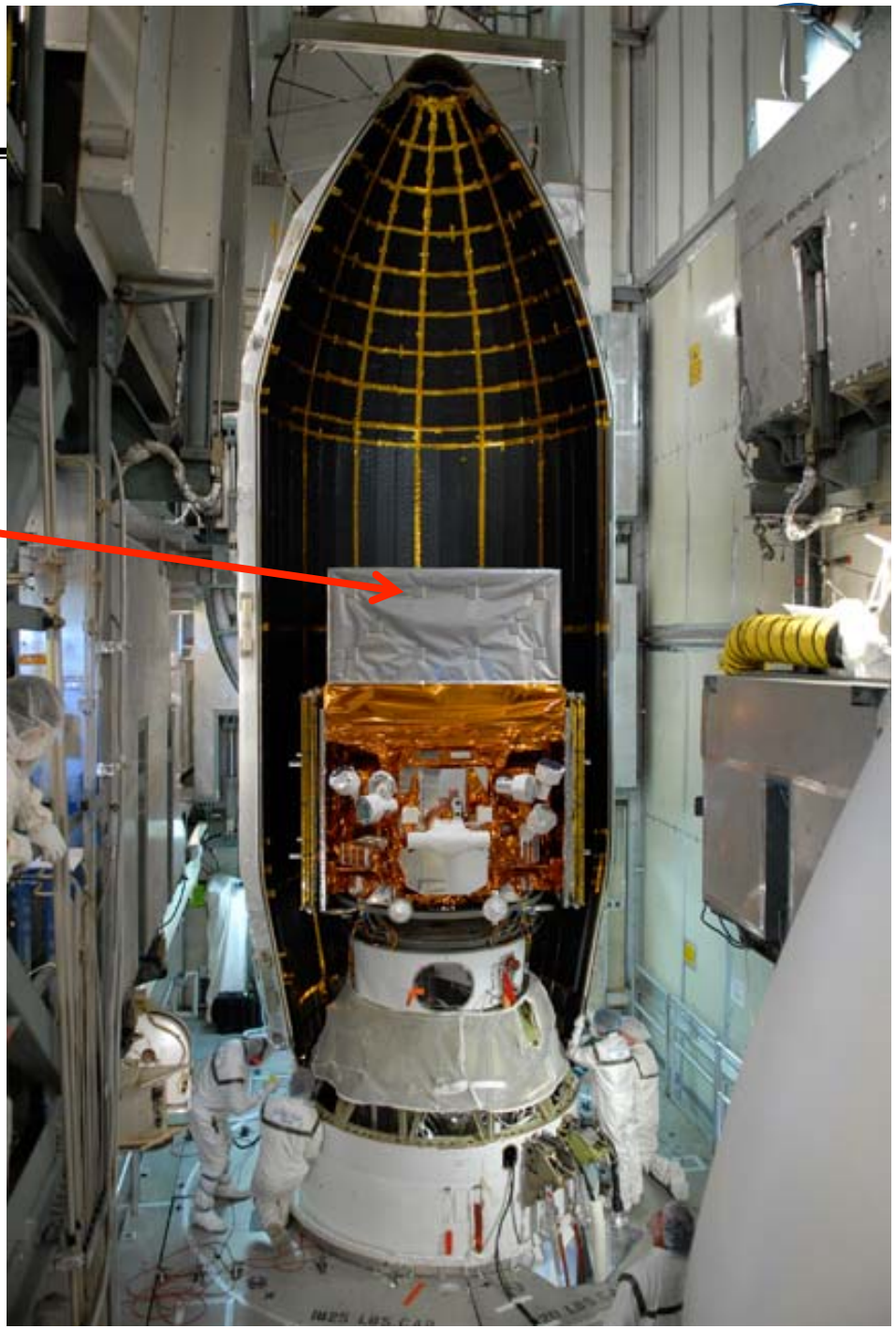
Mission Lifetime:

5 year requirement,

10 year extended mission

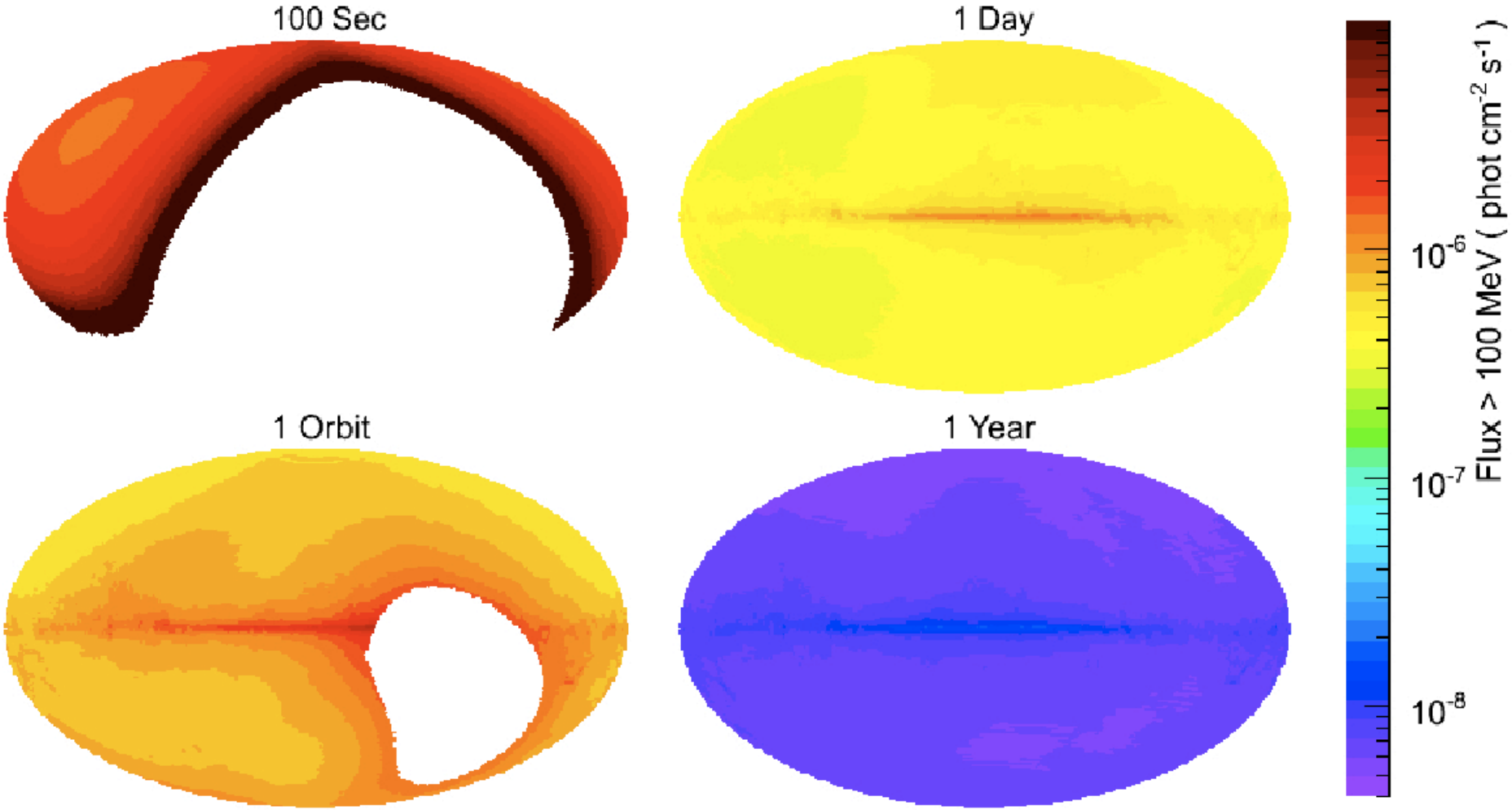
LAT Detector





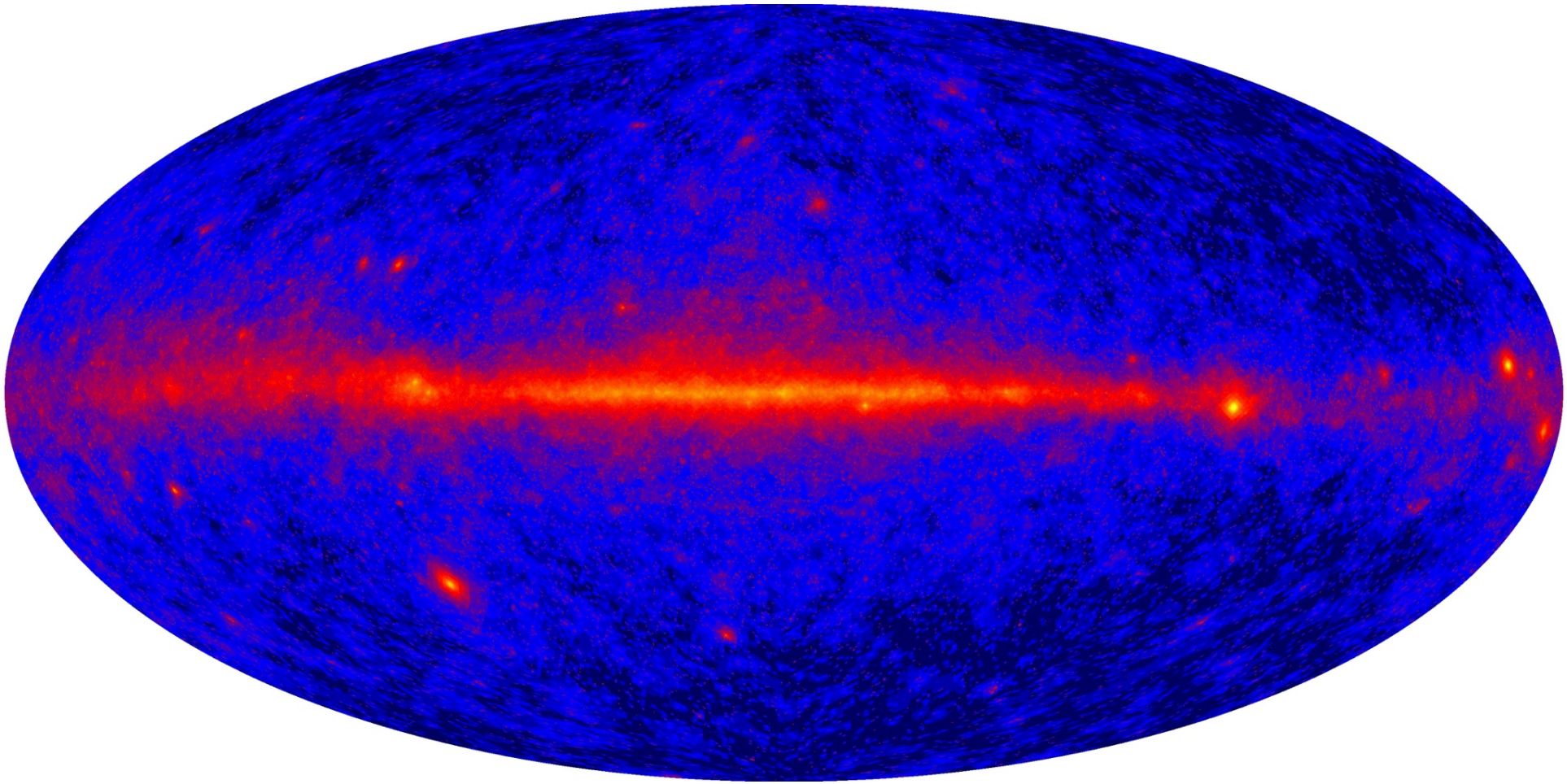
LAT images the sky one photon at a time: γ ray converts in LAT to an electron and a positron; direction and energy of these particles tell us the direction and energy of the photon

LAT All-Sky Sensitivity



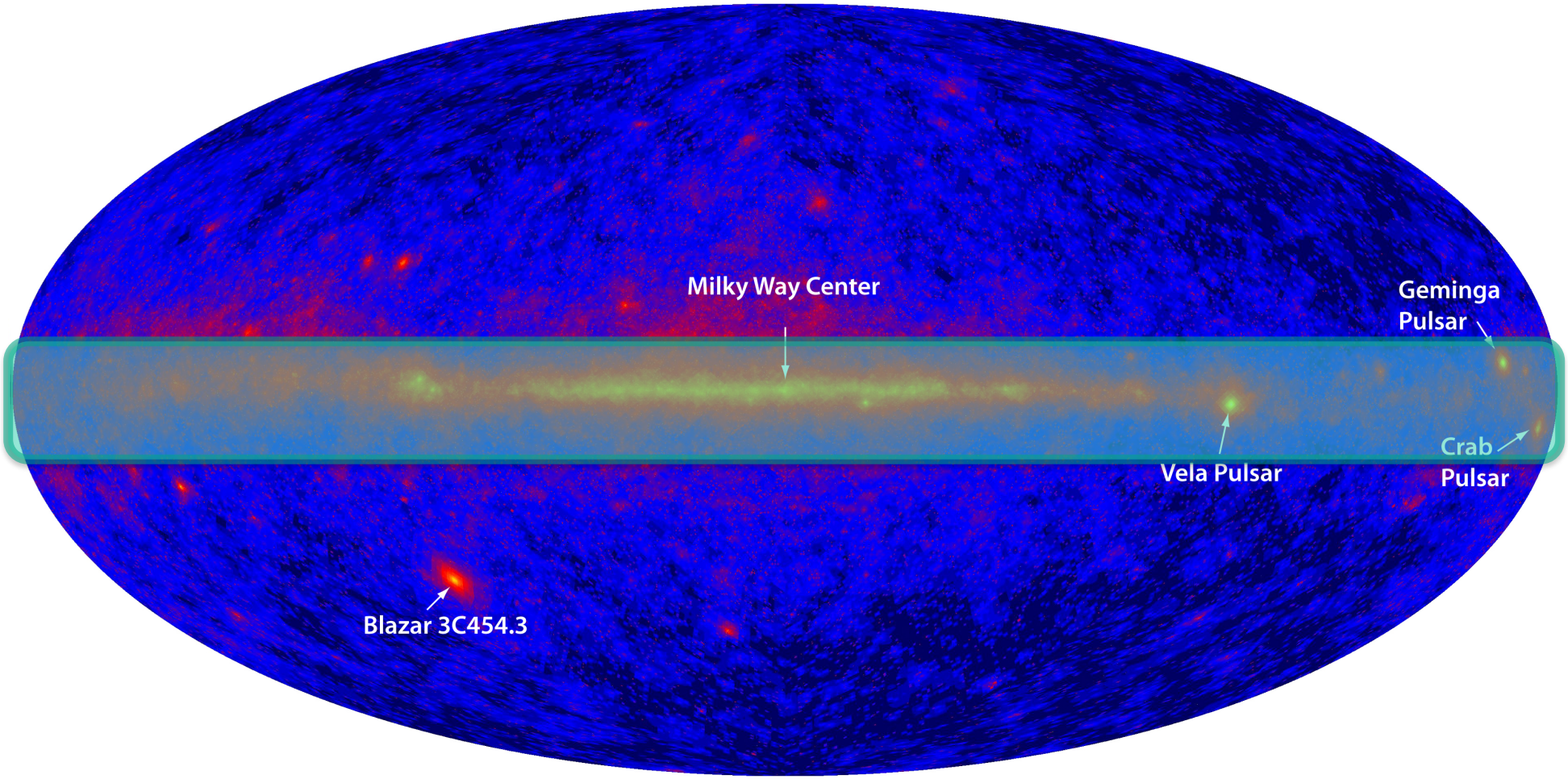
- **In 1 day**, ability to detect (at 5σ) the weakest EGRET sources
- See: https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Fermi-LAT First Light: 2008



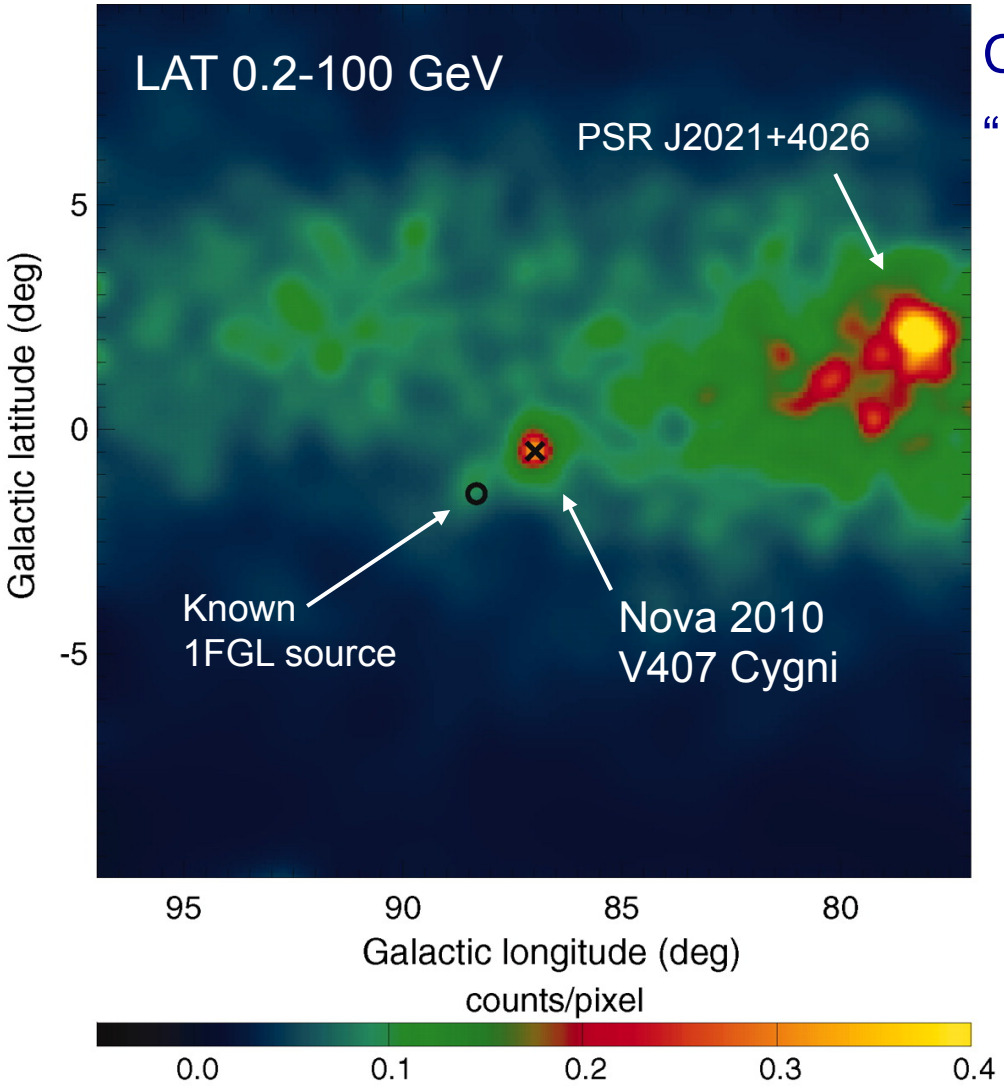
- 4 days of all-sky exposure

Fermi-LAT First Light: 2008



- 4 days of all-sky exposure
- Daily search for LAT transients in Galactic plane…

Fermi Discovery of a γ-ray Nova – the First



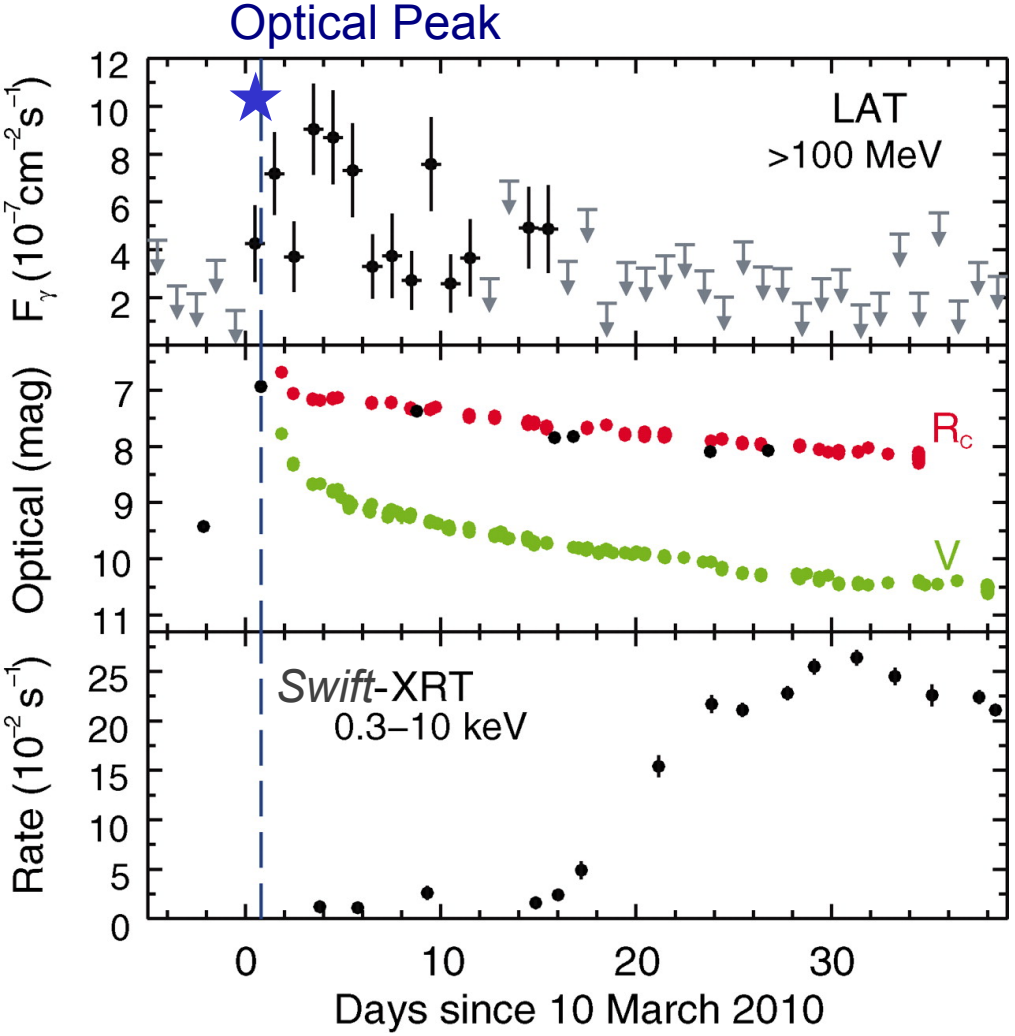
Abdo et al. (2010)

Cheung et al. 2010 ATEL #2487:

"Fermi LAT Detection of a New Galactic Plane Gamma-ray Transient in the Cygnus Region: Fermi J2102+4542 and its Possible Association with V407 Cyg"

- Initial LAT detection 2010 March 10, same day as nova V407 Cyg optical discovery by Nishiyama & Kabashima
- γ-ray identification via spatial ($r_{95\%}$=3.7') & temporal coincidence with a *symbiotic-like recurrent nova*

Fermi Discovery of a γ-ray Nova – the First



Abdo et al. (2010)

→ Particle acceleration in nova ejecta through interactions with dense wind of Red Giant companion (proposed for RS Oph by Tatischeff & Hernanz 2007)

- Initial LAT detection 2010 March 10, same day as nova V407 Cyg optical discovery by Nishiyama & Kabashima
- γ-ray identification via spatial ($r_{95\%}$=3.7') & temporal coincidence with a *symbiotic-like recurrent nova*

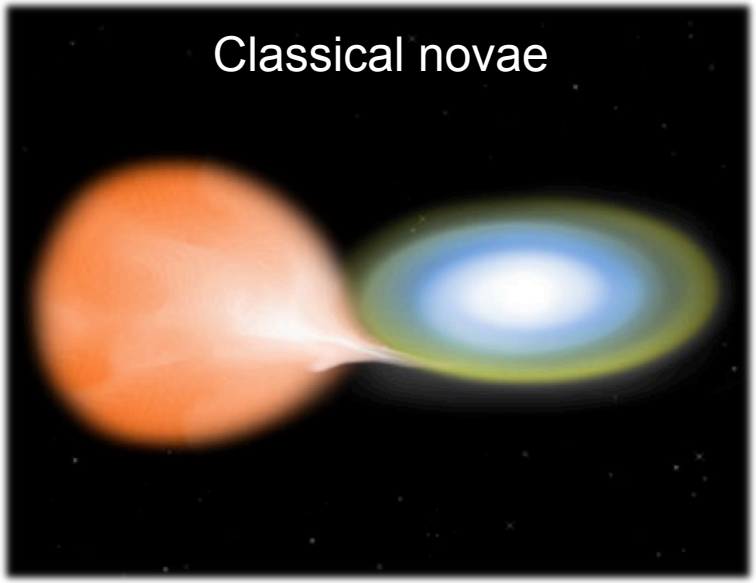
White Dwarfs in Close Binary Systems

Compact cataclysmic variable:

WD + Main Sequence

↓

Roche lobe overflow



- a ~ 10^{11}cm ~ $R_\odot$
- P_{rec} >~ 10^4 yr; P_{orb}~ hr-day
- rate ~ 20 – 50 / yr in Galaxy

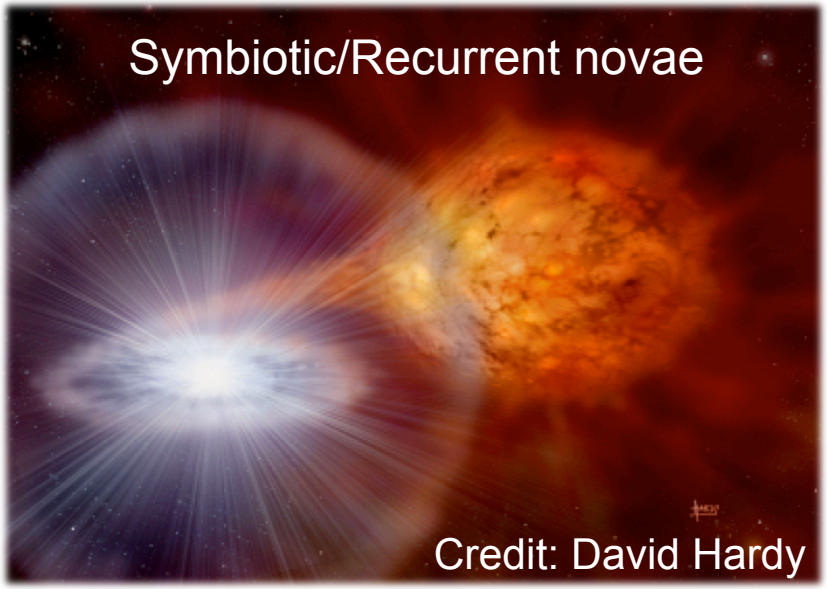
Hydrogen burning in degenerate conditions on top of the white dwarf

Symbiotic system:

Massive WD + Red Giant

↓

accretion from a red giant wind



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

Adapted from M. Hernanz X-ray Universe 2011 talk

Our Understanding of γ-ray Novae (ca. ~2010)

Compact cataclysmic variable:

WD + Main Sequence

↓

Roche lobe overflow

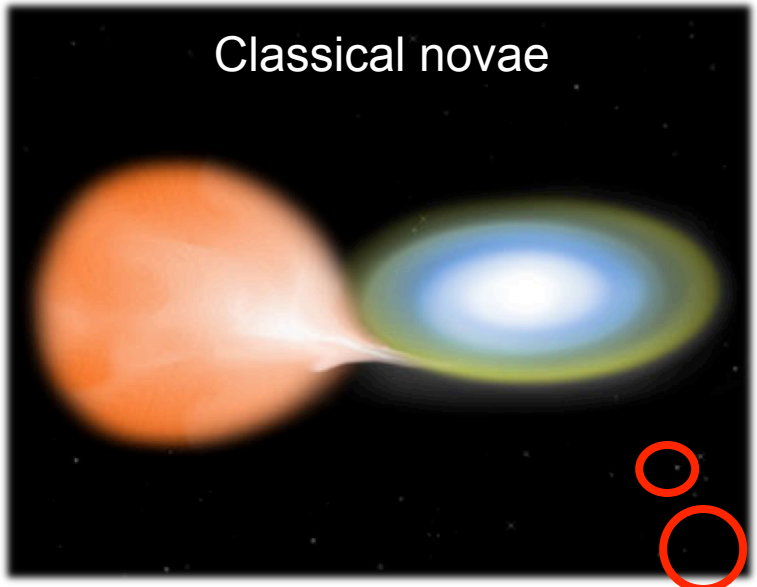
γ-ray sources e.g., V407 Cyg

Symbiotic system:

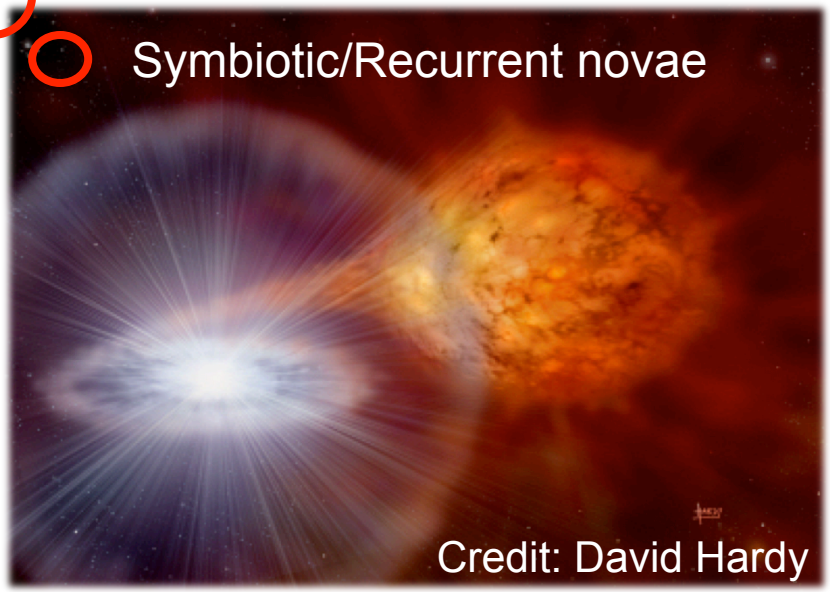
Massive WD + Red Giant

↓

accretion from a red giant wind



Hydrogen burning in degenerate conditions on top of the white dwarf



- a ~ 10^{11}cm ~ $R_\odot$
- P_{rec} >~ 10^4 yr; P_{orb}~ hr-day
- rate ~ 20 – 50 / yr in Galaxy

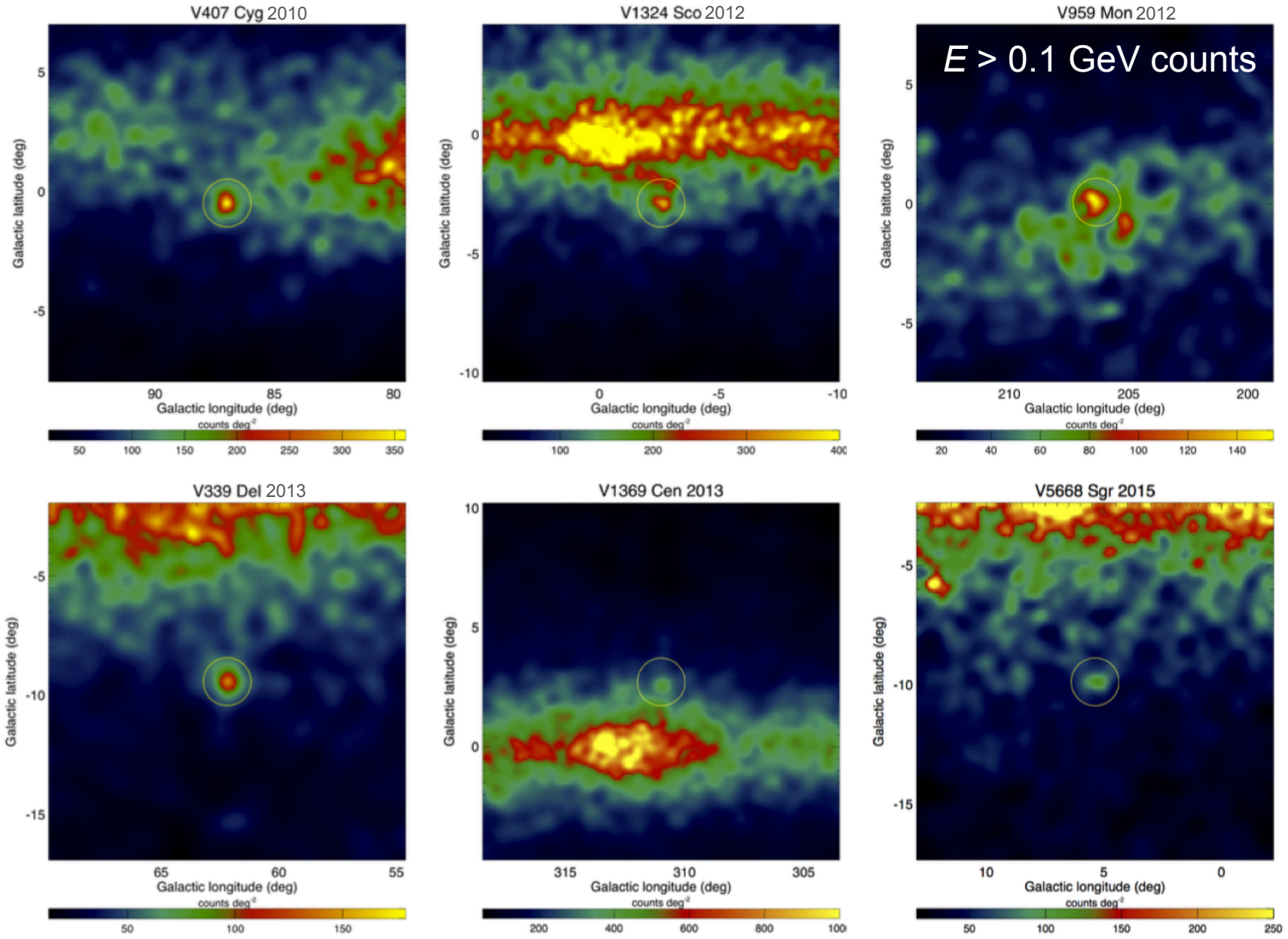
Not γ-ray Sources?

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

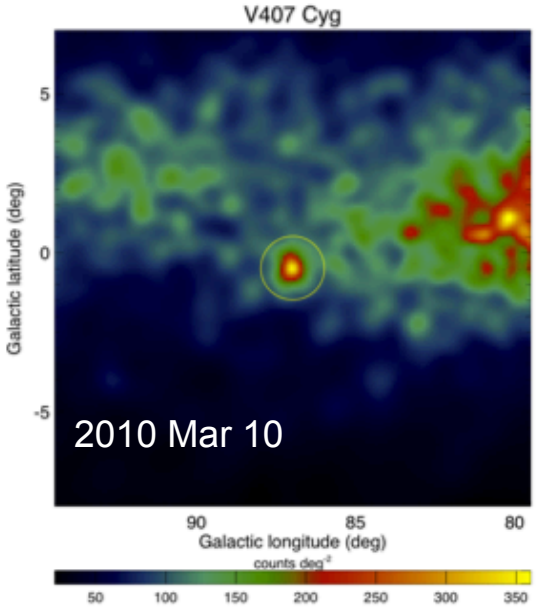
Adapted from M. Hernanz X-ray Universe 2011 talk

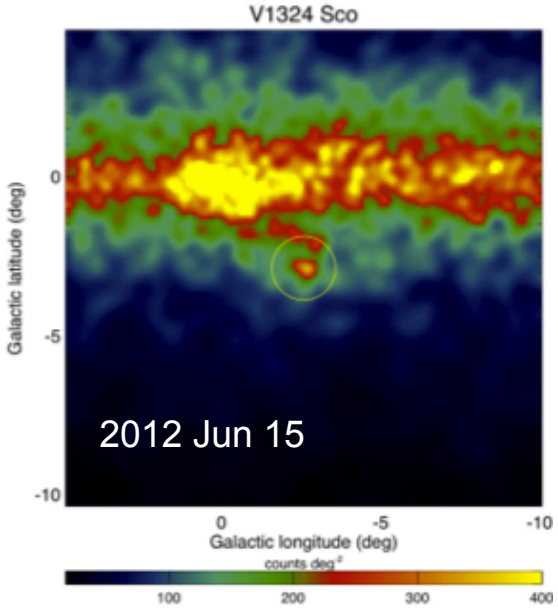
See Bonus for two non-detected examples

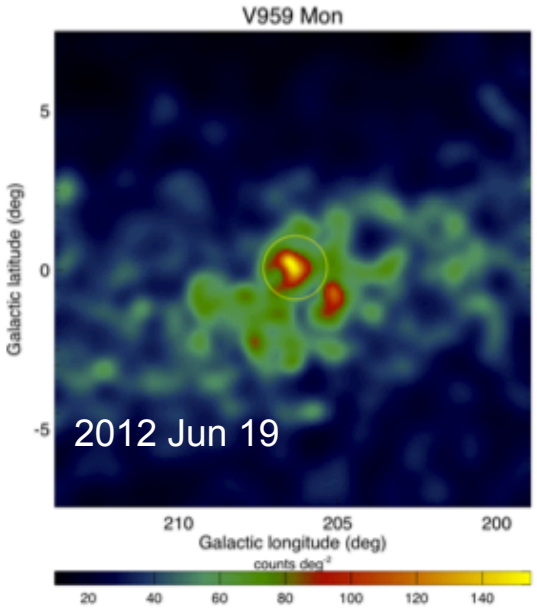
Thermo-Nuclear Family Portrait 2016

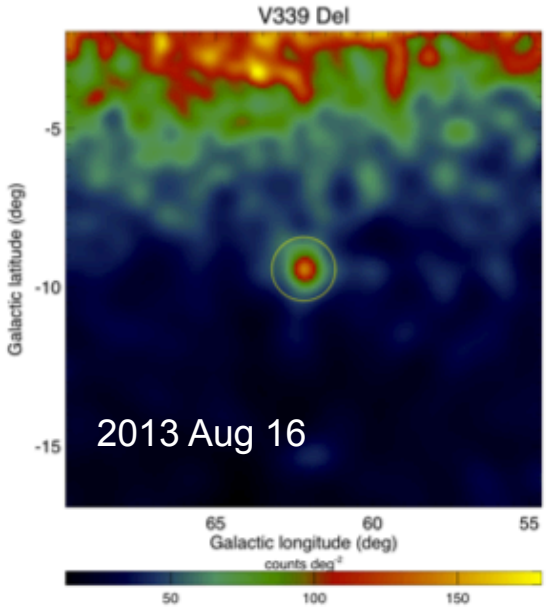


The First Four γ-ray Novae









- V407 Cyg 2010
  Symbiotic
  D ~ 2.7 kpc

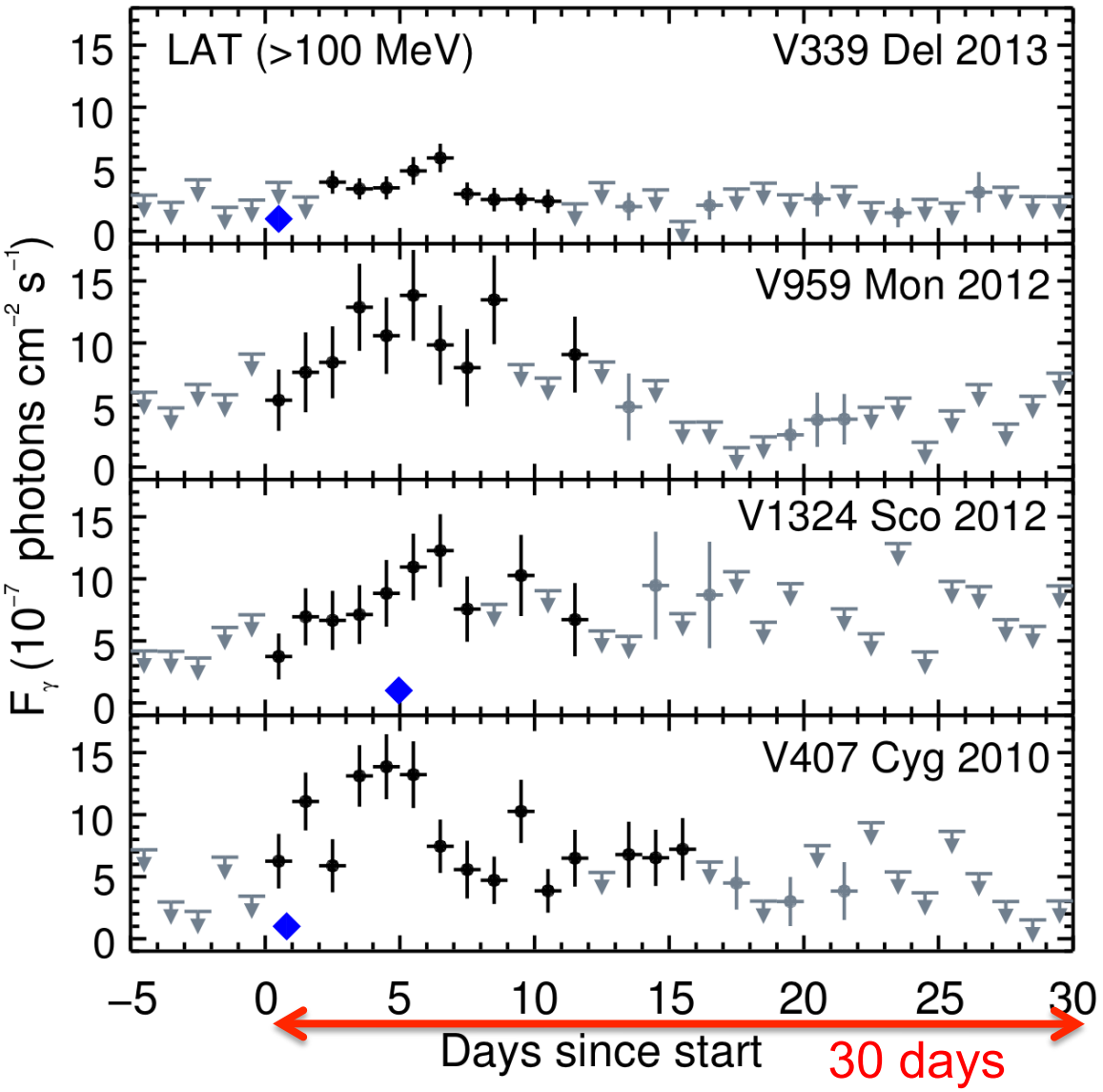
- V1324 Sco 2012
  CO nova
  D ~ 4.5 kpc

- V959 Mon 2012
  ONe nova
  D ~ 3.6 kpc

- V339 Del 2013
  CO nova
  D ~ 4.2 kpc

Ackermann et al. (2014)

Similarity of LAT γ-ray Light curves



- Duration ~ 17-27 days

- t_{rise} ~ t_{fall} ~ 2-7 days

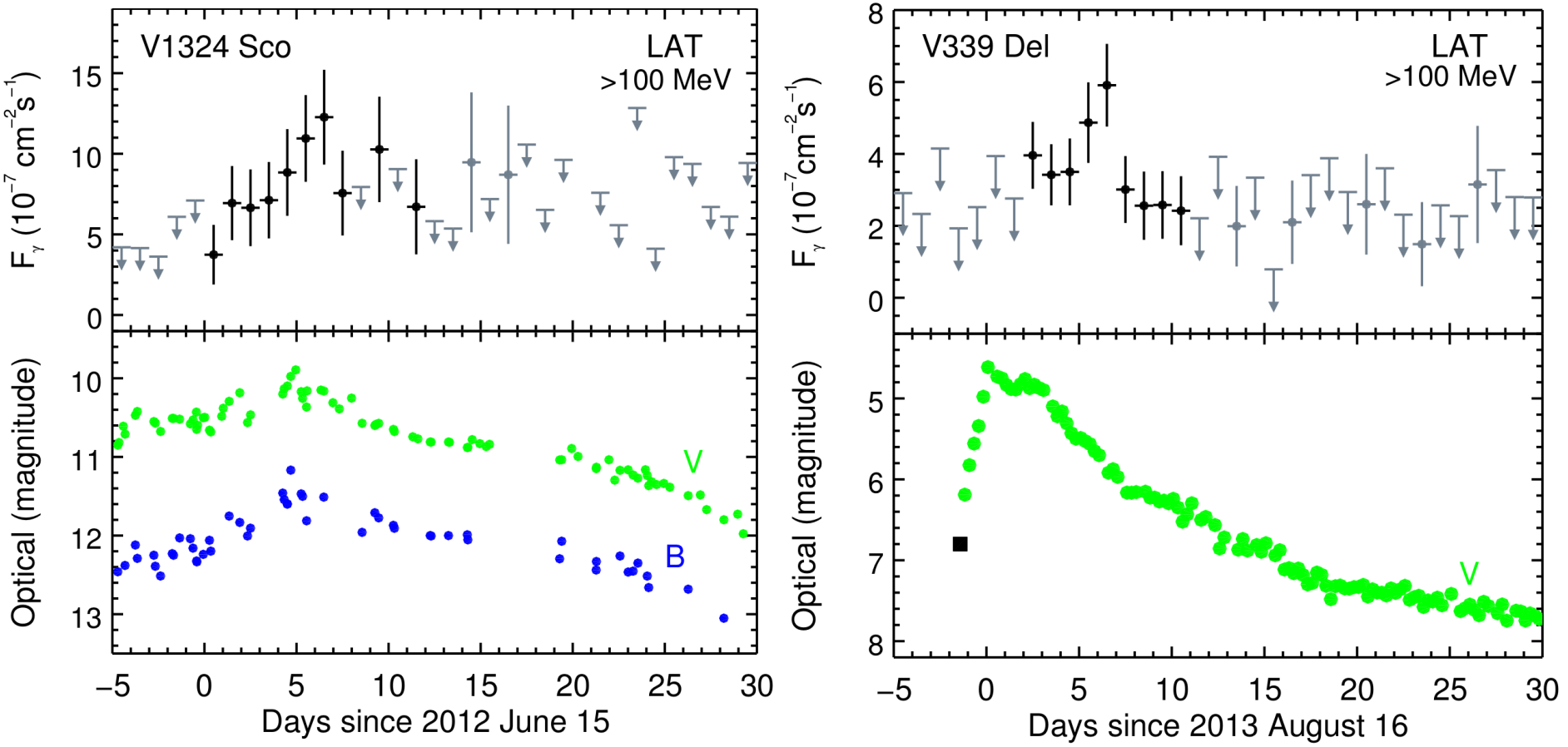
- Flux peaks ~ 0.6-1.4 x 10^{-6} ph cm^{-2} s^{-1}

-Total energy ~ 6-13 x 10^{41} erg

(But, range >0.1 GeV properties widened with recent detections…)

Ackermann et al. (2014)

Optical and γ-ray Peaks / Onsets

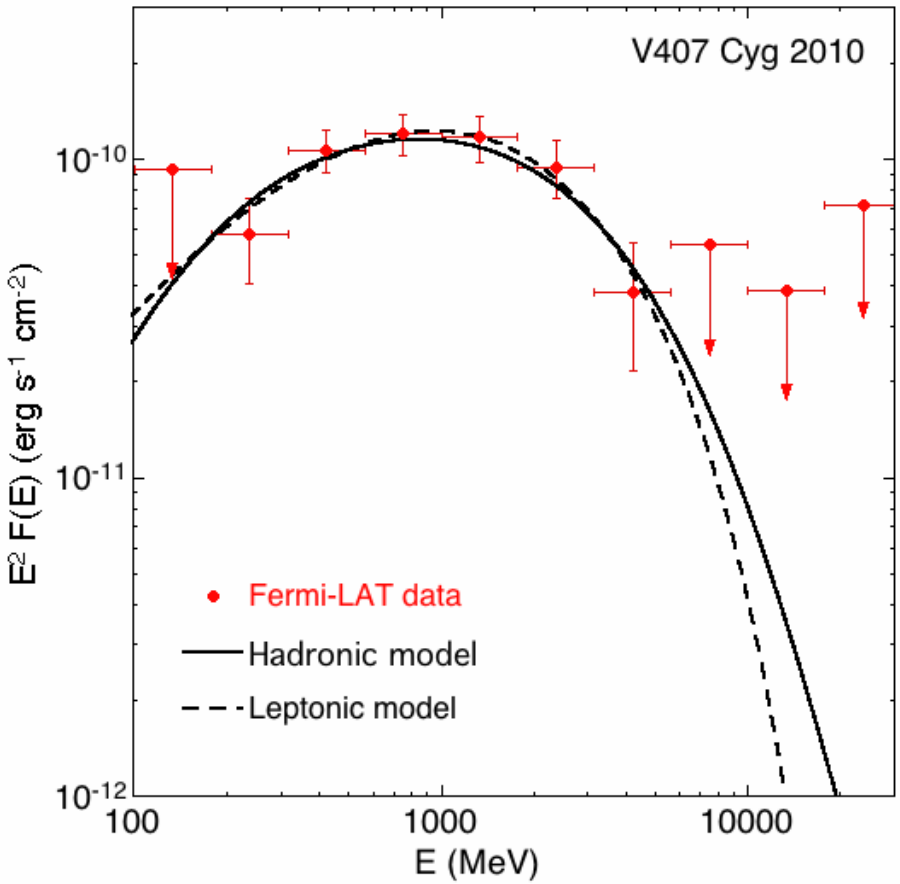


γ-ray peaks lag optical (by up to ~6 days for V339 Del)
γ-ray onset both before (V1324 Sco) and after optical peak (V339 Del)

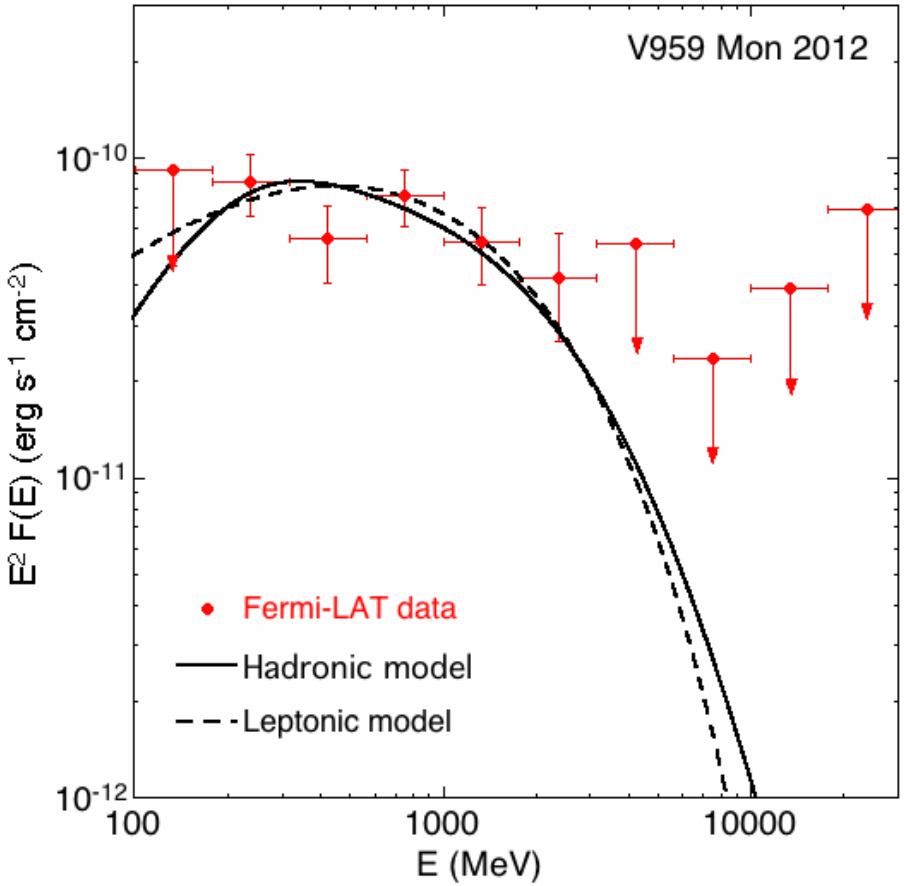
Optical, mostly AAVSO data (see Munari et al. 2015 IBVS for Sco); square = Itagaki discovery.
V1324 Sco from Cheung et al. (2015), V339 Del from Ackermann et al. (2014)

Similarity of LAT γ-ray Spectra

V407 Cyg 2010 (19 days)



Nova Mon 2012 (22 days)

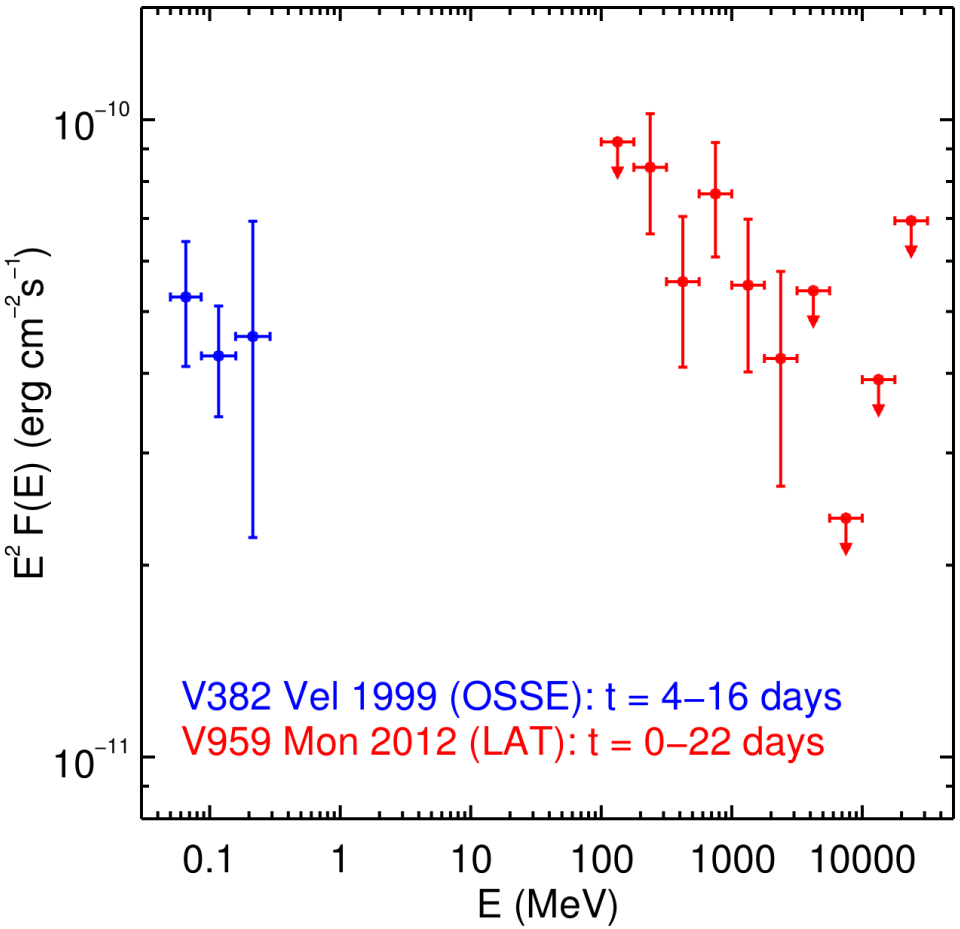


Hadronic and leptonic models satisfactory fits LAT spectra.

Origin and production site of the LAT observed γ-ray emission is an open problem.

(cf., Abdo et al. 2010, for V407 Cyg)

MeV → ← GeV Novae



V382 Vel: Leising et al. 1999, 5th Compton symp.
V959 Mon: Ackermann et al. 2014 Sci. 345, 554
See Cheung et al. 2015 ICRC

- Revisited *Compton (1991-99)* observations of classical novae in light of *Fermi* discoveries
- V382 Vel 1999 peaked at 2.5 mag May 23rd; *Compton*/OSSE 7σ continuum detection over 12-days starting 4 days after peak; non-detection in next 14-day
- Early time OSSE spectrum of V382 Vel 1999 compared to LAT data for V959 Mon 2012, both oxygen-neon novae

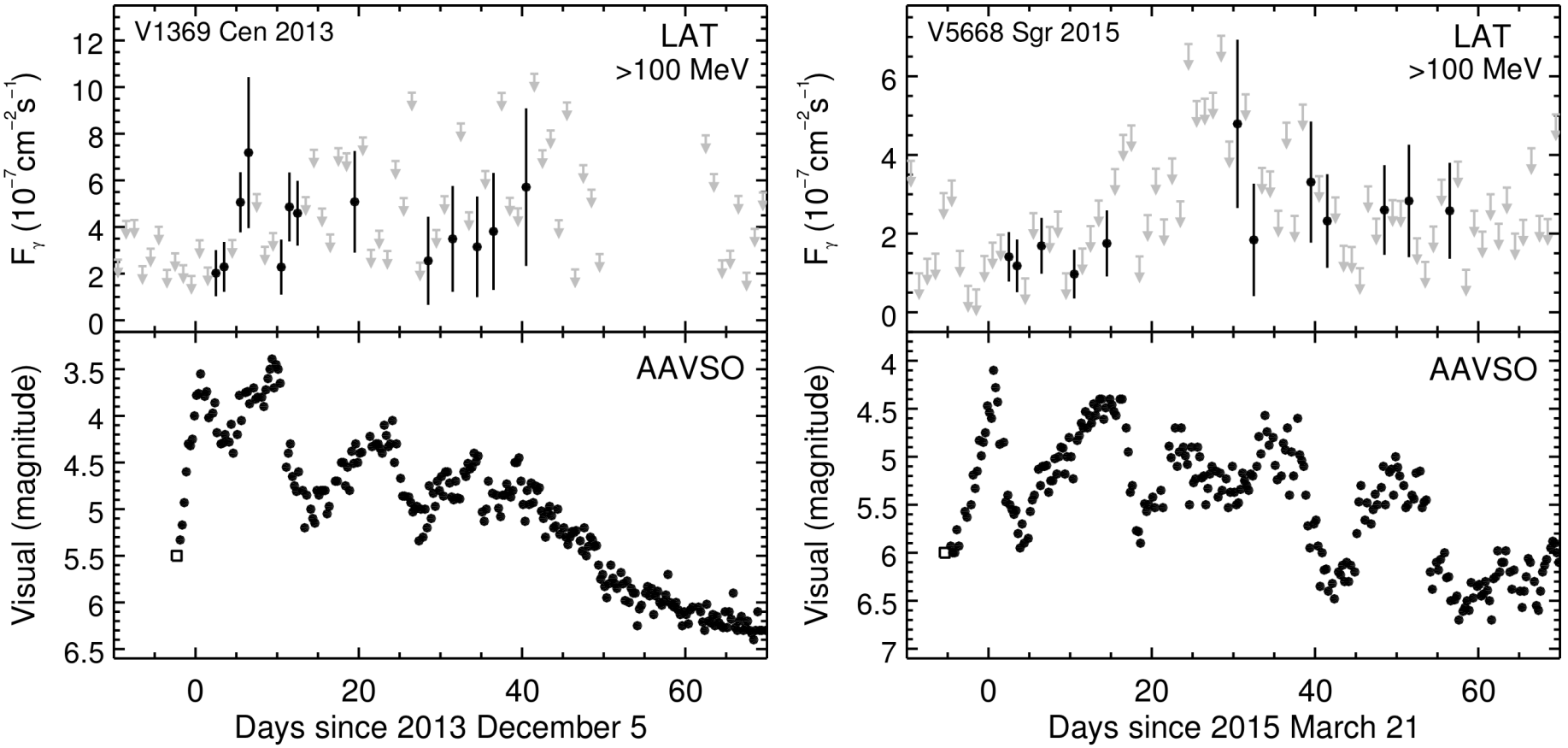
Twists and Turns

- Context:
  - 1st, symbiotic-like V407 Cyg 2010:
    "but few binary systems with a WD are known to have a similar environment; hence, we expect γ-ray novae to be rare."
  - Three classical novae with similar GeV properties (LAT 2014):

rate consistent with expected ~1 per year nearby thus all novae potential γ-ray emitters (*internally and not in print, we debated whether novae were "standard candles in γ-rays*)

- Two more optically-bright LAT-detected classical novae, with γ-rays systematically fainter, lower luminosity, and longer duration (Cheung et al. 2016)
- Widening diversity of γ-ray properties than suggested in 2014 paper; reinforces conclusion that all novae potential γ-ray emitters

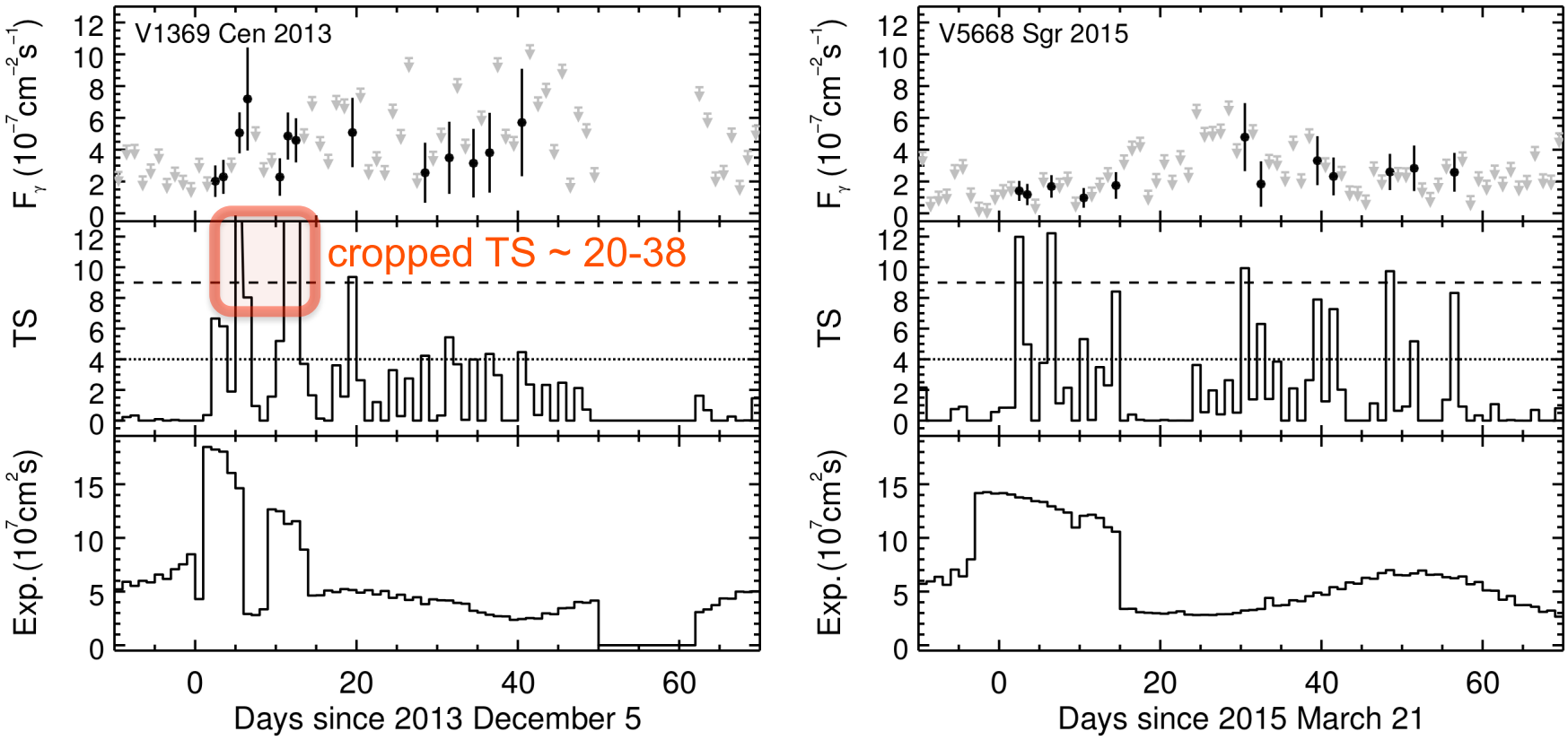
Two Long-Lasting LAT Novae Detections



- Nearby, ~2.0-2.5 kpc (previous 2.7 to >4.5 kpc), optically brightest novae since 1999
- Multiple optical peaks with fainter γ-ray emission detected sporadically for longer-duration than in previous cases

Cheung et al. (2016)

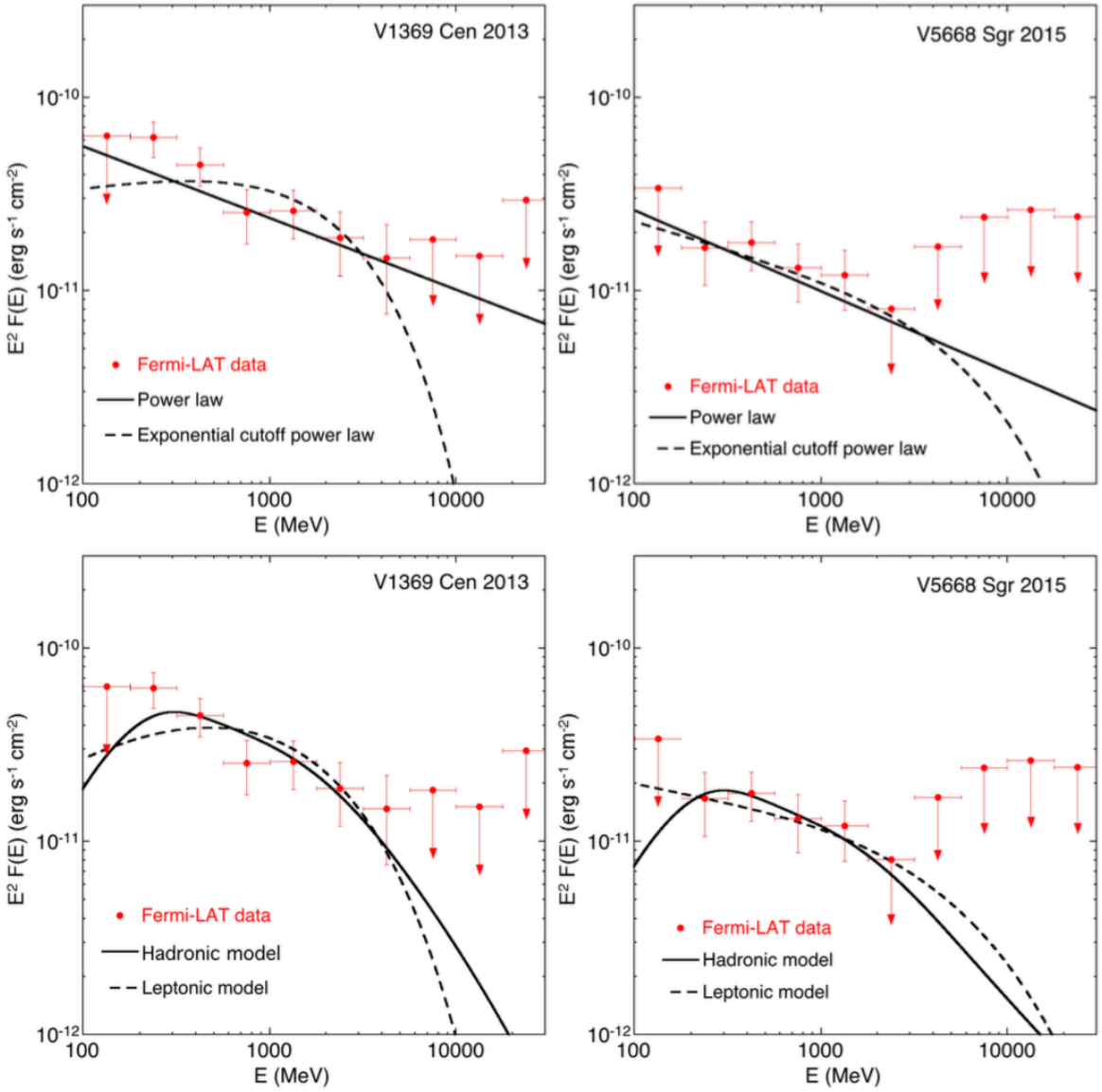
LAT ToO and Sky-survey Details



- Cen ToO 5+5 days with 3 day gap; Sgr ToO 15 days
- Unanticipated signal at late times (past ~2-3 weeks as in previous cases)
- Later Cen 12-day exposure gap due to SN14J / M81 ToO

Cheung et al. (2016)

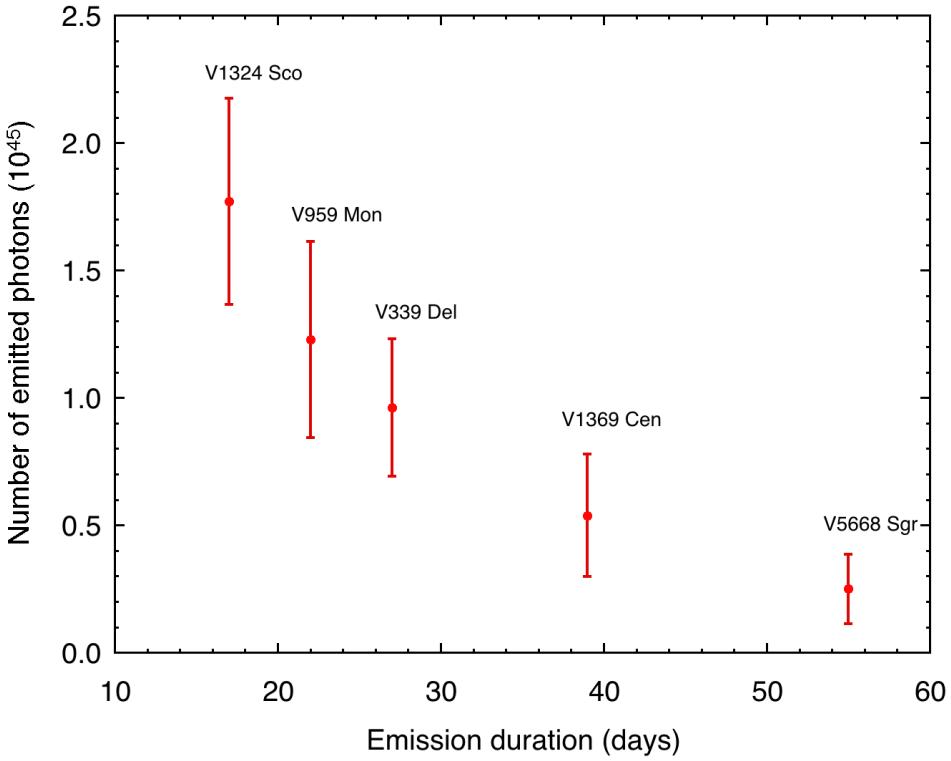
Spectra + Modeling

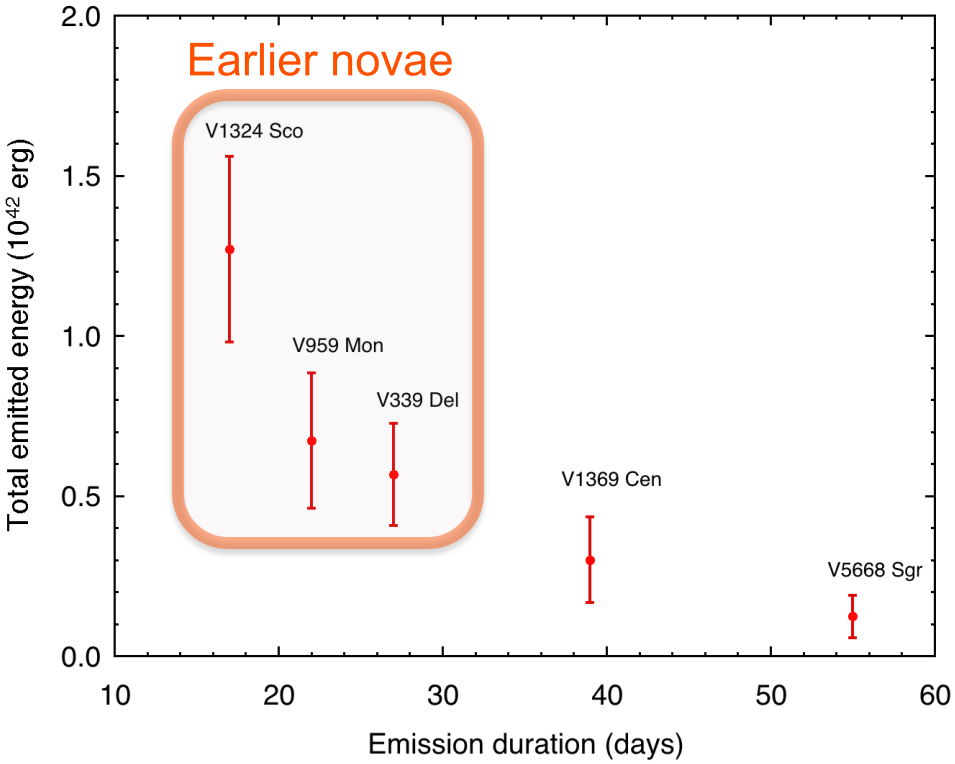


- Fit average LAT spectra with power-law and exponential PL indistinguishable because faint / lower TS than in prior examples
- Hadronic and leptonic indistinguishable also

Cheung et al. (2016)

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

Current View of Novae as γ-ray Sources

- The one symbiotic-like recurrent nova and the five classical novae detected in γ-rays so far share similarities & differences so γ-ray emission mechanism not necessarily the same
- Fermi acceleration in nova shell :
  - interaction with massive red giant wind plays important role in symbiotic recurrent novae (V407 Cyg)
  - shell-shell interactions in classical novae?
  - necessary conditions: massive WD & fast and massive ejecta ?
  - all appear nearby – detects ones within ~4-6 kpc; varying LAT exposure should be considered on case-by-case basis

Summary and Outlook

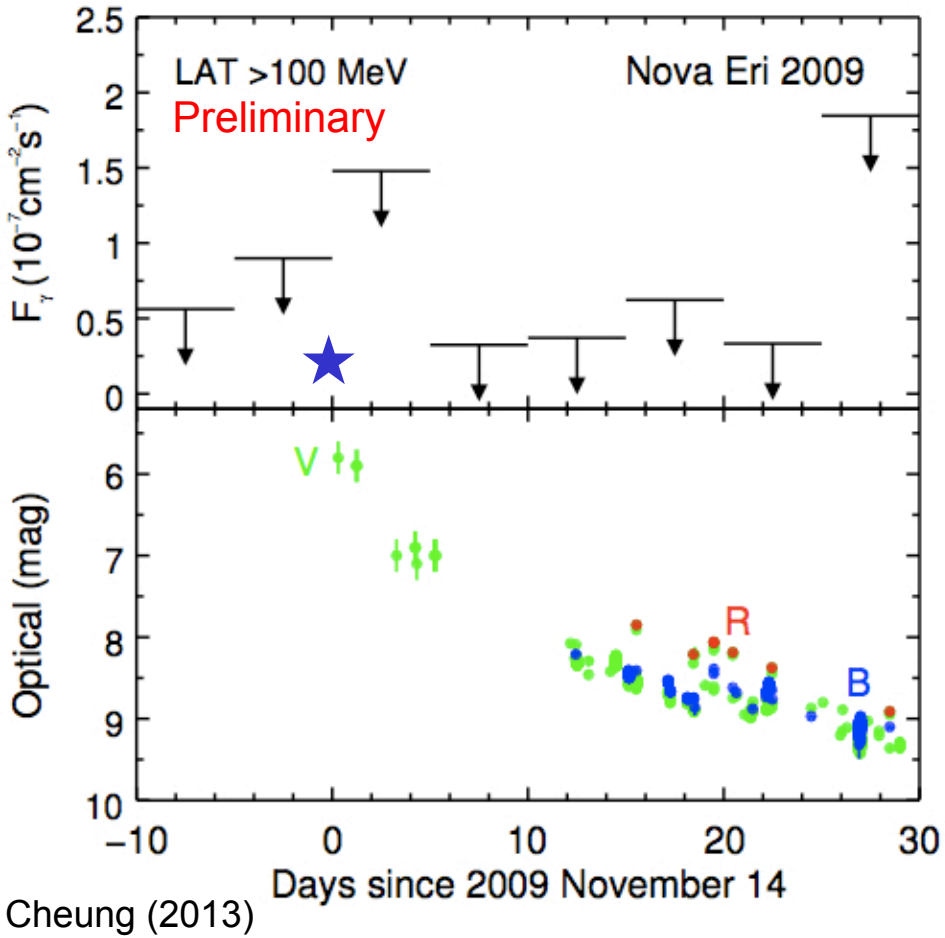
- *Fermi*-LAT E ~ 0.1 – 10 GeV observed spectra and light curves:
  - Soft γ-ray spectra; emission up to ~few GeV (~10 GeV for V1324 Sco 2012) and evidence for curvature in brightest ones
  - Wide range >0.1 GeV luminosities ~(0.3 – 9) x10^{35} ergs s^{-1} and total emitted energies ~(0.1 – 1.3) x10^{42} ergs
  - γ-ray durations of ~2 – 3 weeks for early detections; longer, ~39-55 days for recent optically-brightest cases with systematically lower luminosities and total energies, revealing wider diversity of properties

- LAT γ-ray detection rate ~1 yr^{-1} ≈ expected rate of nearby Galactic novae, suggests all novae are potential γ-ray sources: *more novae expected*
- γ-ray emission mechanism and production site still open problems
- Symbiotic recurrent novae probe role of companions in γ-ray production, not fully explored in classical novae; important recurrents awaiting outbursts in *Fermi* era (RS Oph, T CrB) with expanded energy coverage (>0.1 TeV with CTA and high-energy neutrinos with IceCube-Gen2)
- *Compton*/OSSE continuum observed in V382 Vel 1999 indicate LAT spectra extend to ~0.1 MeV energies; important future missions (AMEGO)

Bonus Slides

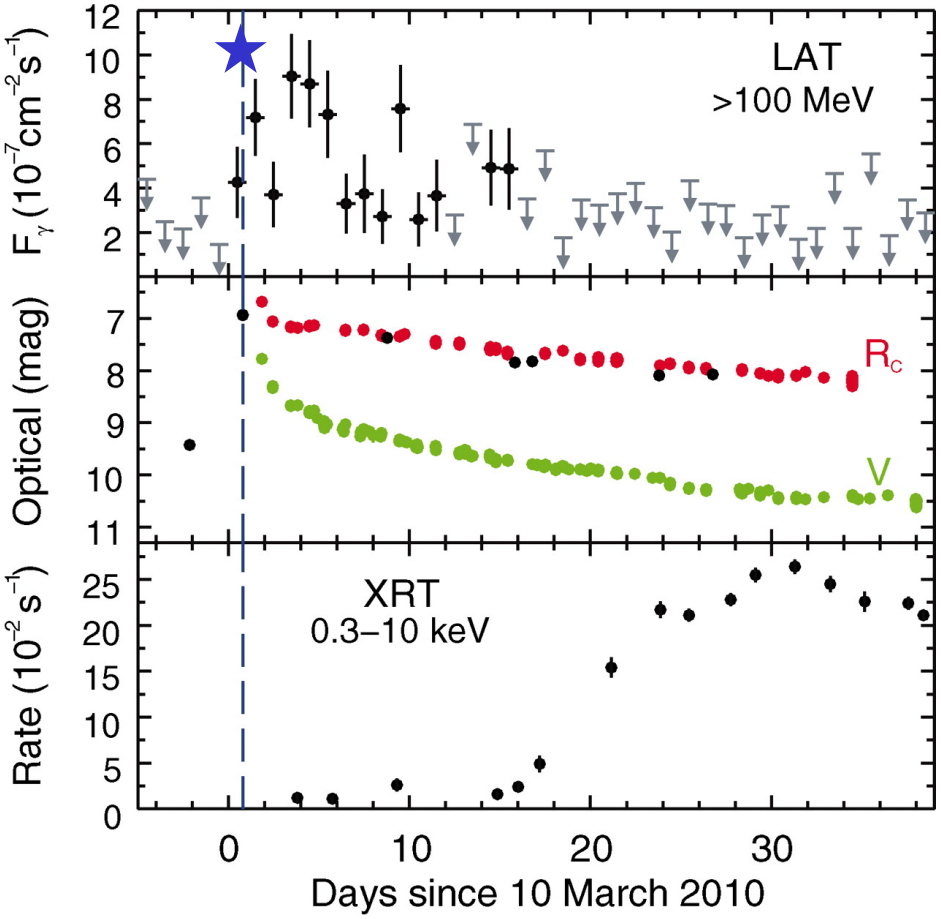
LAT Non-Detections

KT Eri 2009 Classical Nova
(white dwarf + Main sequence star)



Cheung (2013)

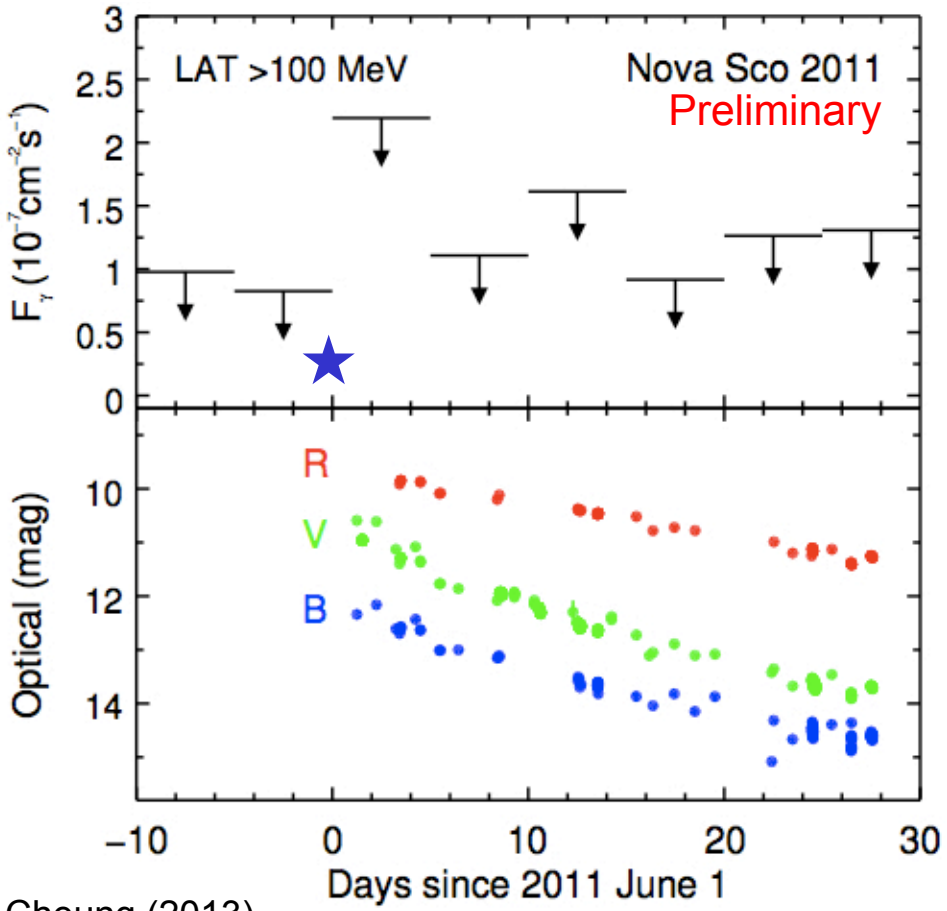
V407 Cyg Symbiotic Recurrent Nova
(white dwarf + Red Giant)



Other novae typically <~10x fainter than V407 Cyg γ-ray peak – why?

LAT Non-Detections

V1312 Sco 2011 Classical Nova
(white dwarf + Main sequence star)



Cheung (2013)

V407 Cyg Symbiotic Recurrent Nova
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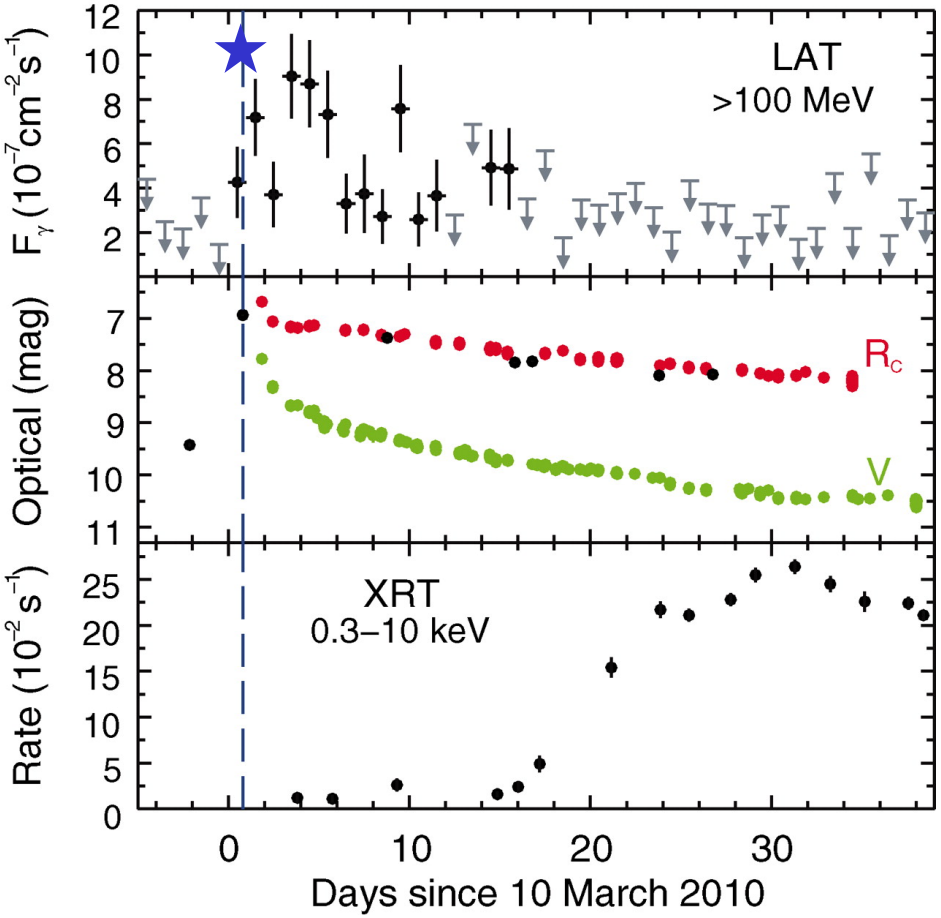
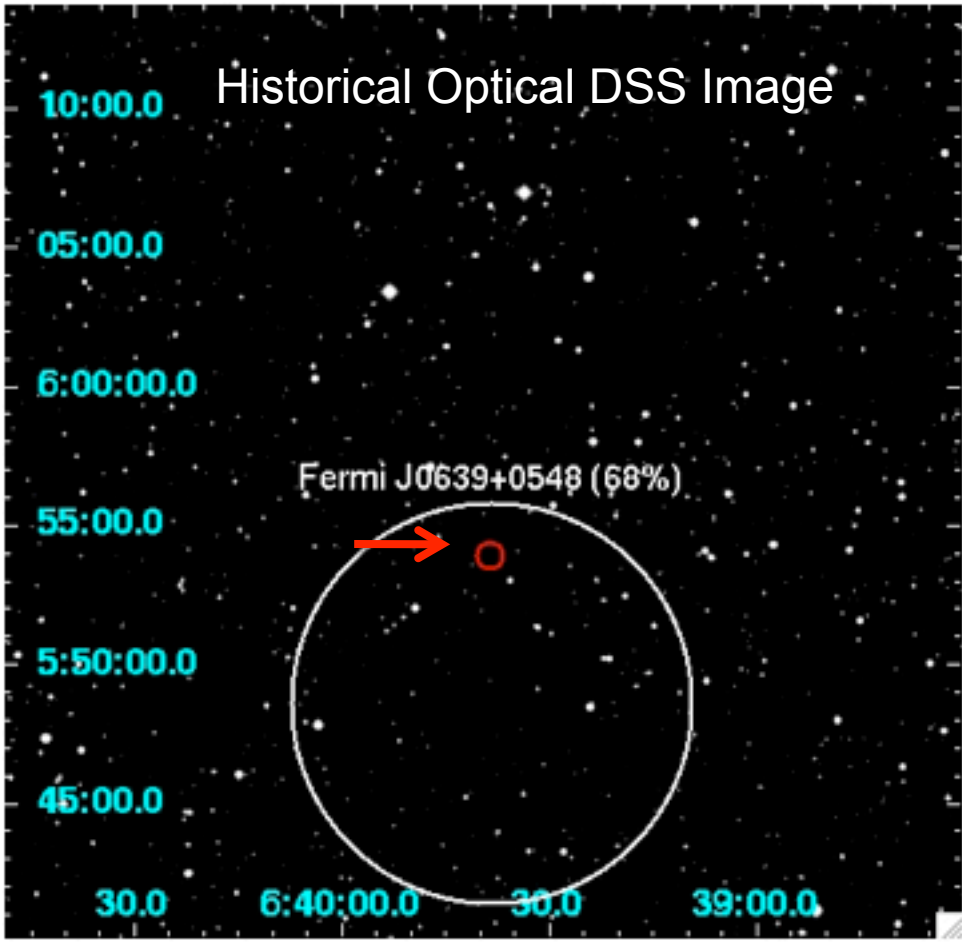


Other novae typically <~10x fainter than V407 Cyg γ-ray peak – why?

Fermi-LAT *Discovery* of Nova Mon 2012



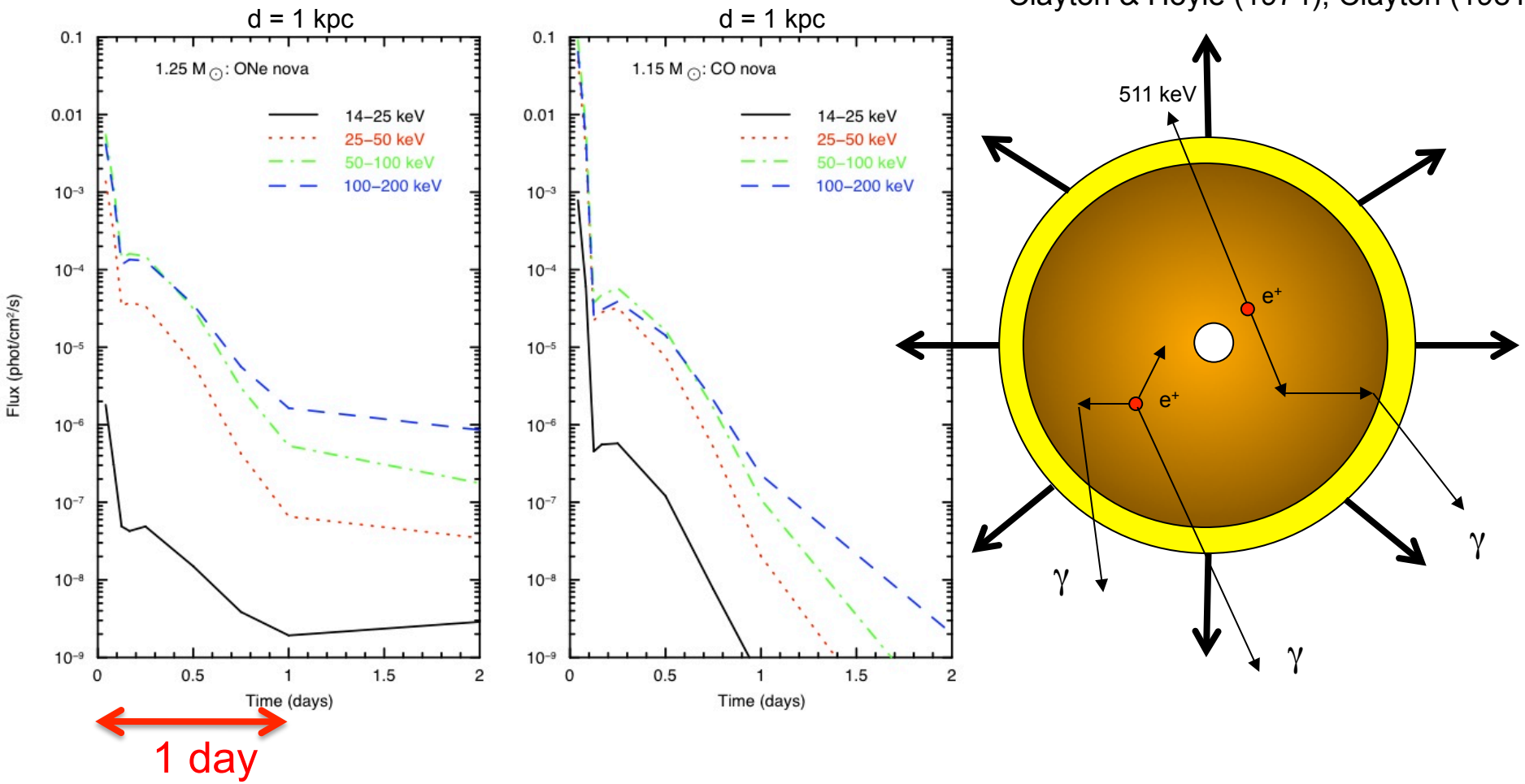
- Initial LAT discovery of Fermi J0639+0548, ~20^{o} from Sun in late-June (Cheung et al. ATel #4224)
- Optical discovery of possible nova August 9 (S. Fujikawa, CBET#3202)
- Amateur spectroscopic confirmation Aug 14-16 as ONe type classical nova **~50 days after outburst**, 3-4 kpc away
  LAT association with Nova Mon 2012 (Cheung, Shore et al. ATel #4310)
- Inferred optical peak in June of ~4.5-5 mag

MeV Nuclear Gamma-ray Emission

^{13}N & $^{18}F \rightarrow$ 511 keV + continuum (Compton diffusion & positronium)

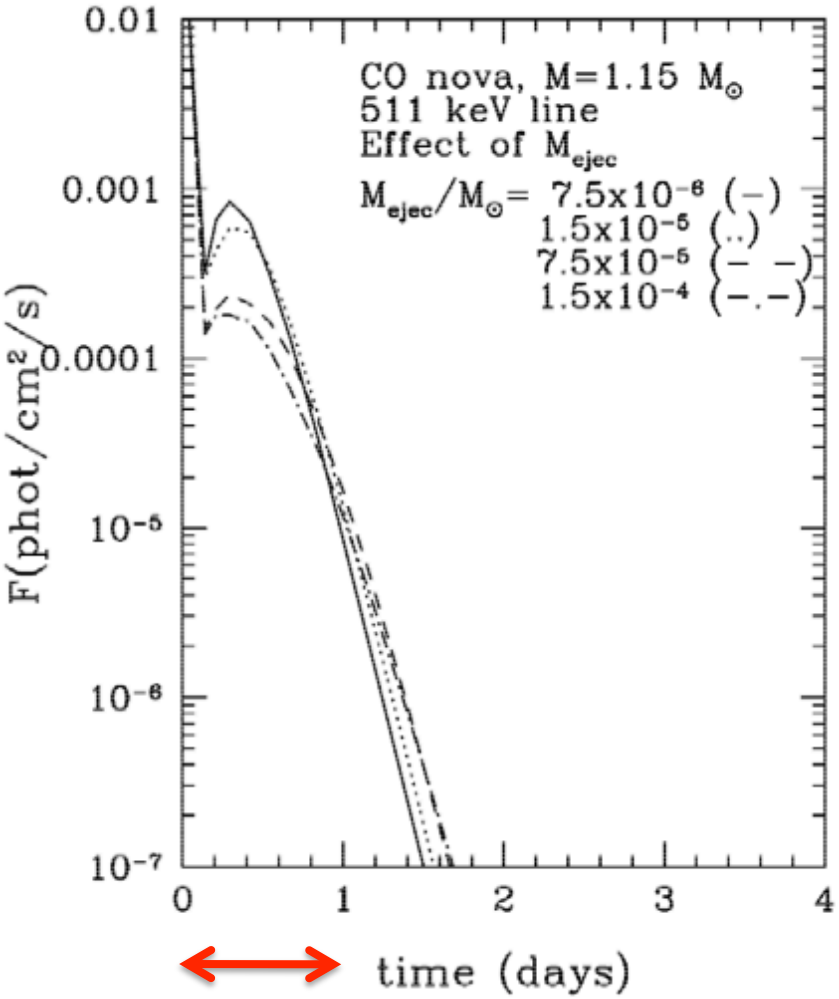
Gamma-ray lines: 478 keV from $^{7}Be \rightarrow {}^{7}Li$ & 1275 keV from $^{22}Na \rightarrow {}^{22}Ne$

Clayton & Hoyle (1974), Clayton (1981)

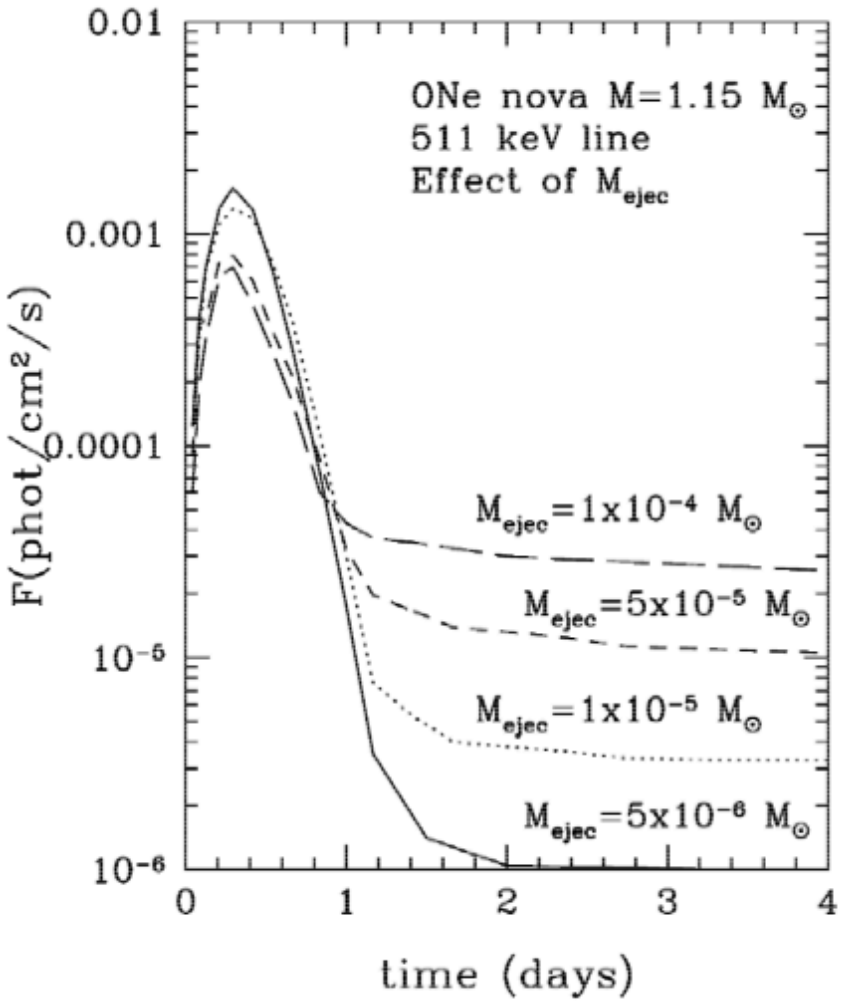


Senziani, Skinner, Jean & Hernanz (2008)

MeV Lightcurves: Ejecta Mass

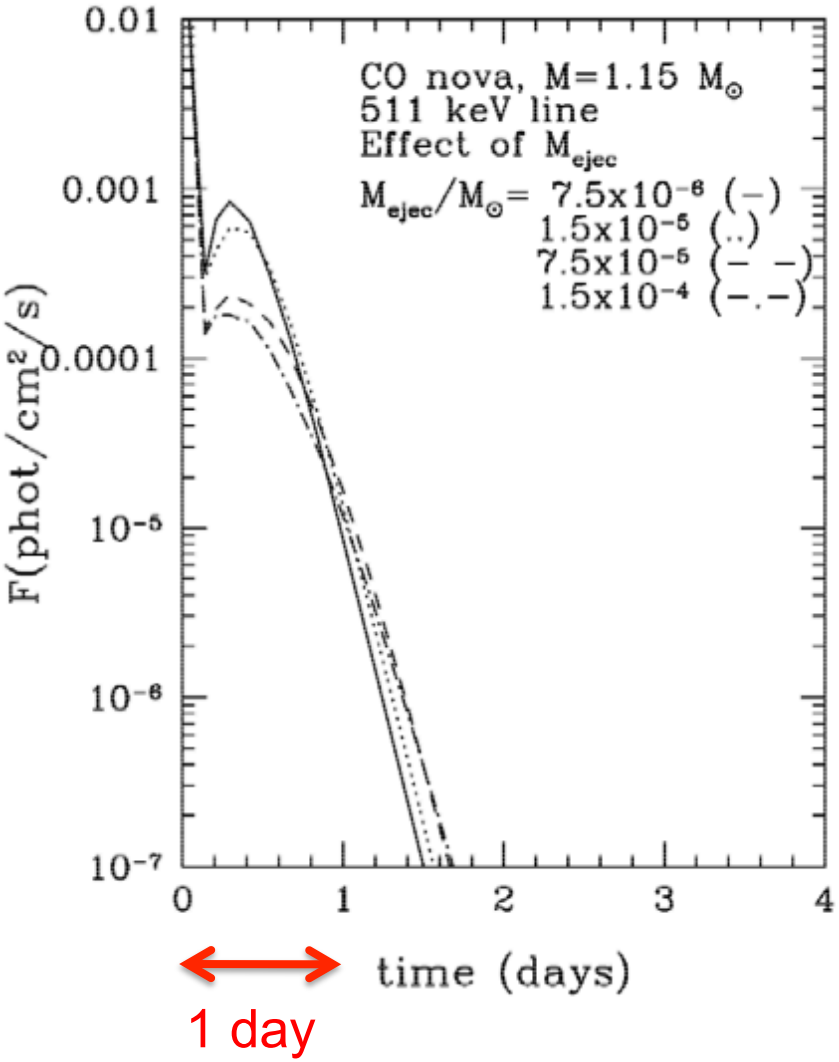


1 day

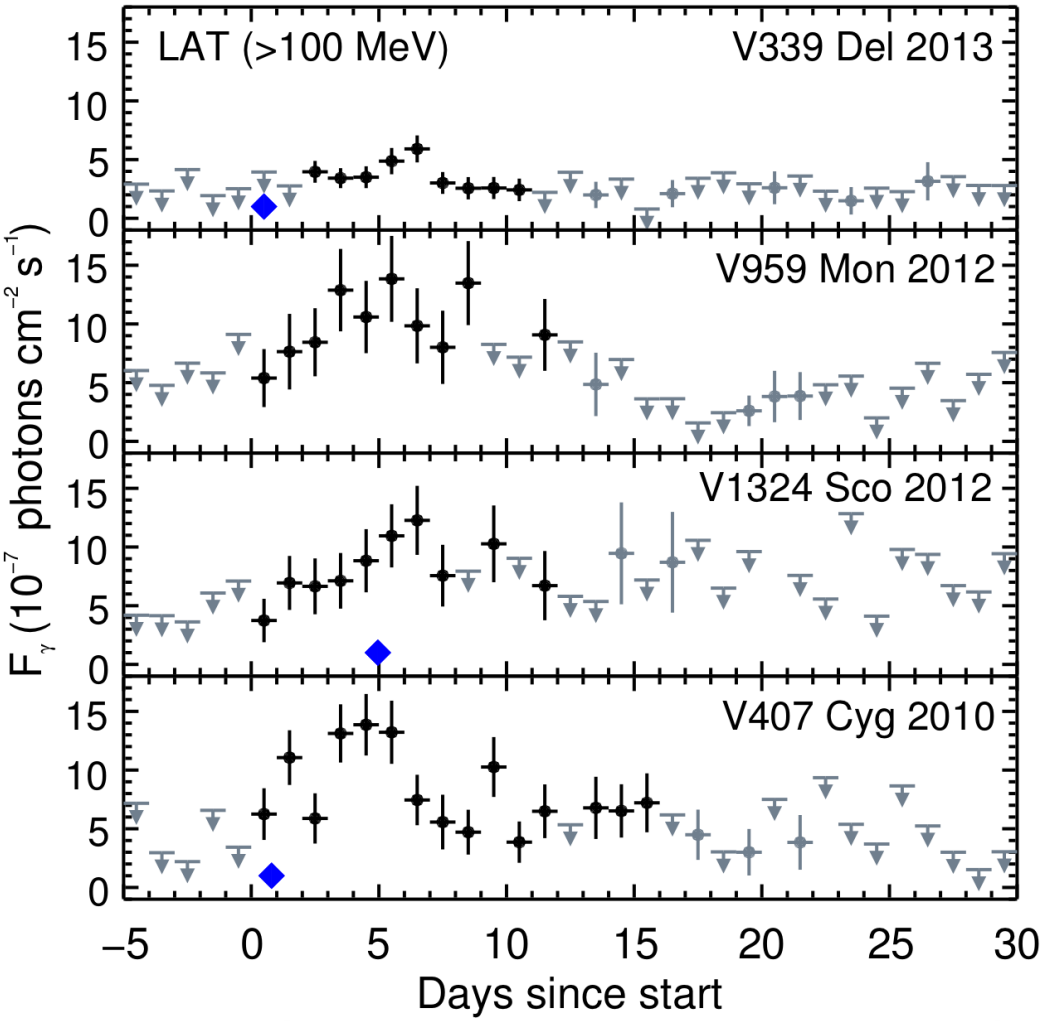


Dependence on ejecta mass, ejecta velocity, white dwarf mass
(Hernanz et al. 2002)

Lightcurves: MeV to GeV

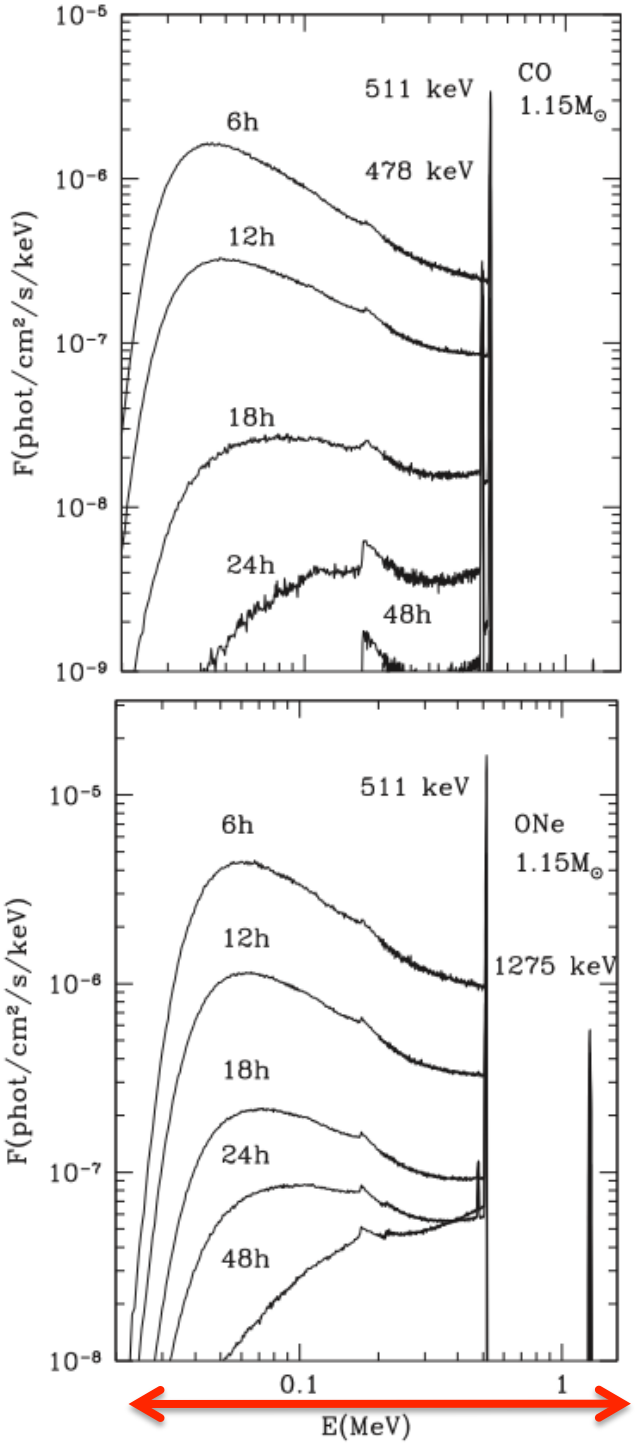


1 day



30 days

Spectra MeV ➔ ➔ GeV

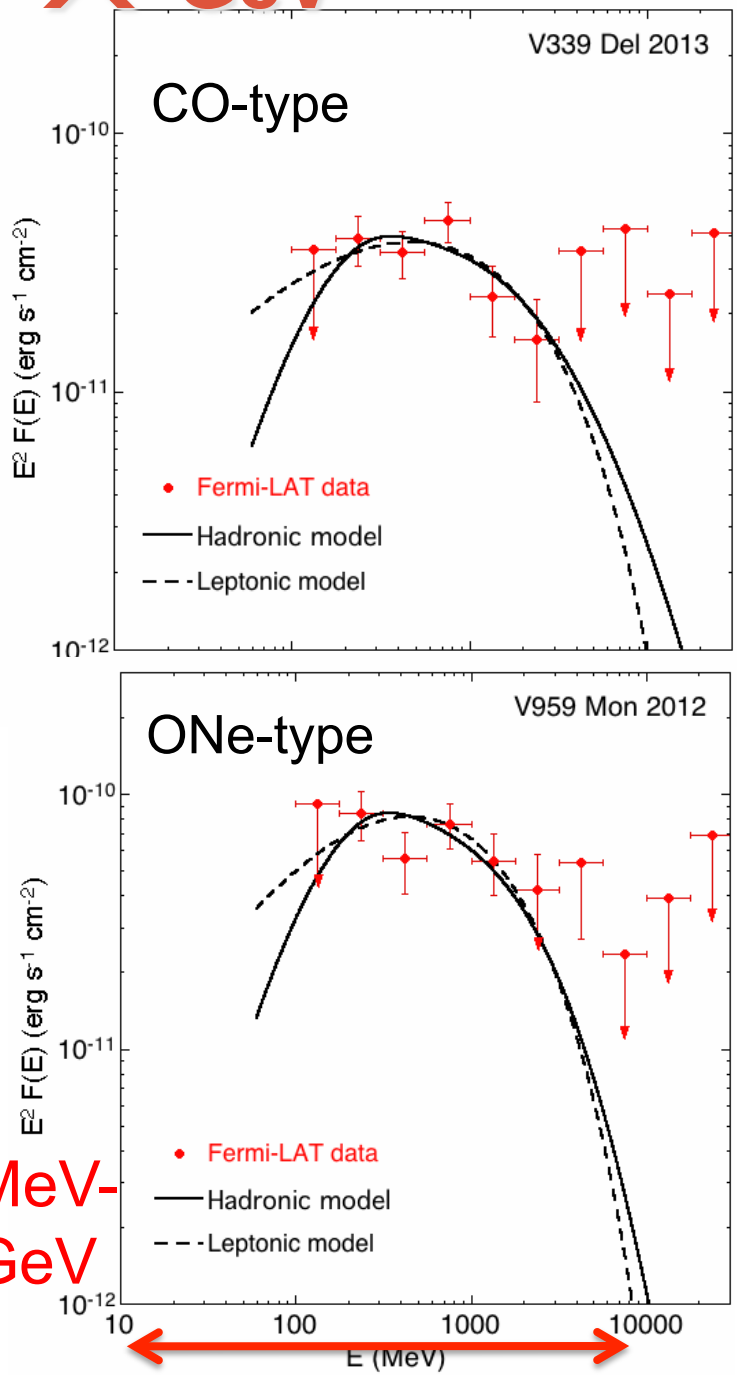


CO-type
478 keV

Hernanz 2014

ONe-type
1275 keV

~0.02-2 MeV



10 MeV-
10 GeV

MeV-GeV Novae: Key Points

- Despite limited angular resolution, novae can be identified as transient sources of **prompt nuclear MeV** line emission with continuum down to ~30 keV, followed by **longer-duration >10 MeV γ-ray continuum** due to shock-accelerated nova ejecta
- Fast response times needed for nuclear decay emission
- keV-MeV to >GeV, and lower-frequency coverage key to particle acceleration (INTEGRAL)
- Nearby recurrents RS Oph (2021?), T CrB (2026?), could be remarkably bright MeV-GeV-TeV γ-ray source, and a transient higher-energy neutrinos expected in the hadronic scenario